NUMO-TR-04-04

Evaluating Site Suitability for a HLW Repository

Scientific Background and Practical Application of NUMO's Siting Factors

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Nuclear Waste Management Organization of Japan (NUMO)

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Preface

The primary objective of government policy, and of NUMO in implementing this policy, is to ensure that a repository for Japan's high-level radioactive waste is located so as to provide secure isolation of the waste and adequate safety for present and future generations. This means that the site has to be chosen carefully, taking full account of all its characteristics. In order to address these characteristics in an orderly and structured manner, we have established a comprehensive set of Siting Factors, which, together, help determine the suitability of any potential repository site. At present, these Siting Factors have been developed only so far as is necessary to address the first stage of our siting programme – the identification of Preliminary Investigation Areas.

Japan lies in a region of active global tectonics – characterised by dynamic geological processes, volcanism and earthquakes. One of the first things that we need to be sure about is that a repository is not located where it could be adversely affected by these events and processes over a long period of time in the future, which means that we need to take account of tectonic mechanisms and how they change with time. The first application of the Siting Factors addresses this issue.

Choosing a suitable site is one of our biggest challenges at NUMO, not only technically but also socially. We have adopted an open and inclusive approach to siting. It begins by seeking volunteer communities prepared to work with us to see whether they would be willing to act as hosts for a repository and to find out whether their location is technically suitable. Communities will thus become involved in the selection and development process and in the evaluation of the Siting Factors.

As well as being safe and secure, the chosen location needs to be in an environment that is feasible for the construction and operation of the repository using available engineering technology, at reasonable expenditure of resources. Location, design and operations must also satisfy the requirements of the communities that host it. The Siting Factors described in this document are eventually intended to address site characteristics comprehensively and provide a clear and transparent route to how we shall achieve these aims through the site selection process. Part 1 explains what the Siting Factors are, how they have been derived so far and how they will be applied in a staged manner. Part 2 provides a more detailed scientific discussion of the tectonic setting of Japan. We have chosen to focus on this issue for two reasons – first, the Siting Factors that cover tectonic stability are applied from the very beginning of our siting programme and, second, because, given Japan's tectonic situation, they have more prominence than in many other national waste management programmes.

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1 INTRODUCTION

1.1 NUMO and its mission

NUMO – the Nuclear Waste Management Organization of Japan – was established in October 2000 on the basis of the Specified Radioactive Waste Final Disposal Act (the "Act") promulgated in June 2000. In this Act, we are given the clearly defined remit to develop a project for the safe disposal of vitrified high-level radioactive waste (HLW). As indicated in Figure 1-1, NUMO operates within a network of government and other relevant organisations which have complementary responsibilities for the technical, legal, regulatory and funding activities associated with HLW disposal in Japan.

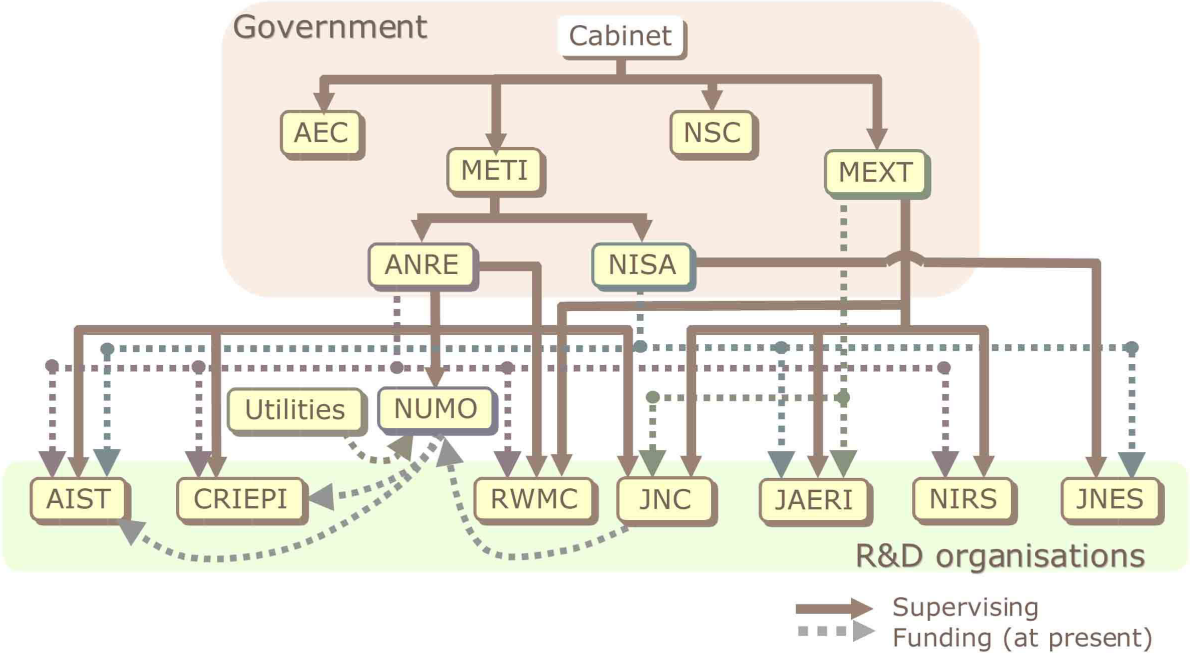

Figure 1-1: NUMO in the context of the Japanese HLW disposal programme.

Acronyms:

AEC: Atomic Energy Commission (http://aec.jst.go.jp/jicst/NC/eng/index.htm)
NSC: Nuclear Safety Commission (http://www.nsc.go.jp/english/english.htm)
METI: Ministry of Economy, Trade and Industry (http://www.meti.go.jp/english/index.html)
ANRE: Agency for Natural Resources and Energy (http://www.enecho.meti.go.jp/english/index.htm)
NISA: Nuclear and Industrial Safety Agency (http://www.nisa.meti.go.jp/english/index.htm)
MEXT: Ministry of Education, Culture, Sports, Science and Technology(http://www.mext.go.jp/english/index.htm)
NUMO: Nuclear Waste Management Organization of Japan (http://www.numo.or.jp/english/index.html)
JNC: Japan Nuclear Cycle Development Institute (http://www.jnc.go.jp/jncweb/02r-d/02index.html)
JAERI: Japan Atomic Energy Research Institute (http://www.jaeri.go.jp/english/index.cgi)
NIRS: National Institute of Radiological Sciences (http://www.nirs.go.jp/ENG/nirs.htm)
RWMC: Radioactive Waste Management Funding and Research Center (http://www.rwmc.or.jp/)
AIST: National Institute of Advanced Industrial Science and Technology (http://www.aist.go.jp/index_en.html)
CRIEPI: Central Research Institute of Electric Power Industry (http://criepi.denken.or.jp)
JNES: Japan Nuclear Energy Safety Organization (http://www.jnes.go.jp/english/index.html)

The Act restricts NUMO's responsibility to the consideration of "specified" radioactive waste – which is defined to be HLW resulting from the reprocessing of spent fuel from commercial power reactors.

The Act is also prescriptive in terms of the management option to be followed. It specifies deep geological disposal in Japan at depths greater than 300 m below surface. Also specified are requirements for geological stability and avoiding conflict with natural resources. The phased process of developing a siting project, involving more detailed characterisation as options are narrowed down, is also outlined in the legislation.

Following extensive discussions with many stakeholders, NUMO decided to take a rather innovative approach to the siting process. Based on consideration of international experience in repository siting, we recognised local acceptance as a critical issue which is essential to the success of such projects. We thus decided on a policy of calling for volunteer communities that would be willing to consider hosting this facility.

We sent a call for volunteers to all 3,239 municipalities in Japan in December 2002. Of course, potential host sites must also satisfy important geological and technical requirements. Accordingly, the documentation accompanying the call included an explicit specification of exclusion criteria which would be used to filter out clearly unsuitable areas[1]. These criteria were based on the geological stability requirements noted in the legislation and the associated documentation included maps showing areas that would be clearly ruled out – e.g. due to risk of volcanic activity or the presence of major active faults. Even if an area is not excluded by such criteria, implementing a repository may be impractical or other volunteer areas may be more suitable. A range of other selection factors ("Favourable Factors") have thus been defined which will allow the staged siting process to proceed in a transparent manner (described in detail in Chapter 5).

The present report describes the Siting Factors for the staged site characterisation and evaluation process and places them in the context of the geological setting of Japan. A companion report (NUMO, 2004) comprises a review of the status in one particular site – the development of "Repository Concepts" appropriate to the siting environments defined during the volunteer process. This term "siting environment" includes not only the geological setting but also all other features which influence repository implementation – such as geography, topography, socio-economic constraints and transportation infrastructure. In practice, the repository design and site characterisation processes are strongly coupled and develop in an iterative manner, with safety assessment during the various stages leading up to repository implementation.

These reports reflect NUMO's commitment to a policy of openness in its dealings with all interested parties. More extensive Japanese language reports covering the same topics are aimed at the potential volunteer communities and relevant organisations in Japan. There is thus a particular focus on the technical detail to support the call for volunteers. It should be emphasised that the English language documentation is not a translation, but is completely reworked to provide the background needed to enable a productive exchange of views with an international technical audience.

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[1] English translations of the documents supporting the call for volunteers, "Information Package", are available via the NUMO website (www.numo.or.jp/english/what/index.html).

1.2 The repository development programme and milestones

Japan has an active nuclear power programme which includes an installed capacity of about 46 GW(e). Plans exist to expand nuclear power generation further and to extend the life of nuclear power plants based on careful safety review and maintenance (AEC, 2000). This strategy is designed to maintain the stable power production required by an industrial nation, while complying with requirements to reduce emissions of greenhouse gases from the combustion of fossil fuels. The decision to reprocess spent fuel reflects this long-term vision of nuclear power generation, which results from Japan's lack of significant resources of uranium and its commitment to sustainable development, which encourages all such recycling activities.

Presently, spent fuel from Japanese reactors is reprocessed in the UK or France and vitrified HLW returned to Japan for interim storage in a special facility at the Rokkasho site of Japan Nuclear Fuel Ltd. (JNFL) as shown in Figure 1-2(a). On a pilot scale, fuel has also been reprocessed and HLW produced by JNC at Tokai (Figure 1-2(b)). In the near future, a full-scale reprocessing plant will become operational in Japan – also run by JNFL at Rokkasho.

For a continually developing programme, establishing a time plan for implementation requires a balance to be struck between various technical and socio-economic considerations. For example, the technical advantages of storing reprocessed waste prior to disposal for as long as possible, in order to reduce radiogenic heat output, needs to be balanced against the ethical goal that the generation benefiting from nuclear power should also implement, or at least initiate, projects to ensure safe management of resulting wastes. Recently, another argument for accelerated implementation of deep geological disposal projects has focused on national security, due to the reduced vulnerability of underground facilities to possible terrorist threats.

Figure 1-2(a): JNFL Vitrified Waste Storage Center (left) and HLW storage pits (right) (photos: courtesy of JNFL).

Figure 1-2(b): JNC Tokai Reprocessing Plant (left) and HLW storage pits (right) (photos: courtesy of JNC).

In Japan, the planned development programme for a first HLW repository is outlined inFigure 1-3. This is based on an assumed capacity of 40,000 waste packages each containing 150 litres of vitrified waste, corresponding to reprocessing of all spent fuel expected to be produced up to 2020. The vitrified HLW will be stored for 30-50 years before disposal (MITI[2], 2000a). According to the Final Disposal Plan (MITI, 2000b), repository operation would start in the late 2030s, with an annual emplacement of 1,000 canisters of vitrified HLW.

Following our call for volunteers, the siting process is planned to proceed in a staged fashion. The first stage involves use of literature information to determine the basic suitability of each volunteer area in the light of established exclusion criteria, and to rank areas, in the event that there are more volunteers than can go through to the second stage of field characterisation. Such ranking may also be useful to set priorities and help plan the strategy for subsequent site characterisation, repository design selection and associated performance assessment.

The initial field characterisation of **"Preliminary Investigation Areas" (PIAs)** is restricted to work carried out from the surface. Following this stage, areas are again compared and a reduced number carried on as **"Detailed Investigation Areas" (DIAs)**, in which an underground characterisation facility is constructed to allow the deep geological environment to be examined in more detail. According to this plan, a site would be selected, the associated repository concept specified and the licensing process initiated in the late 2020s, allowing construction to commence around 2030 with first waste emplacement in the late 2030s. The time plan shown in Figure 1-3 assumes that, to some extent, construction, waste emplacement and sealing of emplacement tunnels proceed in parallel and emplacement operations are completed by the mid- to late 2070s. We also leave open a possible period of monitoring and institutional control, with final closure thus being sometime after 2080.

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[2] Ministry of International Trade and Industry (now METI).

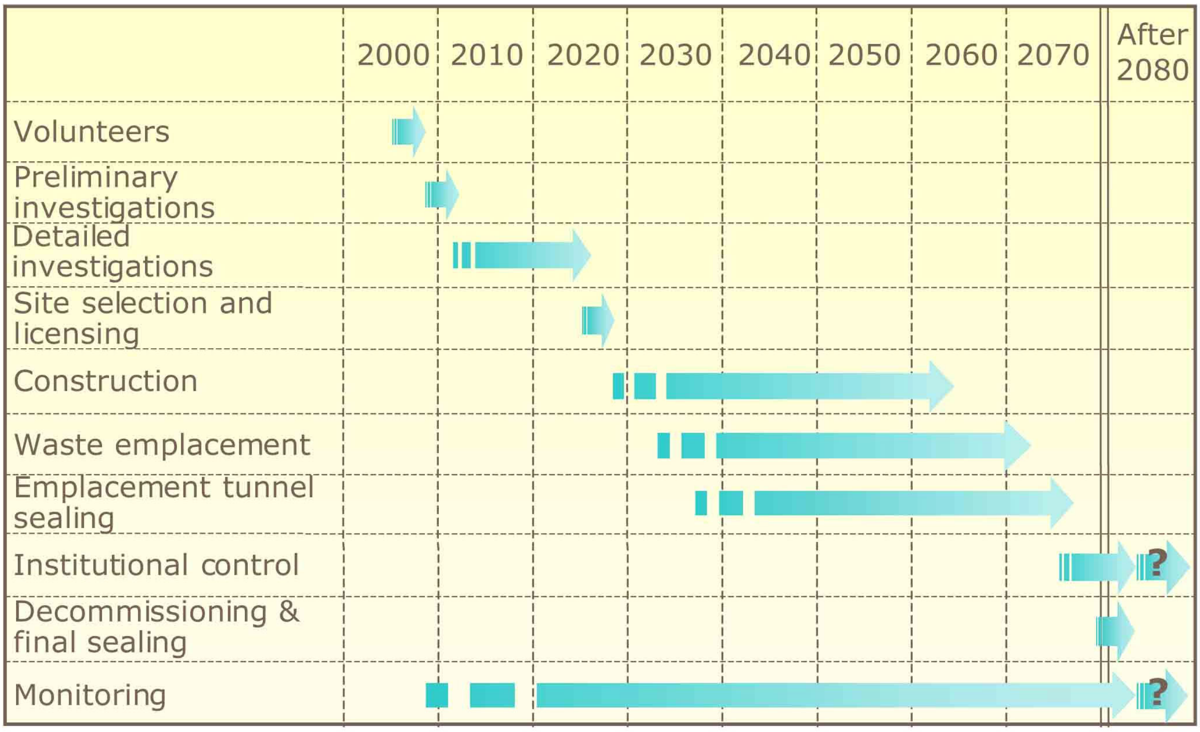

Figure 1-3: The staged repository development programme and possible milestones. The time plan after site selection has a model nature as it will depend, to some extent, on the repository concept selected.

1.3 The siting programme and Siting Factors

When a community volunteers to be considered as a potential repository host, we will need to determine whether the area would qualify as a suitable PIA. In doing this, we will pay close attention to the views of the municipality or municipalities concerned. To assist with this decision, we have identified a set of Siting Factors that can be used to evaluate whether an area has appropriate characteristics for a repository site. The development of these factors is based on the guidelines on geological repository siting prepared by the IAEA (1994). These guidelines, which also identify the possibility of using a volunteer approach to solicit candidate sites, envisage four stages in the siting process:

- conceptual and planning stage;
- area survey stage;
- site characterisation stage;
- site confirmation stage.

In the conceptual and planning stage, the IAEA recommends the establishment of screening guidelines which are then used in the area survey stage in a stepwise fashion to evaluate candidate areas or sites. It is noted that the area survey stage would tend to use available data and this approach has been adopted in our planning, as discussed later. At present, we are about to move from the conceptual and planning stage envisaged by the IAEA into the area survey stage, as volunteers come forward, and we will use the screening approach to evaluate their characteristics. The IAEA site selection guidelines identify the following characteristics for a suitable site:

- The geological setting should be amenable to characterisation, should have geometric, geomechanical, geochemical and hydrogeological characteristics that inhibit radionuclide transport and allow safe repository construction, operation and closure;
- The host rock and repository containment system should not be adversely affected by future dynamic processes of climate change, neotectonics, seismicity, volcanism, diapirism, etc.;
- The hydrogeological environment should tend to restrict groundwater flow and support waste isolation;
- The physicochemical and geochemical characteristics should limit radionuclide releases to the environment;
- Potential future human activities should be considered in siting and the likelihood that such activities could adversely affect the isolation capability should be minimised;
- Surface and underground characteristics should allow optimised infrastructure design in accordance with mining rules;
- The site should be located such that waste transport to it does not give rise to unacceptable radiation or environmental impacts;
- Site choice should mean that the local environmental quality will not be adversely affected, or such effects should be mitigated to an acceptable degree;
- Land use and ownership in the area of the site should be considered in connection with possible future development and regional planning;
- The overall societal impact of developing a repository at the chosen site should be acceptable, with beneficial effects being enhanced and negative effects minimised.

In developing our Siting Factors we have taken account of the above guidelines proposed by the IAEA and each of the topics in this list is included within one or more of the groups of our factors. A similar approach has been used in many other national programmes, with the level of detail of development of Siting Factors varying widely from country to country (IAEA, 2000).

During the development stage of our own Siting Factors, leading up to the distribution of an Information Package to municipalities in 2002 that launched the volunteer process, our approach was reviewed by the High-level Radioactive Waste Disposal Expert Sub-committee and its Technical Working Group, which provided feedback to METI, as shown in the hierarchy in Figure 1-4.

Figure 1-4: Hierarchical review of Siting Factors.

To allow stepwise application, our Siting Factors fall into two main groups:

- **Evaluation Factors for Qualification (EFQ)**: geological characteristics that the volunteer areas must exhibit in order to be considered as PIAs. Principally, these concern stability with regard to potentially disruptive events, such as volcanic eruptions and fault movements. These factors have been defined in a practical way to satisfy the requirements of the Act. Their application will thus lead to some regions of Japan being excluded from further consideration. They are divided into two sets and applied in two steps – nationwide and site-specific (see below).

- **Favourable Factors (FF):** a wide range of geological, environmental, social and economic characteristics of an area that will help to determine the overall practicality of the project and, eventually, to discriminate between potential repository locations. Unlike the EFQ, there are no absolute requirements among these FF. Rather, they express **preferences**, and can be weighed and compared in a flexible manner to highlight the advantages and disadvantages of an area. These factors will also influence the final design of a repository and the details of its development and operational programmes, and can be used to optimise these. Because we want to achieve a solution that is safe, secure and of benefit to the community, we will place great emphasis on these factors, continuing to evaluate them right up to the point of choosing a final repository location. At present, we have not fully developed the FF because they may not have a major influence on the identification of PIAs, unless we have many legally qualifying PIAs to compare. They will assume progressively greater significance as we move further into the programme and begin to assess and compare siting options.

In December 2002, we published an Information Package that provided background on the HLW repository project, initial requirements for finding a suitable site and guidance for municipalities that might wish to consider acting as host communities for the repository. The information was sent to all municipalities in Japan. As noted in Section 1.1, it was also published in English, so that the wider international community could be informed about our approach.

One of the main documents in the Information Package addresses *"Siting Factors for the Selection of Preliminary Investigation Areas"*. Here, we describe a stepwise evaluation approach that we will use to evaluate the volunteer areas and decide whether they will be geologically acceptable for preliminary field evaluation, which could eventually lead on to their detailed investigation as potential repository sites. The first steps in the evaluation process are to apply the EFQ to:

- check whether a volunteer area meets simple, first order, nationwide criteria for qualification (**Nationwide Evaluation Factors: NEF**) – these ensure that a volunteer area is not in a region that is obviously likely to be directly affected by major tectonic events and processes;

- if the volunteer area is not excluded by this first order check, carry out a more detailed evaluation of the geological information that is currently available (i.e. without any additional, new field studies) to decide whether there is reasonable likelihood of the area being geologically stable and thus worth investigating further, basing the decision on the **Site-specific Evaluation Factors (SSEF)**.

If a volunteer passes the legal qualification tests, we will begin to take into account the FF to evaluate overall suitability and, if necessary, to allow us to compare alternative areas transparently and objectively. We will then define selected areas as PIAs and begin several years of field studies in these areas. Based on the information gathered, it will be possible to decide which volunteer areas are the most appropriate for more detailed evaluation for repository siting (selection of DIAs) – a process that will begin after 2010.

The first two steps described above raise some obvious technical questions about what we mean by geological stability, which impacts we would wish to avoid and the future time period over which we need to be confident about these matters. Japan is tectonically highly active and, at first sight, it may appear difficult to find a suitable location for a repository. Nevertheless, because the critical time period for safe waste disposal is relatively short in geological terms and because the deep geological environment provides an effective buffer against many processes, finding a suitable location is by no means an intractable problem.

This document introduces the Siting Factors that we are using. It also provides geological and tectonic background information on Japan and describes how we are addressing the key issue of geological stability, which arises early in our siting programme and which will have to be considered at each stage of siting and site evaluation. It is based on a recently published longer document in Japanese that provides supporting scientific and technical information for the Information Package.

The document is in two main sections:

- **PART 1** looks at the practical implications of using the Siting Factors and how they will be handled as volunteers come forward and we have to consider the actual site-specific geological, geographical and social constraints;
- **PART 2** looks at the tectonic setting and geology of Japan and the scientific basis for the application of the Siting Factors in a staged fashion, as required in the various laws governing the current phase of the HLW disposal programme.

First, however, because the whole basis of the EFQ concerns seeking stable locations, we look at the overarching question of timescales and geological stability.

2 TIME AND STABILITY

High-level radioactive waste that is ready for disposal contains radionuclides with decay half-lives that range from a few tens of years to billions of years[3]. However, as most of the radioactivity is associated with the shorter-lived radionuclides (such as ^{137}Cs and ^{90}Sr, with half-lives of ~30 years), the radioactivity, the radiotoxicity and the heat output of the waste decrease rapidly over the first few hundred years (see Figure 2-1), while the waste container remains intact within the repository. This is followed by a slower decline in radiotoxicity over thousands of years, during which time the engineered containment of the repository is expected to degrade. After a few thousand years, the residual radiotoxicity in the waste approaches that of the original natural ore used to manufacture the fuel – the waste is slowly "returning to nature". A well designed and sited repository will ensure that any slow releases of radioactivity to the natural environment over this period, and at any time subsequently, will give rise to radiation exposures to people that are much less than those from the natural radiation background.

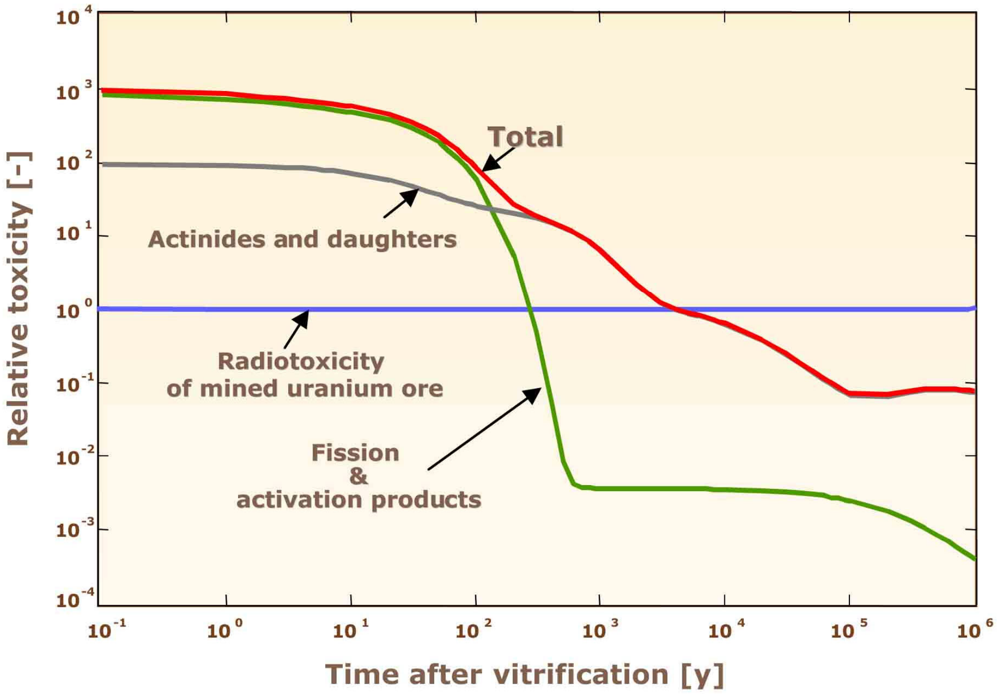

Figure 2-1: The decay in radiotoxicity of vitrified high-level waste with time after manufacture. It can be seen that, while fission product radionuclides dominate radiotoxicity over approximately the first 300 years, actinide radionuclides and their daughters predominate thereafter. After about 3,000 years, the total radiotoxicity declines to the same level as that of the natural uranium ore used to manufacture the equivalent amount of fresh fuel from which the HLW was produced. The data are for one container of JNFL vitrified waste (with 4 years spent fuel cooling before reprocessing and immediate HLW vitrification) and the uranium ore required to produce 0.8 MTU of 4.5% enriched UO_2 fuel.

As discussed in more detail in Part 2, this time period lies well inside the longer period in which it is expected that the basic, large-scale tectonic regime of Japan will change little. The

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[3] Any shorter-lived radionuclides present are supported by longer-lived parents.

distribution and pattern of motion of tectonic plates in the northwest Pacific margin region is considered to be stable over periods of the order of 0.5 to 1 million years, so the crustal and mantle mechanisms that drive local tectonic events will not change significantly in character, direction or magnitude over the period in which we are principally interested.

What, then, do we require from the viewpoint of stability? Clearly, even though the overall, large-scale tectonic regime of the Japanese Islands is considered to be stable over our period of interest, there are active, ongoing tectonic processes and events to be accounted for – seismicity, rock deformation and volcanism, whose potentially adverse impacts on a repository need to be avoided. Seismic events will occur frequently and repeatedly throughout Japan over the next tens of thousands of years and rock deformation and volcanism will continue to affect many areas, as seen in the past geological record of Japan. The issue of predicting stability has also been addressed by other agencies in Japan and in the Act. Table 2-1 summarises the opinions and requirements that have emerged.

Table 2-1: Opinions and requirements for timeframes.

	Period of reasonably assured predictability	Timeframes to be taken into account when selecting PIAs	Timeframes for Safety Assessment
Atomic Energy Commission (AEC)[1]	about 100 ka, based on the record of the past hundreds of thousands of years		no cut-off time, calculate until peak dose
Nuclear Safety Commission (NSC)[2]			no cut-off time, calculate until peak dose (preliminary view only)
Act[3]		tens of thousands of years	
H12 Project (JNC)[4]	about 100 ka, based on the record of the past hundreds of thousands of years		no cut-off time and should calculate until peak dose
Japan Society of Civil Engineers (JSCE)[5]	about 100 ka, based on the record of the past hundreds of thousands of years		

[1] Atomic Energy Commission of Japan, Advisory Committee on Nuclear Fuel Cycle Backend Policy (April 15, 1997): Guidelines on Research and Development Relating to Geological Disposal of High-level Radioactive Waste in Japan (in Japanese).

[2] Nuclear Safety Commission of Japan (November 6, 2000): Basic Principle on Safety Regulation for HLW Disposal – First Report (in Japanese).

[3] Act No.117 (June 7, 2000): Specified Radioactive Waste Final Disposal Act (in Japanese).

[4] Japan Nuclear Cycle Development Institute (April, 2000):H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Project Overview Report, Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan, JNC TN1410 2000-001.

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

Based on this information, the position that we have taken is that a period of about a hundred thousand years provides a suitable envelope of predictability within which the stability is to be assessed in our siting programme. This is not only widely accepted by other organisations as a reasonable period over which the predictability of geological and tectonic stability is expected, but also encompasses the decay in radiotoxicity to natural ore levels discussed above. Within this 100 ka envelope, the Act specifies that there should be high confidence that tectonic processes will not disrupt an area selected as a PIA for some tens of thousands of years. This shorter period is appropriate for PIA identification because the selection process will be based only on available literature information, which will be of variable depth and quality. Furthermore, even this shorter period exceeds the time needed to ensure significant decay in radiotoxicity. Nevertheless, the safety assessments that we will eventually develop to support decisions on site suitability will look beyond both the 10 ka and the 100 ka envelopes, as preliminarily proposed by NSC. Even though the repository has “returned to nature”, it may still represent a potential, man-made hazard. Consequently, we still wish to show that it will never represent an unacceptable risk to people or the environment, even far into the future.

3 MEETING THE LEGAL REQUIREMENTS ON SITING

The Act stipulates that PIAs should be selected on the basis of the survey and evaluation of information that is available in the literature. The legal requirements in the Act and associated regulations are that, in a PIA:

- there should be no record of significant movement in geological formations due to earthquake or fault activity, igneous activity, uplift, erosion and other natural phenomena;
- the possibility of significant movement in the future due to earthquake or fault activity, igneous activity, uplift, erosion and other natural phenomena should be small;
- there should be no record of unconsolidated Quaternary deposits at appropriate depth;
- there should be no record of mineral resources that are economically valuable.

At NUMO, we need to interpret these legal requirements in practical, operational terms. In particular, we have to make it clear to volunteers what is involved in accepting an area as a PIA and in subsequent investigations once the area has been accepted. It is expected that volunteer municipalities will be involved when we judge the suitability of an area proposed for a PIA, with NUMO providing all the technical information and support needed for a joint decision. The practical process of evaluation is outlined in the series of stages below.

(1) A municipality (or group of municipalities) will volunteer, through the mayor, to be considered as a potential location for a repository. Volunteers may either propose a particular area of land or may be willing to have potentially suitable areas identified anywhere within the whole municipality or group (possibly with some specified areas excepted). The minimum spatial requirement for a repository is currently considered to be a land area of about 10 km^2, although repository design development may well be able to reduce this. Larger areas obviously provide considerably more flexibility and a higher probability of locating a suitable volume of rock and of satisfying the spectrum of Favourable Factors (FF).

(2) An initial, “first-pass” screening[4] will be made against the first set of EFQ (the NEF, described earlier) to ensure that the volunteer area qualifies for further consideration. In simple terms, this will mean checking that it is not too near an area of volcanic activity and that its size, shape or location would make it possible to locate a repository so as to avoid any active faults in the neighbourhood (a PIA cannot contain an active fault, according to the Act).

(3) We will then assemble all available information from the municipality and from national data sources to evaluate the volunteer area and its periphery in more detail with respect to the both sets of EFQ (the NEF and SSEF, described earlier). It will be important to assemble information not only on the proposed area, but also on a wider surrounding region, so as to put the characteristics of the area into a proper context. During this “literature survey” stage, we are constrained by the Act to using data already available – we cannot carry out any surveys of our own. The level of information is likely to vary from one region to another and we may thus need to use

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[4] “Prior confirmation of the volunteered area’s geological conditions” in the Information Package.

information from geologically or environmentally analogous areas to help fill some data gaps and address any significant imbalances. Areas that meet these first two sets of Siting Factors (the EFQ) are considered legally acceptable as PIAs.

(4) Simultaneously with assessing the area in terms of the legal EFQ, the information collected will be used to see whether it has sufficiently suitable characteristics with respect to some of the most important FF to make repository siting a reasonable proposition. This will involve, for example, determining whether there are likely to be suitable host rock formations at a feasible depth for construction and whether the topography is suitable for the development (there would be little point in continuing to check against the SSEF if this was clearly not the case). Again, at this stage, there may need to be further discussions about flexibility in the area of land volunteered. If suitable characteristics exist and the local community continues to support the project, the area can be proposed to the national government for approval as a PIA.

(5) At the time of proposal, the areal extent of the PIA[5] will need to be agreed between ourselves and the municipality (or municipalities). The next stage of work after approval of a PIA may involve geological and geophysical surveys and borehole investigations in the PIA[6] to assemble sufficient information to decide whether to proceed to the identification of one or more DIAs and, if so, to define their location(s). This will require several further years work and, again, may require some of the work to be done outside the PIA. We envisage that there will thus be **Supplementary Investigation Areas (SIAs)** outside the PIA, which will allow us to evaluate important aspects of the regional geological environment that extend beyond, or are better represented outside, the PIA. The size of the SIAs will be dependent on the local geological structure and the presence of any major tectonic features in the vicinity (active faults, volcanic centres). Even though a repository will not have active faults running through it, or be adjacent to a volcano, it will be essential to look at any nearby faults or volcanoes to determine whether they could affect the repository or its location[7]. Activities throughout the PIA phase will thus be controlled by constraints on land area that include the boundary of volunteered land and limits set to avoid any natural or environmental features excluded by the Act[8].

It can thus be seen that, as a PIA is accepted and field work begins, a distinction needs to be drawn between the area of land volunteered which is not excluded by the EFQ (the PIA) and the areas in which either additional literature studies or field surveys may need to be carried out (SIAs). It is important to note that the SIAs may thus include areas outside the volunteer area and, perhaps, outside the municipality containing the volunteer area. Our ability to work in this way is vital for thorough site investigations.

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[5] A PIA may be larger than a volunteer area, depending on the location with respect to areas with active faults and igneous activity, also on the size of the volunteer area.

[6] Even if the PIA is larger than the volunteer area and field activities are carried out, the zone outside of the actual volunteer area will not be eligible for a repository site.

[7] Evaluation of active faults is discussed in more detail later.

[8] Volcanic areas, active faults, unconsolidated sediments, mineral resources, high land uplift areas, environmentally protected zones (see later detailed discussion).

4 EVALUATION FACTORS FOR QUALIFICATION

We have established two groups of EFQ that will be used to determine whether a volunteer area meets the general requirements of the Act, in terms of geological stability and the presence of mineral resources. These factors will be used first when determining the suitability of a volunteer area. They are minimum requirements to avoid regions that have clear potential for obviously disruptive processes and events – both geological and by the actions of people in the future. It must be emphasised that meeting these requirements alone would not necessarily guarantee that an area would be a suitable host for a repository.

(1) **Nationwide Evaluation Factors (NEF):** designed to identify, at the very start of the evaluation process, only those areas where a repository (of any design) could not be directly disrupted or destroyed by volcanic activity or would not inevitably be transected by known active faults within the next hundred thousand years. Whether an area qualifies against these factors can be readily established using information on the nationwide distribution of volcanoes and active faults. These factors are a decisive means of excluding clearly unstable locations, and will be applied in a simple "first-pass" screening process.

(2) **Site-specific Evaluation Factors (SSEF):** designed to assess those areas that meet the NEF qualification factors in more detail, with respect to potential volcanism, seismicity, rock deformation and faulting, land uplift and erosion, and the presence of unconsolidated sediments or mineral resources.

In this chapter, we look at how the EFQ have been developed into quantitative guidelines, based on our understanding of the geological environment of Japan, which is elaborated in Part 2 of this document.

4.1 Nationwide Evaluation Factors

There are only two NEF – one concerning volcanic activity, the other concerning active faults.

4.1.1 NEF volcanic activity

Locations where a repository has a significant probability of being disrupted or destroyed by volcanic activity are not acceptable as PIAs. For the NEF, we want to avoid locations which are likely to be subject to magmatic intrusion or volcanic eruptions over the next tens of thousands of years[9] – essentially, areas close to existing volcanic centres and that exhibit recent volcanic activity that might continue to be active. Lava, ash and hot gases may reach the surface at one or more points in a volcanic centre. Magma may also be injected into fractures in the rock at depth beneath a volcanic centre, where it solidifies as dykes and sills.

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[9] The SSEF consider a longer term and a wider spectrum of potential volcanic impacts: see Section 4.2.1.

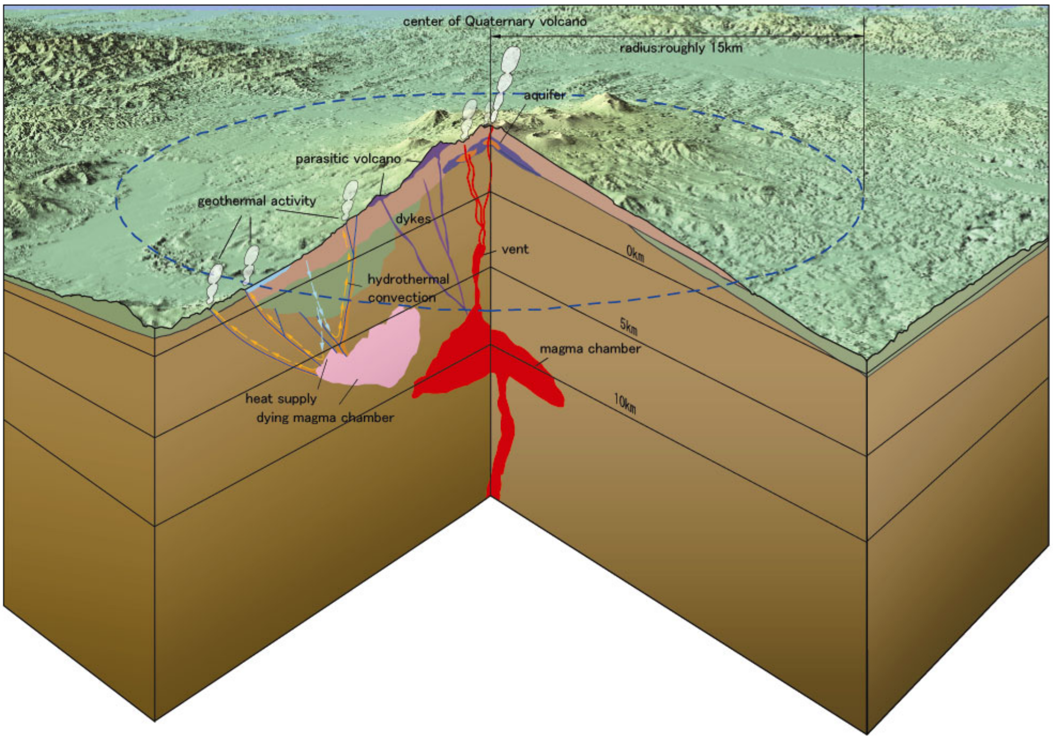

Figure 4-1: Illustration of the typical extent of igneous activity at depth around a Quaternary volcanic vent. A radius of 15 km has been selected for first-cut exclusion of areas in the Nationwide Evaluation Factors.

The evidence in Japan indicates that such intrusions are of limited extent around a volcanic centre. Older, polygenetic volcanoes have the largest areas of magmatic activity, but even so this is restricted to a radius of about 15 km around the centre of the volcano (Figure 4-1). There are exceptions to this rule, however. Some monogenetic volcanoes (see Chapter 9) exhibit more diffuse and widely distributed activity over space and time. Also, periodically, a volcano may be subject to huge explosive eruptions that destroy much of the existing volcanic edifice, with the remains of the volcano collapsing into a large caldera. Calderas represent the surface expression of large bodies of magma that existed below the surface in the past, which may extend beyond a radius of 15 km (Committee for the Catalogue of Quaternary Volcanoes, 1999; Nakata and Tanaka, 2001). Present day activity within a caldera may be focused on later volcanic vents formed within the caldera walls.

The following approach is thus used to set quantitative boundaries for this first-pass NEF qualification. For catalogued Quaternary volcanoes, an exclusion zone of 15 km radius is drawn around each volcanic vent.

Volunteer areas must lie outside this exclusion zone if they are to be considered as PIAs. Given the approximate nature of the 15 km criterion discussed above, even though an area is not immediately excluded using this first-pass NEF screening, if it is close to the margin of excluded areas, or in a region that might be susceptible to volcanic activity over the longer term (around the next hundred thousand years), volcanism will need to be given further consideration in the SSEF stage.

4.1.2 NEF active faults

Faults that have been repeatedly active during the last few hundred thousand years are classified as "active faults" in Japan (see Part 2). There is a high likelihood that these faults may move again, perhaps repeatedly, during the next hundred thousand years. Typically, faults are not simple fractures, but zones of fracturing and shear in the rock that may be some tens or hundreds of metres wide.

For the first-pass NEF qualification, it is sufficient to show that the area of land volunteered is not transected by any faults shown on the two national-scale maps of active faults (onshore and offshore). The onshore map is based on aerial photographs and geological survey information and the offshore map is based on seismic profiling and borehole data.

Active fault movements, the potential for small-scale shear in fractures located some distance from them and the potential impacts on the repository and its surface facilities from seismic shaking will be considered further in the SSEF and during the PIA and DIA stage investigations. The development of a methodology for evaluating rock deformation is discussed in Part 2.

4.2 Site-specific Evaluation Factors

If a volunteer area qualifies for further consideration after comparison with the national scale NEF, it will be evaluated in more detail using site-specific literature information (e.g. reports, maps and data on geological/structural, geophysical, seismological, geodetic, topographic, geo-/hydrothermal, mineral exploration and civil engineering surveys). Both volcanic activity and active faults may need to be revisited at this stage, depending on the location of the area. In addition, further factors concerning land uplift and erosion and the possible presence of unconsolidated sediments or mineral resources will be considered.

Information coverage and quality is not the same for all parts of the country and, in some areas, there may not be sufficient data available to reach a judgement on conformity with the SSEF. According to the Act, we conduct only literature surveys on the volunteer area before it is nominated as a PIA. However, the absence of information on any factor will not mean that an area is disqualified. Rather, we will endeavour, via comparison with analogous areas in Japan, to assemble sufficient data to make a decision on whether to proceed further.

4.2.1 SSEF volcanic activity

The NEF are designed to exclude areas that are likely to be affected by eruption or intrusion of magma in the next tens of thousands of years. The SSEF will take both a longer term and broader view of impacts, looking at other potentially disruptive effects of volcanism in areas that are susceptible to volcanic activity (some regions of eastern Japan are outside the zone affected by volcanic activity – see Part 2). Disruption means direct impacts on the waste, the disposal tunnels and the immediately surrounding rock by:

- injection of magma (e.g. dykes);
- hydrothermal fluids (hot or corrosive groundwaters and/or gases);
- high thermal loads (high temperatures and/or temperature gradients in the rock);

- formation of conduits through which ash, gas or lava are erupted to the surface;
- brecciation of the rock mass by explosive eruptive activity.

For example, two possible situations are considered in the SSEF:

(1) where a volunteer area is near to, but not within, an excluded area of polygenetic volcanic activity – perhaps within a "gap" region behind the volcanic front, as discussed in Part 2;

(2) where a volunteer area lies in a region that has been subject to monogenetic volcanic activity, although the area lies beyond a radius of 15 km of such activity.

At this stage of our work, no quantitative criteria have been developed to define what would constitute an acceptably low probability of future volcanic activity affecting a repository site at different times in the far future. This will depend upon the types of impact, as well as their likelihood, and the consequent associated radiological risks. This will be part of the work that we will undertake in the next few years and will be guided by the developing regulatory safety guidelines in Japan.

Our present aim is to begin developing a methodology for quantifying the probability of future polygenetic and monogenetic volcanic activity within an area. For qualifying areas (i.e. those not excluded by the NEF and SSEF and accepted as PIAs, but still potentially prone to volcanic impacts), these probabilities will need to be correlated with potential consequences of different types of disruption to assess whether the overall long-term risks of volcanism are acceptable for a site. This work will be carried out during the PIA and DIA investigations. However, during the site-specific literature review stage we will adopt simpler SSEF guidelines to determine whether an area can be accepted as a PIA:

Outside the 15 km radius of the NEF we will also exclude areas that are definitely expected to have magmatic intrusions or eruptions in the next tens of thousands of years and areas that are expected to experience significant thermal effects, highly acidic thermal waters or hydrothermal convection of groundwaters.

4.2.2 SSEF rock deformation and seismicity

The NEF review selects only those areas in which the available volunteered land does not include an active fault, as defined on the nationwide active fault maps. Nevertheless, an area selected using this criterion may still have unmapped active faults or active folds or flexure zones within it, or known or unmapped active faults in its vicinity. In this case, a further evaluation will be necessary at the SSEF stage.

We will exclude areas that:

[a] contain active faults that are not on the national active fault maps but which are identified during literature reviews;

[b] are within the "process zone" that contains fractures around an active fault;

[c] are likely to contain an active fault splay (bifurcation);

[d] contain folds or flexures that have shown significant activity during the last several hundred thousand years.

The primary concern with active faults and associated active deformation phenomena is that future shear movement along rock fractures might disrupt part of the engineered barriers and damage some of the waste containers – hence areas subject to such phenomena are excluded at the SSEF stage. For example, a reverse fault located near the boundary between a ridge and a plain may splay, with the original active fault bifurcating to form a splay fault under the plain. Active faults may also propagate progressively at their tips over long periods of time as a result of repeated seismic activity, so areas close to the end of active faults will be excluded at the SSEF stage.

If it is not possible to judge from a literature survey whether a mapped fault in the volunteer area is active, the area will not be excluded on the basis of the EFQ. However, subsequent field investigations within the PIA should clarify the fault properties before a decision is made for DIAs.

In the case where previously unknown active faults are encountered, for example during underground excavation and rock characterisation work at a preferred DIA (e.g. deep active faults with no surface expression), detailed evaluation of the potential impacts of the discovered faults will play a key role in any decisions on overall siting.

Using the guidelines above, areas that are close to active faults and/or folds can be accepted as PIAs. This is justifiable because a repository could be located relatively close to an active fault or fold without sustaining any damage from shearing by future fault displacements. A large earthquake along an active fault may cause small (mm or cm) shear displacements along existing fractures some hundreds of metres away from the active fault (see Part 2). The extent to which this can occur will be highly site-specific, depending on the size of active faults in the area, the magnitudes of earthquakes associated with them, the local stress regime in the rock, the properties of the repository host rock , the age and frequency of previous deformation and the distance from the fault.

In addition, the significance of such small movements (perhaps developing cumulatively over a hundred thousand years) for the safety of the repository will depend on the repository design proposed for a specific site. This will need to be analysed on a case-by-case basis. Research in other national repository programmes (see Section 8.2) indicates that avoidance of active faults by distances of a few hundred metres up to one or two kilometres may be sufficient to reduce the risk of damage to insignificant levels. These issues will be considered in the PIA and DIA investigations. As discussed in Part 2, we are now developing approaches to do this.

The **seismicity** associated with subducting plates or with movement at active faults in the shallow crust onland (see Part 2 for a description of seismicity) may result in a number of impacts on a repository:

Seismic shaking: unlike surface structures, which can move freely during earthquakes and consequently may suffer extensive damage, underground structures respond mainly by moving together with the surrounding rock. As a general rule, loads caused by forces of inertia are negligible compared with those imposed by the deformation of the host rock, which are dealt with separately . All regions of Japan are subject to seismicity, and a repository and all its facilities will have to be designed taking seismic shaking into account. Consequently, possible variations in seismic shaking in the deep underground are not a useful discriminator at this stage of site selection.

Seismic shaking is thus not considered within the EFQ. However, the susceptibility of potential siting areas to large magnitude earthquakes and the possible impact of seismic shaking on a repository and its access and surface facilities will be evaluated during the PIA and DIA investigations when comparing alternative locations.

Perturbation of groundwater flow: the passage of seismic pressure waves through the rock mass can result in short-term (usually hours or days) changes in the local groundwater flow pattern. Soft sediments, especially those that occur at or near the surface, are most prone to such effects. Evidence from the deep geological environment in Japan indicates that the transient effects at depth are small.

Seismic perturbation of groundwater flow is not considered in the EFQ. It will be evaluated on a site- and design-specific basis during the PIA and DIA investigations.

4.2.3 SSEF uplift and erosion

Much of Japan is undergoing vertical crustal movements (uplift or subsidence) as a result of tectonic processes (see Part 2). Whilst subsidence would result in the deeper burial of a repository and can be regarded as of little significance (or possibly beneficial) for its long-term containment capacity, uplift may lead to reduced containment. As the land rises it is also eroded by rain, flowing water, freezing and thawing of water in rock pores, reaction with chemicals in the air, and by wind. Over hundreds of thousands of years, the land surface may thus be eroded down towards the level of a deep repository. As this happens, the environment of the repository will slowly change. Within tens, or perhaps a hundred or so metres of the surface (depending on rock type and location), the repository will begin to lose some of its isolation properties as rock hydraulic conductivity increases with stress unloading and conditions become more oxidising. The Act stipulates that a repository must be located deeper than 300 m and this is thus the minimum depth that we can consider.

Rates of uplift vary from area to area and have changed during the past. There are uncertainties in calculated values of both uplift and erosion, which vary in magnitude between different regions of Japan. Current research is continually improving the accuracy of these values. Future uplift rates can, nevertheless, be estimated from average rates over the past few hundred thousand years. As discussed in Part 2, there are several types of geomorphological and geochemical information that can be integrated to evaluate past rates of uplift, although erosion rates are more difficult to quantify.

We will thus consider only those areas as PIAs where there is no clear literature evidence of uplift amounting to more than 300 m during the last one hundred thousand years, which would clearly be unsuitable.

We will continue to evaluate uplift and erosion for accepted areas during the PIA and DIA investigations. The significance of uplift and erosion will depend on the potential environment in which a repository could be located within a volunteer area. Although the activity of the waste will be similar to, or less than, the natural uranium ore used to manufacture the equivalent amount of fresh fuel from which the HLW is produced after a few tens of thousands of years, we nevertheless want to avoid locations where the exposure rate (combined uplift and erosion rate) over our hundred thousand years evaluation envelope is estimated to be large. Where it is possible to locate a repository at depths between 500 and 1000 m in hard rocks that are only weakly susceptible to erosion, then a relatively high uplift rate may present no difficulties. If it is only possible to locate a repository in softer rocks at depths less than 500 m, then the same uplift rate could be problematic. In addition, the impacts of interseismic and coseismic vertical crustal movements will need to be assessed in some parts of Japan.

Consequently, each PIA and DIA will require a specific evaluation that combines knowledge of potential host rocks, their depths and estimates of future exposure rates. In some areas it may not be possible to complete this evaluation without long-term field studies and monitoring after a PIA or DIA is selected. As discussed in Part 2, we are developing techniques to assign an index of stability to areas and sites that will integrate many types of data on crustal strain rates and historic patterns of vertical movement.

4.2.4 SSEF unconsolidated deposits

Some regions of Japan are characterised by the presence of thick sequences of unconsolidated Quaternary deposits (gravels, sands and muds) which are unsuitable for constructing a repository.

PIAs will not be located where unconsolidated Quaternary sediments are so thick that they are the only feasible formations for locating a repository.

If there are unconsolidated deposits present at a PIA that has not been disqualified, we would evaluate whether their presence and thickness would affect the feasibility of constructing access to a more deeply located repository during the PIA investigations.

4.2.5 SSEF mineral resources

The existence of mineral resources such as metals, coal or hydrocarbons in a potential repository siting area makes it more probable that future generations could inadvertently damage or intrude into a repository during exploration (drilling) or mining activities, if records of the location of the repository have been lost. Consequently, areas are preferred where there is no evidence for the presence of potentially valuable resources, either locally or in similar geological environments in the region.

For the SSEF stage, areas will be excluded if they contain economically viable mineral resources, as identified from consideration of the Mining Law and associated Mining Rights. This includes resources being mined today and resources where mining has been suspended but which contain workable reserves that are equal to or better than those currently being mined. The Mining Law defines the following elements and minerals, among others, as resources: Au, Ag, Cu, Pb, Bi, Sn, Sb, Hg, Zn, Fe, Cr, Mn, W, Mo, As, Ni, Co, U, Th, S, iron sulphide, phosphates, graphite, coal, lignite, oil, asphalt, natural gas, gypsum, barites, alunite, fluorite, asbestos, limestone, dolomite, silica stone, feldspar, pyrophyllite, talc and fireclay.

In due course, we will need to consider the suitability of areas not excluded by the SSEF but containing what, today and in the foreseeable future, could be regarded as potentially significant resources. Views on what constitutes a likely prospect for future economic resources will change with time, as exploration and production technology change, as commodity values vary, as materials find new applications and as developing strategic resource demands place new requirements on producers. Many rocks contain some degree of mineralisation, but would not be regarded as having serious resource potential.

Potentially significant resources are those that might reasonably be expected to be evaluated or worked in the future, even if they are not being looked at today. We will need to take into account whether resources are worked nearby, in geological units and environments that are closely related to those in the volunteer area (and whose presence might consequently lead to future exploration within the volunteer area). These issues will need to be evaluated in more detail during the site investigations, possibly using a similar approach to that currently being used in Sweden by SKB during its site investigation work (Lindroos et al., 2004).

After the selection of PIAs, we will need to consider broadening our evaluation of resources to include groundwater, hot springs and geothermal energy. None of these is classified as a resource in the Mining Law. Clearly, however, they have resource potential that we may need to take into account.

4.2.6 Example applications of the Evaluation Factors for Qualification

Figure 4-2 compiles the main aspects of the legal EFQ described above, to show how they affect the geometrical features of PIAs and SIAs. The illustrations in Figure 4-3(a-c) then show several hypothetical examples of how their application in different tectonic and geographical situations might affect PIA identification in practice.

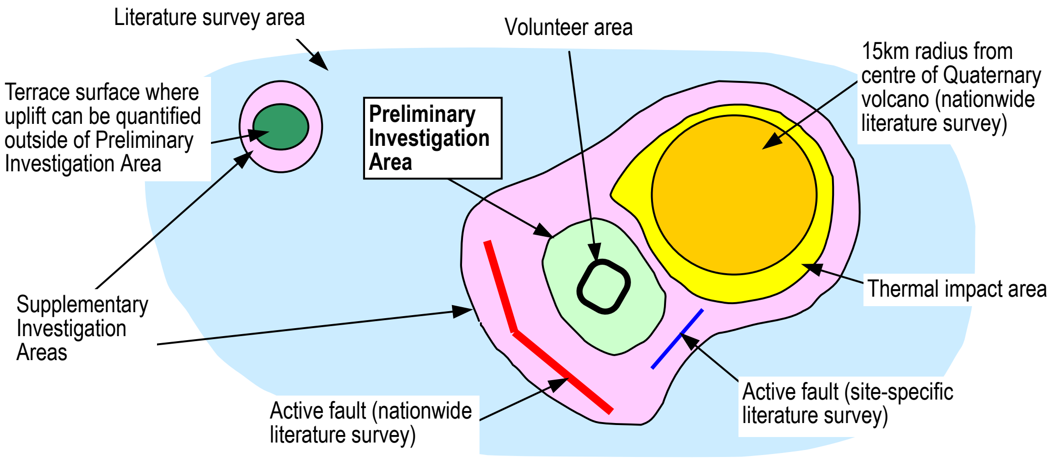

Figure 4-2: Schematic figure showing how the legal Evaluation Factors for Qualification affect the identification of the location and geometry of a Preliminary Investigation Area.

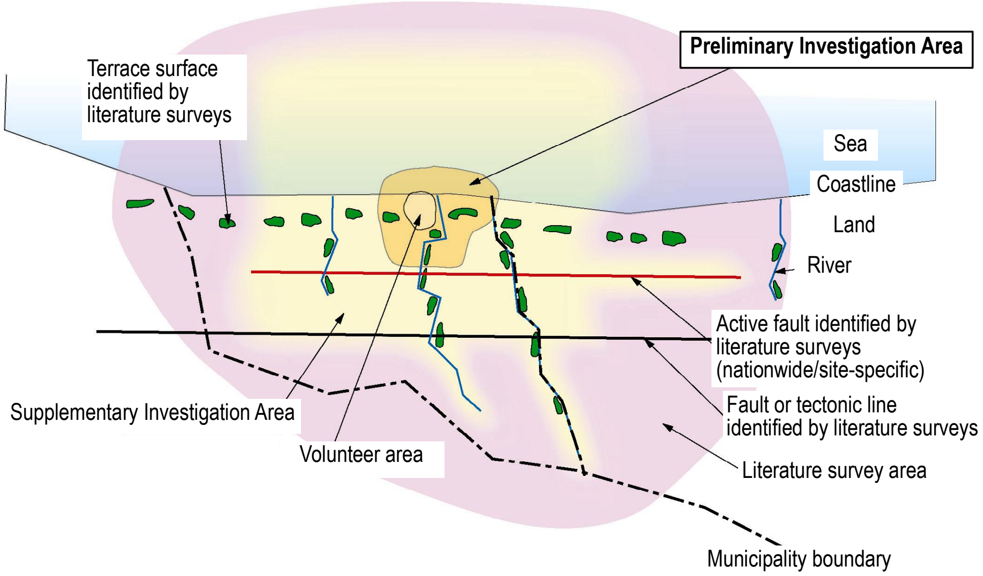

Figure 4-3(a): An example of a hypothetical Preliminary Investigation Area where Quaternary volcanoes are absent and an active fault is identified by literature surveys near the volunteer area.

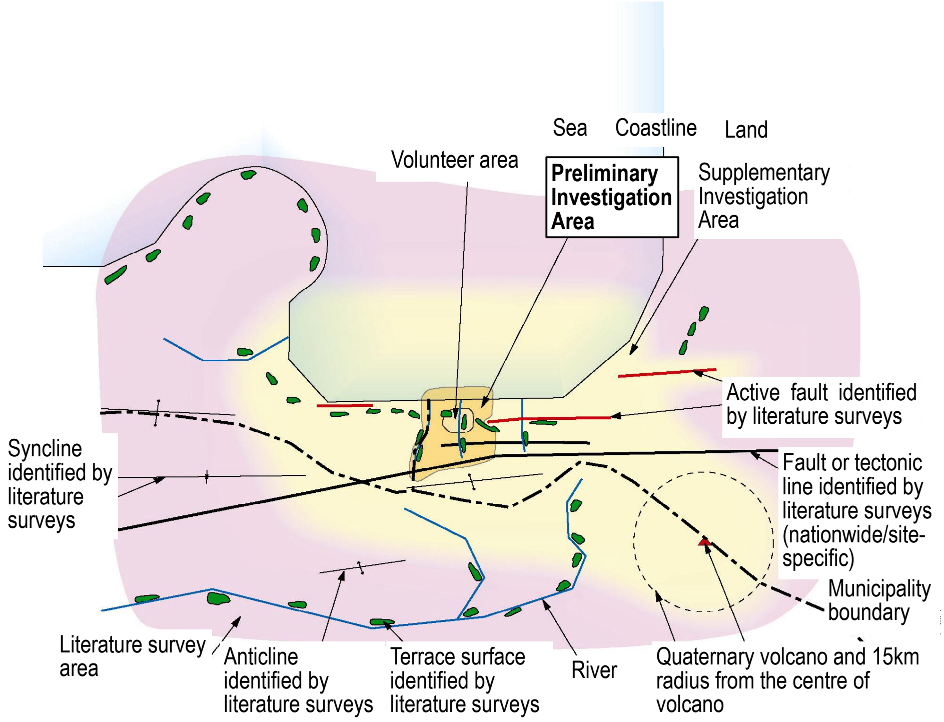

Figure 4-3(b): An example of a hypothetical Preliminary Investigation Area where a Quaternary volcano and active faults are identified by literature surveys near the volunteer area.

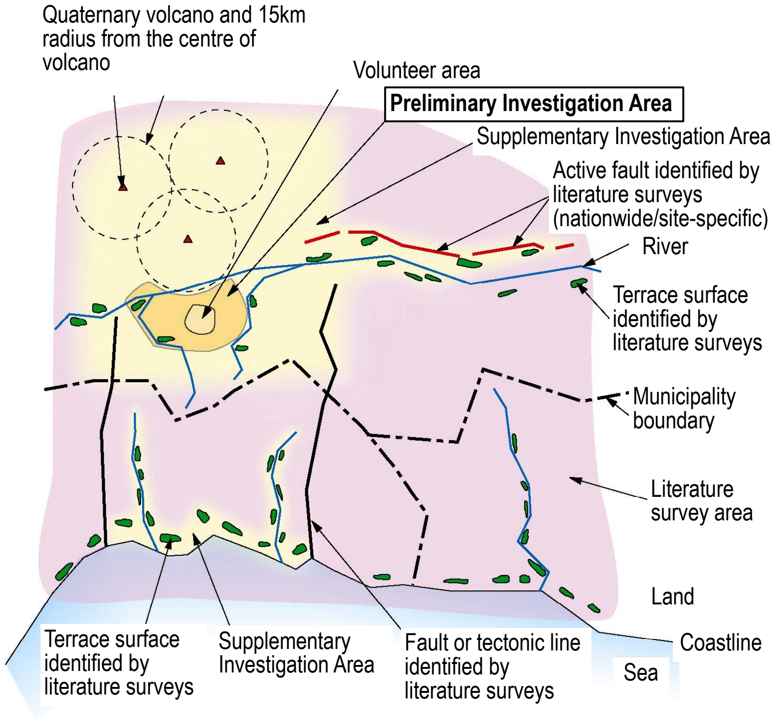

Figure 4-3(c): An example of a hypothetical Preliminary Investigation Area where Quaternary volcanoes and active faults are identified near the volunteer area, and significant terrace surfaces away from the volunteer area are identified by the literature surveys.

5 FAVOURABLE FACTORS

The Favourable Factors (FF) are used after volunteer areas have qualified for consideration using the Evaluation Factors for Qualification (EFQ). The FF will help to determine the overall practicality of a repository project and, possibly, to discriminate between potential repository locations. They cover geological, geographical, environmental and social aspects of volunteer areas (see Table 5-1). Some geological aspects in the FF were already covered by the EFQ. In these cases, the FF go into further detail, even though areas have already been through the first-pass qualification test. At present, we have not fully developed the FF, as they will be of secondary importance when identifying PIAs, unless we have many possible options to compare. In the near future, we will be working on their more detailed definition and on how to apply them.

Unlike the EFQ, there are no definitive, individual requirements for the FF and they will all be considered together as a whole when judging any site. Treated as members of a group, they can each be weighed to highlight the advantages and disadvantages of an area. If there are several potential sites, we can use the FF at any stage of the siting programme to compare them in a flexible manner (see below).

The FF will assist in identifying locations where it will be most straightforward to demonstrate compliance with future regulatory radiological safety criteria. They will also influence the final design of a repository and the details of its development and operational programmes and allow optimisation of each of these aspects. The relative importance of a FF depends on the repository design. For a given site, a design is sought that makes the best use of the site properties. For this reason we are developing several design options (see the companion document on Repository Concepts, which also addresses in more depth how the FF identified here may affect repository design decisions). This means that it is not possible directly to weigh the FF for different sites without also considering the appropriate design(s) for those sites. We are exploring various techniques for making such comparisons and illustrating the results, including multi-attribute analysis (MAA), which allows us to look at options from different stakeholder perspectives.

Because we want to achieve a solution that is safe, secure and of benefit to the community, we will place great emphasis on these factors and will use them throughout the site selection process, up to the point of final repository location. We also intend to involve communities in the evaluation of many of these factors.

Examples of the FF in the Information Package for volunteers are shown in the Table 5-1. Section 5.1 looks in more detail at the issues within each of these factors and the aspects of concern that we will take into account as we begin to develop them further. At present, we have only identified simple geological, hydrogeological and engineering FF. In future we shall have to consider both environmental and social FF as well. In the initial stages of siting we shall be guided principally by existing environmental legislation.

In Section 5.2, we discuss some of the economic aspects of repository siting. Whilst factors such as environmental and social FF are not clearly defined within our FF at present, they are clearly a matter of interest and concern for the volunteer communities and for many other stakeholders in the HLW disposal programme and will need to be taken into account at a later stage of the siting programme.

Table 5-1: Examples of Favourable Factors and issues of concern.

Favourable Factors	Issues of concern
Properties and condition of geological formations at a site	• mechanical strength of rocks • deformation regime • fracturing • weathering and alteration • geothermal gradient • geometric configuration and size of rock mass • uplift and erosion rates • potential for abnormal porewater pressures • swelling host rocks • potential for gas • potential for rock bursts • potential for large-scale water inflows
Hydrogeological properties of rock formations	• groundwater flux • groundwater flow velocity • temperature of groundwater • pH and Eh of groundwater
Investigation and assessment of the geological environment	• scale, scope and duration of investigations required • applicability of available investigation technology • applicability of available assessment methods • ease of assessment and modelling of geological environment • constraints on site investigation (e.g. land use restrictions)
Potential for natural disasters during repository construction and operation	• earthquakes • landslides • flooding • tsunami
Land procurement	• availability of land and ease of procurement
Transportation	• ease of transportation to the site, such as distance from harbours

5.1 Favourable Factors related to the geological environment

As discussed previously, the following factors that were considered as part of the EFQ will continue to be evaluated for PIAs that have qualified for further study:

- **Location and impacts of active faults and other fractures:** all categories of fractures and faults within the host rock and surrounding geological formations will be evaluated in progressively more detail. Even if not classified as "active", large fractures within the potential repository rock volume will affect the layout of the repository. The impact of nearby active faults will need to be assessed on a site-specific basis. Seismic hazard studies will be required to determine the likelihood and impacts of potential large magnitude earthquakes during the operational period. A similar approach will be used to that taken for analyses of existing nuclear facilities (N.B.: surface and underground openings/activities).

- **Uplift and erosion:** refinement of estimates of exposure rates using site-specific data and monitoring. Areas with stable patterns of subsidence and progressive burial may be preferred.
- **Mineral resources:** detailed assessment of the potential of volunteer areas, looking at a wide range of natural resources.

In addition, the following geological, hydrogeological and engineering factors will come into play:

- **Depth, geometry and engineering properties of potential host formations:** an immediate consideration for qualifying PIAs will be the feasibility of locating a repository in a volume of rock that is at an easily accessible depth, is sufficiently large and has good engineering properties (rock strength) for construction. Ease of access and engineering will facilitate construction, operation and closure and will improve flexibility with respect to the staged management of the repository, including options for waste retrieval. Areas where there is a range of possibilities in terms of potential host formations, in repository depth and in lateral location would be preferred. This will allow flexibility to respond to the findings of site investigations.

- **Avoidance of engineering problems:** geological formations that have no evidence of excessively high water or gas pore pressures, excessive swelling pressures, high rock stress environments that could cause rock burst in deep excavations, or other rock stability and support problems are preferred. This will improve the engineering feasibility of the project, as well as safety during construction and operation.

- **Favourable hydrogeological and hydrochemical properties:** host rocks should have groundwater flow systems that display evidence of long-term stability and are chemically reducing (assessed by redox measurements, lack of dissolved oxygen), with moderate pH and temperature. Together with the ability to sorb and retard the movement of radionuclides, these form the basis for the isolation properties of the repository and surrounding rock. Isolation potential is a function of low fluxes of groundwater, with associated low groundwater heads and flow velocities and lack of significant fast pathways to the biosphere.

- **Geological and hydrogeological simplicity:** areas with geological structures and groundwater flow systems that are less complex and more readily predictable are preferred. They are also easier to investigate and characterise. Sedimentary rocks with uniform lithology and structure over many kilometres, and crystalline rocks that are relatively homogeneous and undeformed, are considered to provide the simplest geological environments in this respect. The geological environment that can be characterised using currently available remote sensing, geological, geophysical, drilling and borehole investigation techniques are preferred. We are currently developing approaches to site characterisation in different geological environments and this will be the subject of a later report.

- **Robustness to future climate change:** locations that are less likely to be adversely affected by major changes in climate over the next hundred thousand years or so are preferred. The predicted continued cycling of Earth's climate through glacial and warm eras is likely to cause large changes in global sea level and in regional rainfall and temperatures. Some coastal and mountainous areas of Japan will be more susceptible to increased erosion, river deepening and modifications to groundwater flow. Depending on topography, some offshore locations may become dry land for long periods in the future. The extent to which any of these changes could have adverse impacts needs to be evaluated in more detail as the siting programme progresses – mainly in performance assessment studies at the DIA stage.

5.2 Economic aspects of siting the repository

Although not directly identified within the FF, the overall cost of the project and its impacts on the economy of the host municipality or municipalities are factors of interest in identifying suitable repository locations. We will meet all costs that are required to ensure a safe and beneficial solution for disposal of the waste. However, cost optimisation is also important, although such considerations must not take priority to the detriment of operational or long-term safety. At the same time, we wish to ensure that the local community obtains maximum benefit from involvement. This latter factor, which involves long-term investment in the community, should be broadly equivalent for any eventual repository location and should not be a factor in deciding on the suitability of a site. The following aspects need to be considered:

- **Cost of investigations, research and development:** areas are preferred where geological and environmental properties can be readily characterised, and where an engineering design that has been well tested in Japan or internationally can be used. This will keep R&D and site investigation costs down and should also reduce the costs of providing information to obtain licenses and permissions.

- **Purchase cost of the land:** this should not be unreasonable.

- **Construction and operation costs:** these will depend on the depth and design of the repository, as well as on the properties of the host rock and the difficulties of engineering the access. Costs will closely mirror engineering feasibility.

- **Transport costs:** more remote areas and those without existing infrastructure will be less favourable than accessible developed areas.

6 TECTONIC SETTING AND EVOLUTION OF JAPAN

In order to discuss the feasibility of predicting future natural phenomena such as earthquakes in the Japanese Islands, it is important to consider how long the present tectonic setting – as characterised, for example, by the movement of oceanic plates and the distribution of tectonic stresses – has been stable. The following sections briefly review current understanding in relevant fields.

Japan lies on the eastern edge of the Asian continental plate, facing the subducting plates of the Pacific Ocean. The regional geography is shown in Figure 6-1. The basement rocks of the Japanese Islands comprise geologically young rocks, mostly younger than 200 Ma, derived from plate margin, subduction zone, trough and island arc tectonic processes. Many sedimentary rocks are “accretionary prisms” consisting of terrigeneous, hemipelagic and pelagic sediments, accompanied by small amount of limestones, cherts and basalts. These sedimentary rocks are intruded by Mesozoic and Tertiary granitic rocks and island arc volcanic rocks. Japan is a tectonically active region and it is widely acknowledged to be the best-studied arc-trench system in the western Pacific area. Intensive monitoring of seismicity and crustal deformation, combined with studies of active faults, has allowed a detailed picture of tectonic processes and deformation over different timescales to be built up over recent decades.

6.1 Tectonic setting

The Japanese Islands lie at the junction of four major tectonic plates – the Pacific and the Philippine Sea oceanic plates and the North American (or Okhotsk) and the Eurasian (or Amurian) continental plates (see Figure 6-2). The Pacific Plate moves towards the WNW at a rate of about 8 cm/year and is subducted beneath the Kuril Arc and the Izu-Bonin (or Izu-Ogasawara) Arc (Wei and Seno, 1998). The Kuril Trench, the Japan Trench and the Izu-Bonin Trench are deeper than 6000 m in the region where the Pacific Plate is subducted. The Quaternary volcanoes lie parallel to these trenches and form a “volcanic front”. In the north, subduction of the Pacific Plate is oblique to the Kuril Trench, causing a strike-slip movement along the Kuril Arc, which results in a local collision zone within the Okhotsk Plate in central Hokkaido.

The Philippine Sea Plate moves towards the NW at a rate of approximately 5 cm/year (Wei and Seno, 1998) and is subducting beneath SW Japan and the Ryukyu Arc. In SW Japan, the volcanic front lies parallel to the Ryukyu Trench and the Nankai Trough. The volcanic front becomes less significant in the central part of Honshu and in Shikoku, as the depth of subduction of the Philippine Sea Plate is less than 100 km – above the depth of partial melting . In the south, the Philippine Sea Plate is also subducting obliquely to the Nankai Trough, comprising a tectonic sliver that is moving westward along the strike-slip “Median Tectonic Line”.

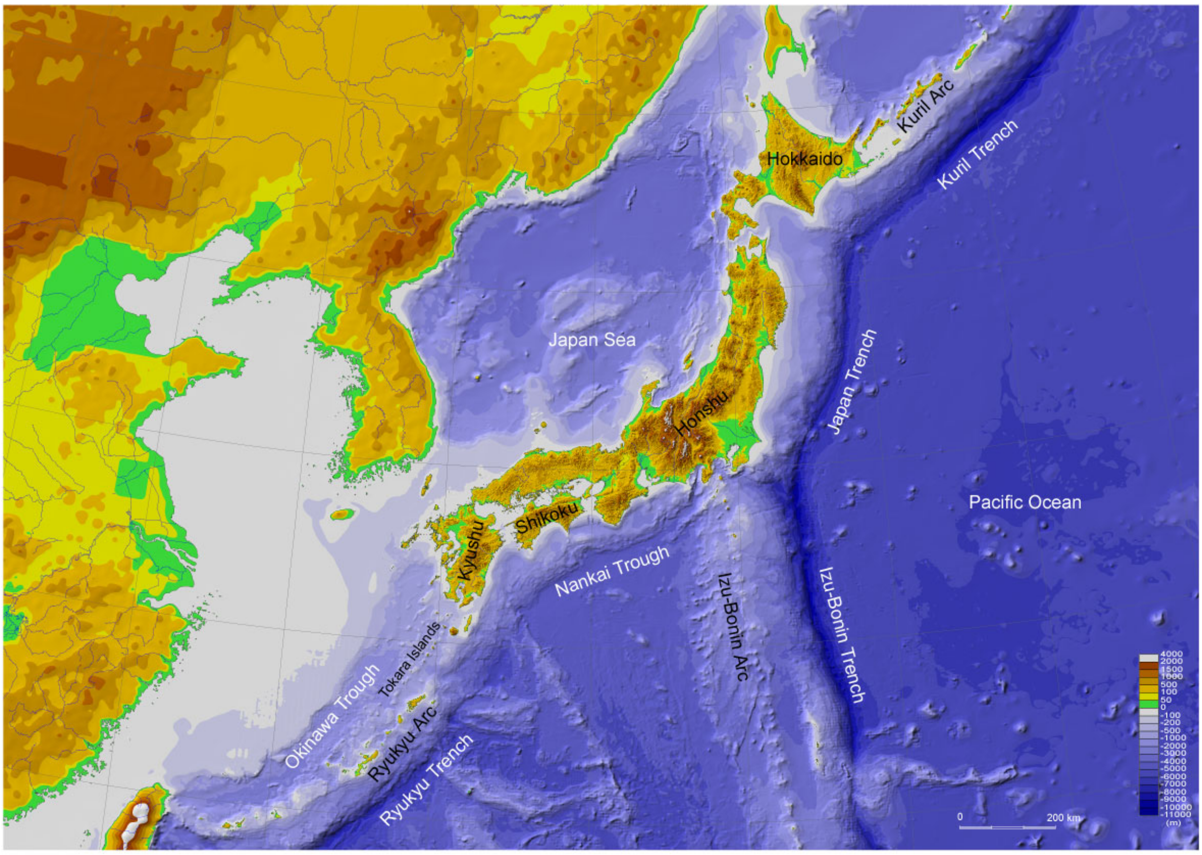

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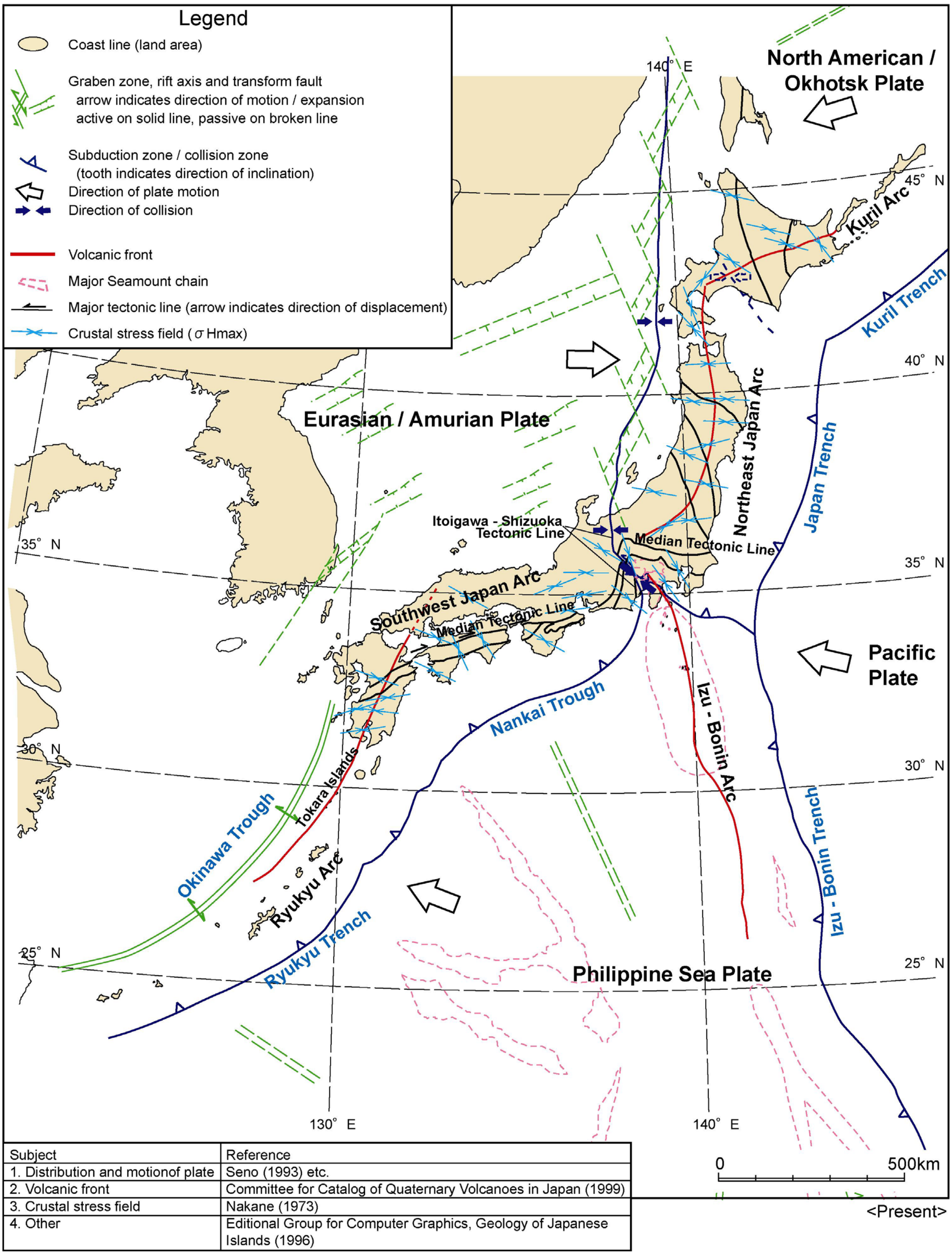
Figure 6-1: Topography and main geographical regions of Japan (modified from Editorial Group for Computer Graphics, Geology of Japanese Islands, MARUZEN Co., Ltd., 1996).

There are various interpretations of the boundaries of the North American/Okhotsk Plate and the Eurasian/Amurian Plate. A recent interpretation, based upon geodetic, seismic and geological observations, suggests that these boundaries run from Sakhalin, via the eastern margin of the Japan Sea, and reach the Itoigawa-Shizuoka Tectonic Line (Nakamura, 1983; Kobayashi, 1983; Seno et al., 1996; Tada, 1997). The Itoigawa-Shizuoka Tectonic Line divides the Japanese Island Arc into the Northeast Japan Arc (NE Japan Arc) and the Southwest Japan Arc (SW Japan Arc). Because the east-west compression at this plate boundary cannot be fully explained only by the subduction of the Pacific Plate and Philippine Sea Plate, a small amount of eastward movement of the Eurasian/Amurian Plate is suggested (Wei and Seno, 1998). The tectonic situation is complicated in the area where the North American/Okhotsk Plate, Eurasian/Amurian Plate and Philippine Sea Plate converge.

In the extreme south, the Ryukyu Arc is backed to the west within the Eurasian/Amurian Plate by a zone of active extensional rifting – the enlarging Okinawa Trough. This horizontal extensional field extends to the west of Kyushu.



Subject	Reference
1. Distribution and motionof plate	Seno (1993) etc.
2. Volcanic front	Committee for Catalog of Quaternary Volcanoes in Japan (1999)
3. Crustal stress field	Nakane (1973)
4. Other	Editional Group for Computer Graphics, Geology of Japanese Islands (1996)

Figure 6-2: Current tectonic situation of Japan and key tectonic features.

The volcanic arc system caused by subduction of the Pacific and Philippine Sea Plates is evident in the chains of volcanoes in northern Honshu and along the Kuril and Izu-Bonin Arcs, and in Kyushu and along the Tokara Islands. In northern Honshu, arc volcanoes form the main backbone of the island. In this area, on the back-arc (Japan Sea) side, the structure is controlled by inversion tectonics, where extensional basin formation has changed to contraction, folding and uplift. By contrast, the fore-arc region of northern Honshu has less rugged topography. The mountains of central Honshu are in part formed by the collision of the Izu-Bonin Arc with the Eurasian/Amurian Plate, and the interaction between the North American/Okhotsk and the Eurasian/Amurian Plates. In the south, Shikoku Island lies on the fore-arc side and is split by the Median Tectonic Line. On the southeastern side of the Median Tectonic Line, the structure is principally that of an accretionary prism and the area is subject to active uplift as a result of ongoing accretion of material from the subducting zone. In the extreme south of the Japanese Islands, the back-arc extension and rifting in the Okinawa Trough has resulted in crustal thinning that has led to submersion of much of the Ryukyu Arc (Taira, 2001).

Relative plate movements, along with detailed regional crustal deformation, can be clearly detected from the growing database of GPS strain data from the large network of monitoring stations across Japan. Combined with detailed surveys of Quaternary active faults both onshore and offshore, this information provides evidence for interpreting and confirming the tectonics of the region. For example, the reverse faulting characteristic of compressional stresses in northern Honshu, strike-slip and rotational strain in central to SW Honshu and right-lateral strike-slip along the Median Tectonic Line in Shikoku are evident (See Figures 8-4 and 8-5 in Section 8).

6.2 Geological structure and evolution

A distinct picture of the tectonic history of the Japanese Islands can be traced back for about 30 Ma, although the geological history, as reflected by the presence of much older rocks, clearly extends much further back in time. The current outline of the Japanese Islands took shape during the period between 30 Ma and 15-14 Ma, accompanied by the spreading of the Japan Sea. The present rate and pattern of movement of the major plates became established around 2 Ma. This section summarises the geological history before 30 Ma and then presents a more detailed time sequence evolution of the tectonics over the last 30 Ma, in map form.

6.2.1 Summary of geological history before 30 Ma

The Japan region has been in a zone of subduction-related accretionary tectonics since the Permo-Jurassic (>295-135 Ma), when it lay on the eastern edge of Gondwanaland. Accretion has continued since then, on the western margin of the Panthalassa (proto-Pacific) and then Pacific Oceans, with wedges (prisms) of oceanic sediments and underlying ocean crust basalts being detached from the subducting ocean plate and accreted to the fore-arc zone of the continental plate to the west. The crust of the Japanese Islands area has thus grown progressively from the west (Asian continental side), with the rocks becoming younger towards the Pacific side. Crustal thickening by accretion was associated with granite formation, especially during the Cretaceous (135-65 Ma). Consequently, the basement rocks of the islands comprise largely Mesozoic to Palaeogene accretionary prisms, with the older rocks intruded by Cretaceous and Tertiary granites.

6.2.2 Detailed tectonic evolution in the last 30 million years

Figure 6-3(a-d) shows a time sequence reconstruction of the tectonic evolution of the Japanese Islands during the last 30 million years, the period over which such an analysis can be made with confidence. The same information is shown in a longer time context in Table 6-1.

(1) **Figure 6-3(a): Approximately 30 Ma – Start of rifting at the eastern margin of the Eurasian Plate.** Before spreading of the Japan Sea was initiated, the Japanese Islands were attached to the coastal region of the eastern margin of the Eurasian continent (known as Primoski Krai: Yamakita and Oohuji, 1999; 2000). The Pacific Plate was moving towards the WNW (Jolivet et al., 1994). The Philippine Sea Plate was migrating towards the NNW, but subduction ceased about 30 Ma (Seno and Maruyama, 1984; Nishimura and Yuasa, 1991). Around the same time, rifting took place in the east of Primoski Krai and in the east of Sakhalin, and right-lateral transform faulting was initiated in the palaeo-Kuril Arc (central and eastern Hokkaido) (Jolivet et al., 1994). The Tanakura Tectonic Line and the Hatagawa Tectonic Line exhibited right-lateral movement while the Median Tectonic Line showed left-lateral movement (Amano, 1991; Oide et al., 1989; Ichikawa, 1980).

(2) **Figure 6-3 (b): Approximately 20 Ma – Start of spreading of the Japan Sea, the Kuril Basin and the Shikoku Basin, along with rotation of the NE Japan Arc.** As spreading of the Shikoku Basin occurred, the palaeo-Izu-Bonin Arc divided into the Izu-Bonin Arc and the Kyushu-Palau Ridge, around 25 Ma (Taira, 2000). As the Japan Sea continued to spread, the NE Japan Arc began to rotate anti-clockwise, at around 20 Ma. As a result, areas of fresh water were formed, with seawater encroaching into them later (Jolivet et al. 1994; Hamano and Tosha, 1985; Niitsuma, 1985; Sato and Ikeda, 1999). The volcanic front shifted from inland towards the ocean (Kano et al., 1991).

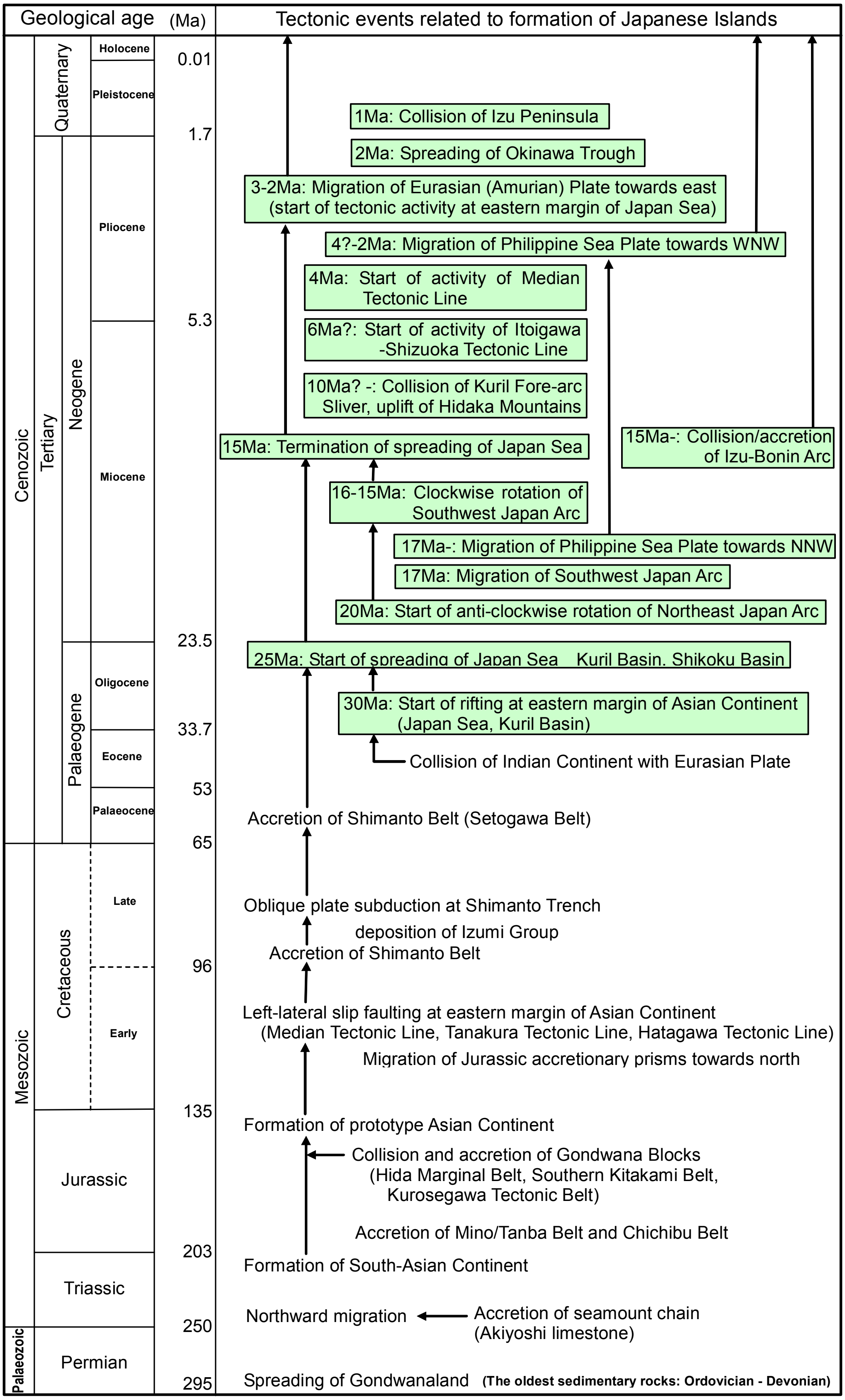
(3) **Figure 6-3 (c): Approximately 15-14 Ma – Completion of rotation of NE and SW Japan Arcs, spreading of the Japan Sea, the Kuril Basin and the Shikoku Basin, and start of collision of the Izu-Bonin Arc.** Subsequent to rotation of the NE Japan Arc, the SW Japan Arc began to rotate clockwise (Jolivet et al., 1994; Tamaki et al., 1992). The subduction zone of the Pacific Plate was located in almost its present location by around 17 Ma (Kano et al., 1991). The Philippine Sea Plate began to migrate towards the NNW (Nishimura and Yuasa, 1991). By around 15-14 Ma, spreading of the Japan Sea, the Kuril Basin and the Shikoku Basin was approaching its end, the Japanese Islands settled in their present location and the framework of the current geological structure of Japan was established. Collision of the Izu-Bonin Arc against Japan was initiated during this period (Takahashi, 1994). In SW Japan, the volcanic front shifted significantly towards the fore-arc side in connection with subduction of the Philippine Sea Plate, which was young and at high temperature (Kano et al., 1991; Uto, 1995).

(4) **Figure 6-3 (d): Approximately 1.8 Ma - Start of collision of the Kuril Fore-arc Sliver, uplifting of the Hidaka Mountains, development of the Itoigawa-Shizuoka Tectonic Line, activation of the Median Tectonic Line, tectonic events at the eastern margin of the Japan Sea, spreading of the Okinawa Trough and Izu-**

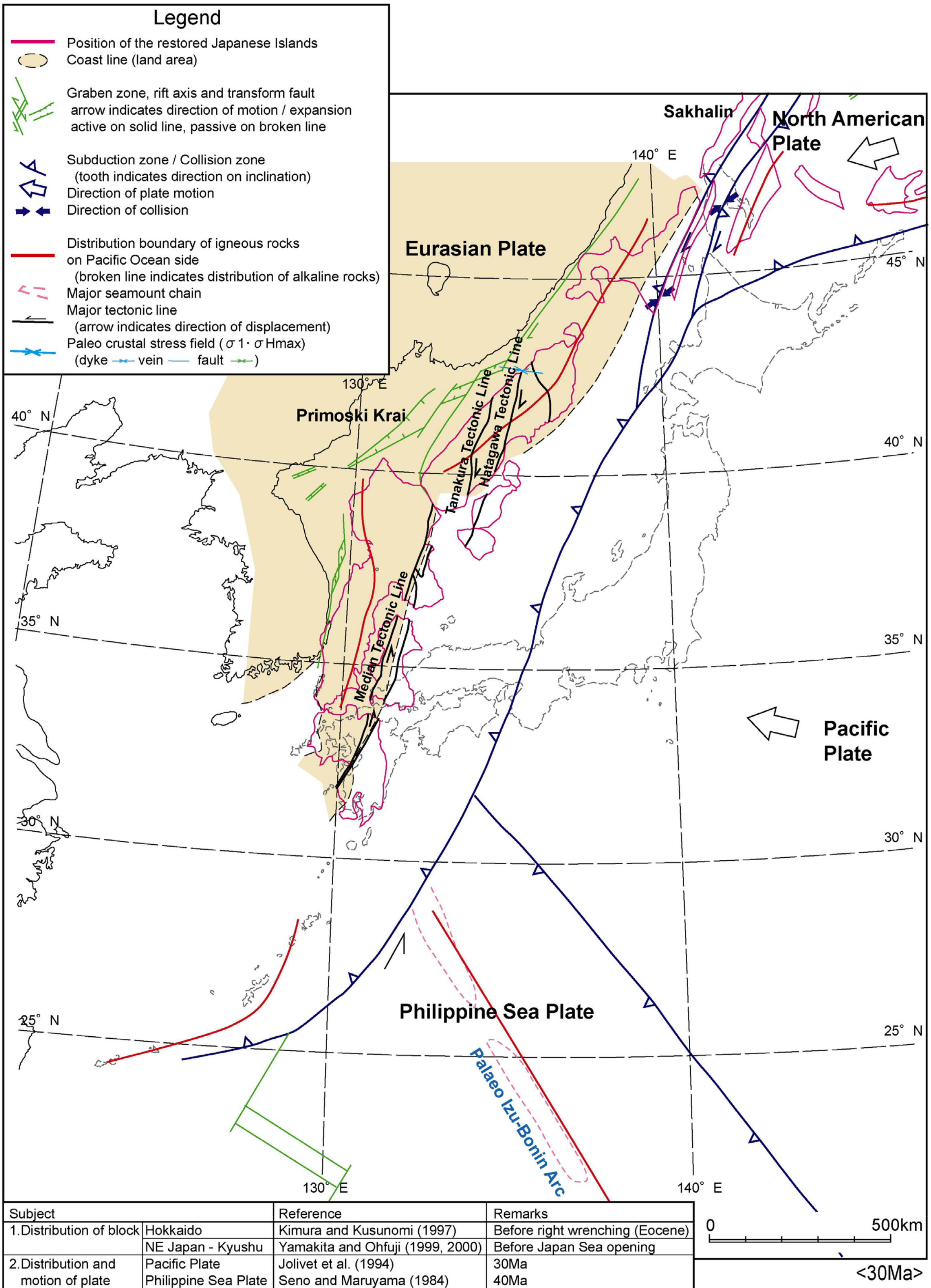
> **Bonin Back-arc Basins.** During the period from 10 to 4 Ma, the Kuril Fore-arc Sliver collided with the Hidaka Main Thrust (Kimura, 1996) and the Hidaka Mountains formed (Miyasaka, 1987). Around 6 Ma, the Itoigawa-Shizuoka Tectonic Line began left-lateral or reverse displacement (Yamashita ed., 1995; Jolivet et al., 1994). Around 5 Ma, right-lateral displacement began from the eastern side of the Median Tectonic Line (Sugiyama, 1991; 1992). At around 3 Ma, tectonic activity occurred on the eastern margin of the Japan Sea, along with eastward advance of the Eurasian (Amurian) Plate (Okamura et al., 1995). Reverse faults also began to appear inland (Sato, 1994; Awata, 1988). About 2 Ma, the Philippine Sea Plate changed its direction of movement from NNW to WNW (Seno, 1984; Nishimura and Yuasa, 1991) and the Okinawa Trough and the back-arc basins of the Izu-Bonin Arc began to spread (Kimura, 1990; Kimura et al. 1999). During the period from 11-5 Ma, the volcanic front regressed towards the back-arc side, both in NE and SW Japan, and some alkaline activity occurred in SW Japan and in the western offshore region of Hokkaido (Kano et al, 1991; Uto, 1995). In SW Japan, after 5 Ma, the subducting Philippine Sea Plate reached to the north of Shikoku. Consequently, the areas of volcanic activity shifted towards the coast of the Japan Sea and eruption of sub-alkaline rocks with alkali basalt took place (Uto, 1995).

The **present-day situation** is shown in **Figure 6-2 - Collision of the Izu Peninsula and conversion of plates along the eastern margin of the Japan Sea.** Around 1 Ma, the Izu Peninsula collided with Honshu (Matsuda, 1989). Along the eastern margin of the Japan Sea, the Eurasian Plate began to form a convergent boundary against NE Japan (the North American/Okhotsk Plate)(Nakamura, 1983; Kobayashi, 1983). Part of the Median Tectonic Line shows right-lateral displacement (Sugiyama, 1991), while the Itoigawa-Shizuoka Tectonic Line shows left-lateral or reverse displacement (Maruyama, 1984).

Table 6-1: Major events related to formation of the Japanese Islands.

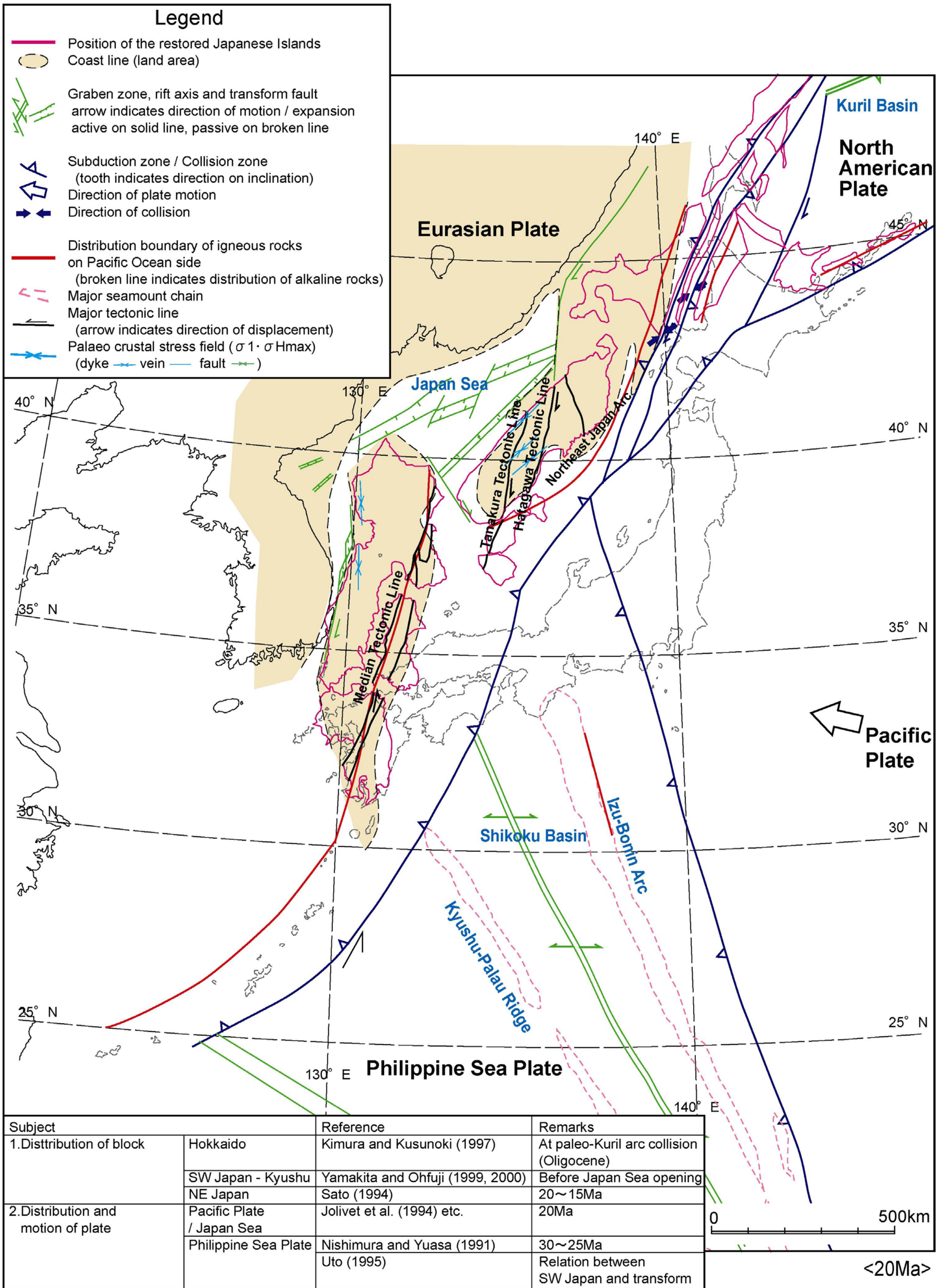


The age of the Pliocene-Pleistocene boundary is based on Japan Association for Quaternary Research and other ages on IUGS (2000).



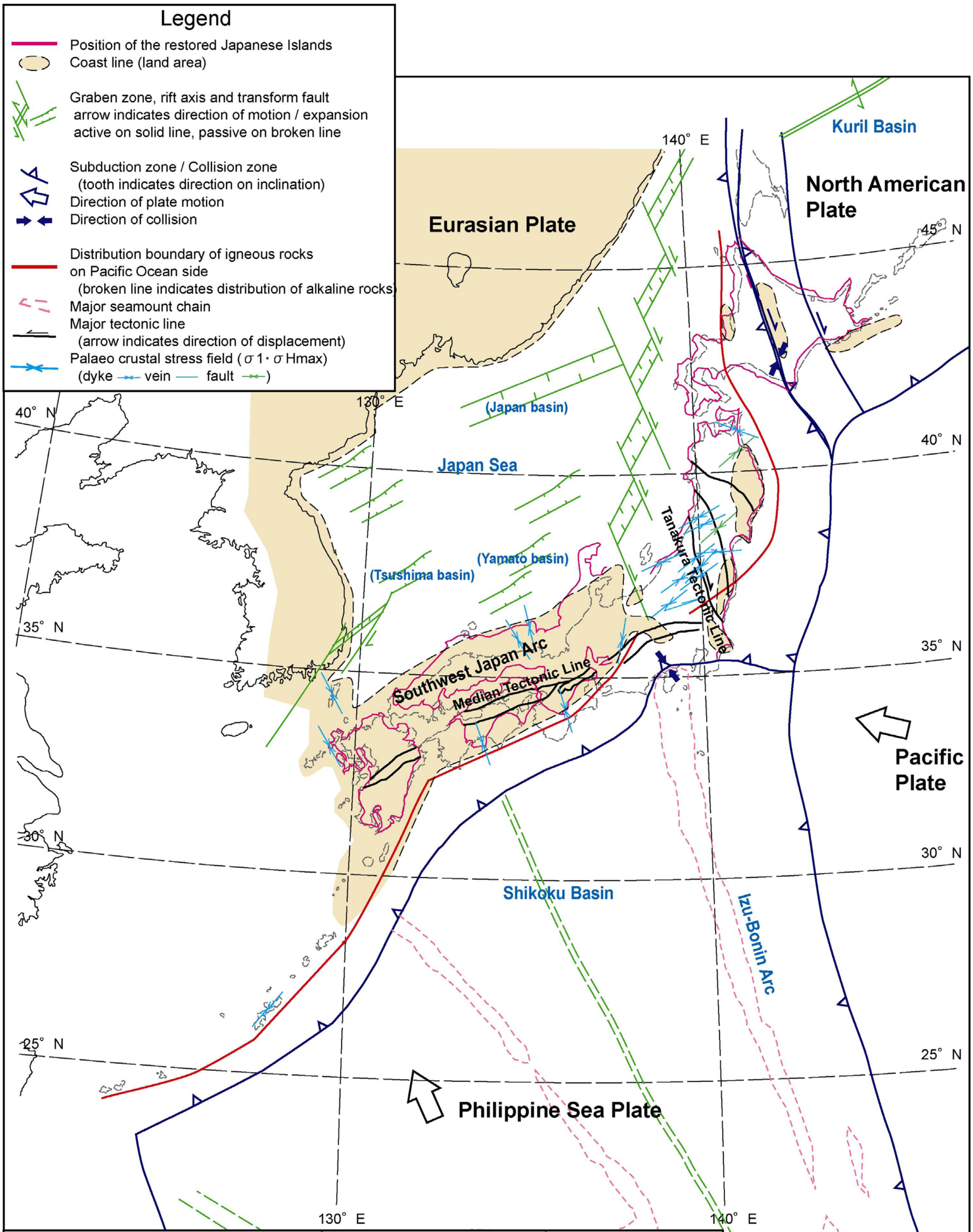
Subject		Reference	Remarks
1.Distribution of block	Hokkaido	Kimura and Kusunomi (1997)	Before right wrenching (Eocene)
	NE Japan - Kyushu	Yamakita and Ohfuji (1999, 2000)	Before Japan Sea opening
2.Distribution and motion of plate	Pacific Plate	Jolivet et al. (1994)	30Ma
	Philippine Sea Plate	Seno and Maruyama (1984)	40Ma
3.Volcanic front		Kano et al. (1991)	40 － 32Ma
4.Coast line		Kano et al. (1991)	40 － 32Ma
5.Other	Tectonic line	Oide et al. (1989), Amano (1991), Ichikawa (1980)	

Figure 6-3 (a): Tectonic situation around 30 Ma.



Subject		Reference	Remarks
1.Disttribution of block	Hokkaido	Kimura and Kusunoki (1997)	At paleo-Kuril arc collision (Oligocene)
	SW Japan - Kyushu	Yamakita and Ohfuji (1999, 2000)	Before Japan Sea opening
	NE Japan	Sato (1994)	20～15Ma
2.Distribution and motion of plate	Pacific Plate / Japan Sea	Jolivet et al. (1994) etc.	20Ma
	Philippine Sea Plate	Nishimura and Yuasa (1991)	30～25Ma
		Uto (1995)	Relation between SW Japan and transform
3.Volcanic front		Kano et al. (1991)	22～18Ma
4.Palaeo crustal stress field		Kano et al. (1991)	22～18Ma
5.Coast line		Kano et al. (1991)	22～18Ma
6.Other	Tectonic line	Kimura et al. (1983), Oka (1997), Jolivet et al. (1994), Ichikawa (1980) etc.	

Figure 6-3 (b): Tectonic situation around 20 Ma.

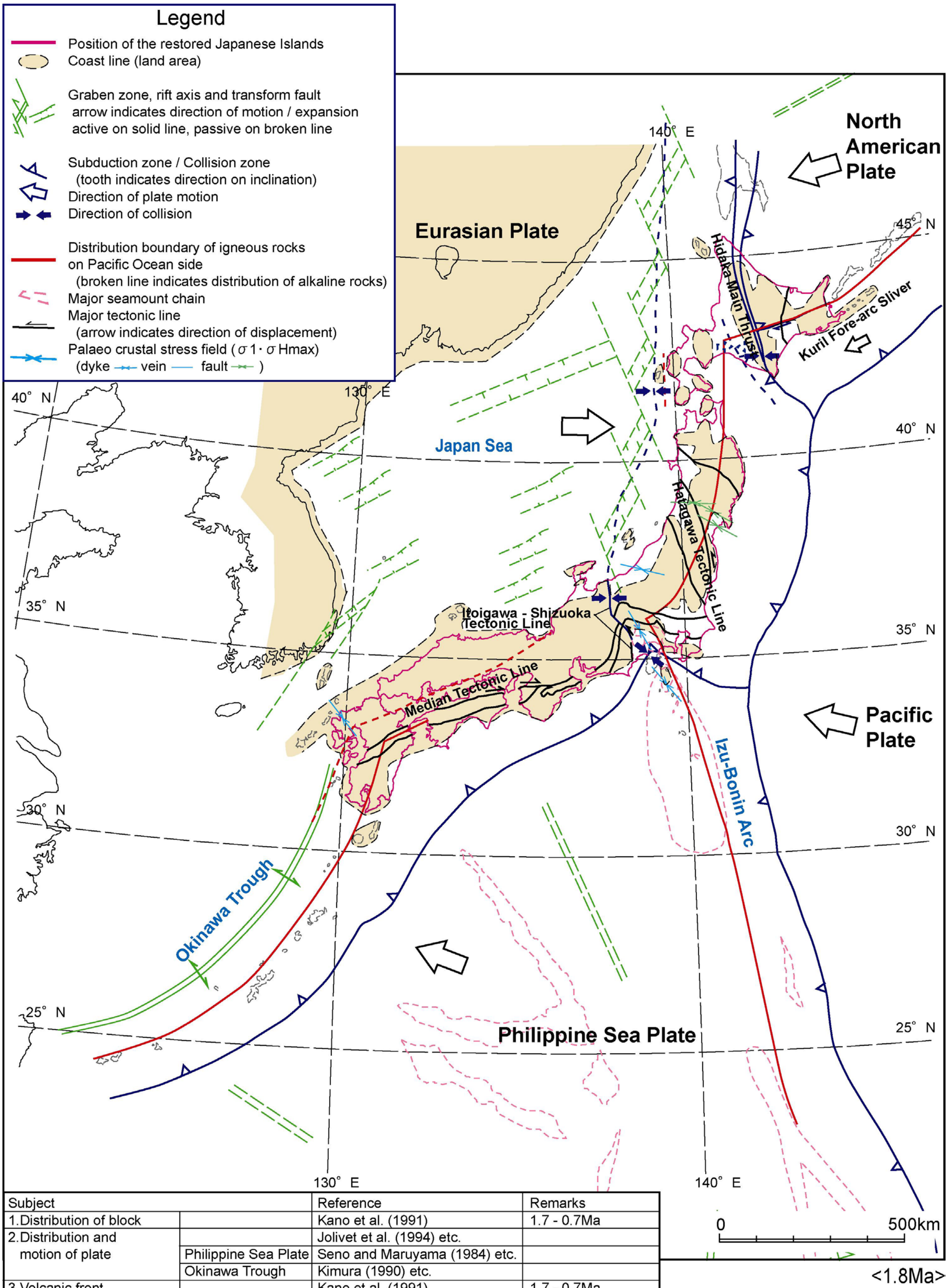


Subject		Reference	Remarks
1.Distribution of block	Hokkaido - Kyushu	Jolivet et al. (1994)	15Ma
	SW Japan	Yamakita and Ohfuji (1999, 2000)	Before Japan Sea opening
	NE Japan	Sato (1994)	15 - 13Ma
2.Distribution and motion of plate		Jolivet et al. (1994) etc.	15Ma
	Philippine Sea Plate	Seno and Maruyama (1984) etc.	
3.Volcanic front		Kano et al. (1991)	15 - 12Ma
4.Palaeo crustal stress field		Kano et al. (1991)	15 - 12Ma
5.Coast line		Kano et al. (1991)	15 - 12Ma
6.Other	Tectonic line	Kimura et al. (1983), Miyasaka (1987), Kimura (1981), Jolivet et al. (1994), Amano (1991) etc.	

0 500km

<14 - 15Ma>

Figure 6-3 (c): Tectonic situation around 14-15 Ma.



Subject		Reference	Remarks
1.Distribution of block		Kano et al. (1991)	1.7 - 0.7Ma
2.Distribution and motion of plate		Jolivet et al. (1994) etc.	
	Philippine Sea Plate	Seno and Maruyama (1984) etc.	
	Okinawa Trough	Kimura (1990) etc.	
3.Volcanic front		Kano et al. (1991)	1.7 - 0.7Ma
4.Palaeo crustal stress field		Kano et al. (1991)	1.7 - 0.7Ma
5.Coast line		Kano et al. (1991)	1.7 - 0.7Ma
6.Other	Tectonic line	Miyasaka (1987), Kimura (1981), Oka (1997), Nakamura (1983), Sugiyama (1991), Yamashita (1995)	

Figure 6-3 (d): Tectonic situation around 1.8 Ma.

7 THE GEOLOGICAL ENVIRONMENT FOR REPOSITORY SITING

The Japanese Islands have been formed through complex tectonic evolution, as described in the previous chapter, resulting in a wide variety of rock types and their distinctive distribution. This chapter overviews the distribution of the main rock units in Japan and summarises their characteristics in terms of repository siting through comparison with those in other countries.

7.1 Distribution of the geological environment in Japan

The geological units of Japan comprise various types of sedimentary, igneous and metamorphic rocks, and unconsolidated sediments. The outcrop and near-surface occurrence of these units generally follows a zonal distribution, approximately parallel to the axis of the Japanese Island Arc (Figure 7-1(a)). Such zones form the basic structure of the Japanese Islands and consist mostly of pre-Neogene sedimentary rocks including accretionary complexes and igneous rocks. In contrast, the distribution of the Neogene and Quaternary sedimentary and igneous rocks that overlie or intrude the pre-Neogene basement rocks reflects plate motion.

Sedimentary, igneous (volcanic and plutonic) and metamorphic rocks occupy about 56%, 40 % and 3 % of the subsurface geology, respectively, and, in terms of the age of these rocks, the pre-Neogene, Neogene and Quaternary rocks form about 42%, 25% and 33%, respectively. The pre-Neogene rocks, regardless of rock type, belong to “well-lithified hard rocks” by the Japanese civil engineering standard. The Neogene rocks belong to “well- to semi-lithified rocks” or “soft rocks”. The Quaternary rocks comprise unconsolidated to weakly lithified sediments and unconsolidated to consolidated eruptive volcanic rocks (JSCE, 2001).

The distribution of each rock type, along with age and lithofacies, is summarised below, based on Kimura et al. (1993), JSCE (2001) and the Editorial Group for Computer Graphics, Geology of Japanese Islands (1996).

(1) Sedimentary rocks: Figure 7-1(b)

Pre-Neogene rocks

Ordovician to Devonian rocks, mainly comprising tuffaceous sandstones, mudstones and limestones, have very limited distribution, occurring in the northern part of NE Japan and in central Japan. Carboniferous to Jurassic rocks, comprising mostly melanges of sandstones, mudstones (shales), bedded cherts, limestones and basalts, occur intermittently from Hokkaido to the Ryukyu Arc. Cretaceous and Palaeogene rocks, comprising bedded sequences and melanges of sandstones, mudstones and alternations of sandstone/mudstone (largely of turbiditic origin), are widely distributed from Hokkaido to the Ryukyu Arc. In particular, in the Shimanto Belt to the south of the Median Tectonic Line, turbiditic melanges dominate. Non-marine to neritic sedimentary rocks of the same age, such as conglomerates, sandstones and mudstones, also coexist. In particular, Palaeogene rocks include the majority of the coal beds in Japan.

Neogene and Quaternary rocks

Neogene rocks comprise neritic to hemipelagic sandstones, mudstones and alternations of sandstone/mudstone together with andesitic to rhyolitic (in part basaltic) volcanic material in the "Green Tuff Region" – from western Hokkaido to the western and southern part of NW Japan. Similar rocks, but from lacustrine to neritic environments, also occur sporadically in SW Japan. In addition, neritic to hemipelagic rocks, but with less associated volcanic rocks, exist in eastern Hokkaido and along the Pacific coast of Honshu and Kyushu. Quaternary sedimentary rocks and unconsolidated sediments form predominantly in alluvial plains.

(2) Volcanic rocks: Figure 7-1(c)

Pre-Neogene rocks

Palaeozoic andesitic and basaltic lavas and tuffs are intercalated in the sedimentary rocks. Basalts are generally observed as small rock masses including olistoliths, but large bodies with thicknesses over several hundreds metres are sometimes found associated with limestones and banded cherts. Mesozoic volcanic rocks are dominated by voluminous rhyolitic to andesitic welded tuffs associated with Cretaceous granites in central and western Honshu. Palaeogene rhyolites occur sporadically in southern Hokkaido and along the axial part and Japan Sea side of Honshu.

Neogene and Quaternary rocks

Neogene andesitic to rhyolitic (in part basaltic) lavas, pyroclastics and tuffs are associated with the sedimentary rocks as described above. Quaternary volcanic rocks, including unconsolidated volcanic sediments, occur in the back-arc side of the present volcanic front. The distribution of volcanoes is sparse in SW Japan compared to NE Japan.

(3) Plutonic rocks: Figure 7-1(d)

Palaeozoic plutonic rocks generally comprise sporadic small intrusive bodies of granite, granodiorite, gabbro and ultrabasic rocks (serpentinites). Cretaceous granitic rocks are widely distributed in Honshu and northern Kyushu. The large complexes often cover 1000-3000 km^2. Palaeogene granitic rocks occur as sporadic small intrusive bodies on the Japan Sea side. Neogene granitic rocks are distributed in central Honshu and on the Pacific side of SE Japan. In general, they are less strongly jointed than the Cretaceous granites, because they are younger and less tectonically disrupted.

(4) Metamorphic rocks: Figure 7-1(e)

The majority of metamorphic rocks in Japan were formed in the Mesozoic (Triassic to Jurassic), predominantly from sedimentary rocks of Palaeozoic to Jurassic age. Mesozoic metamorphic rocks are classified into high-temperature and high-pressure types. The former type consists mainly of psammitic and pelitic gneisses, and is distributed in the areas of granitic rocks in eastern and central Honshu. The latter type consists of psammitic, pelitic and basic schists, and is distributed in central Hokkaido to the south of the Median Tectonic Line, and in NW Kyushu.

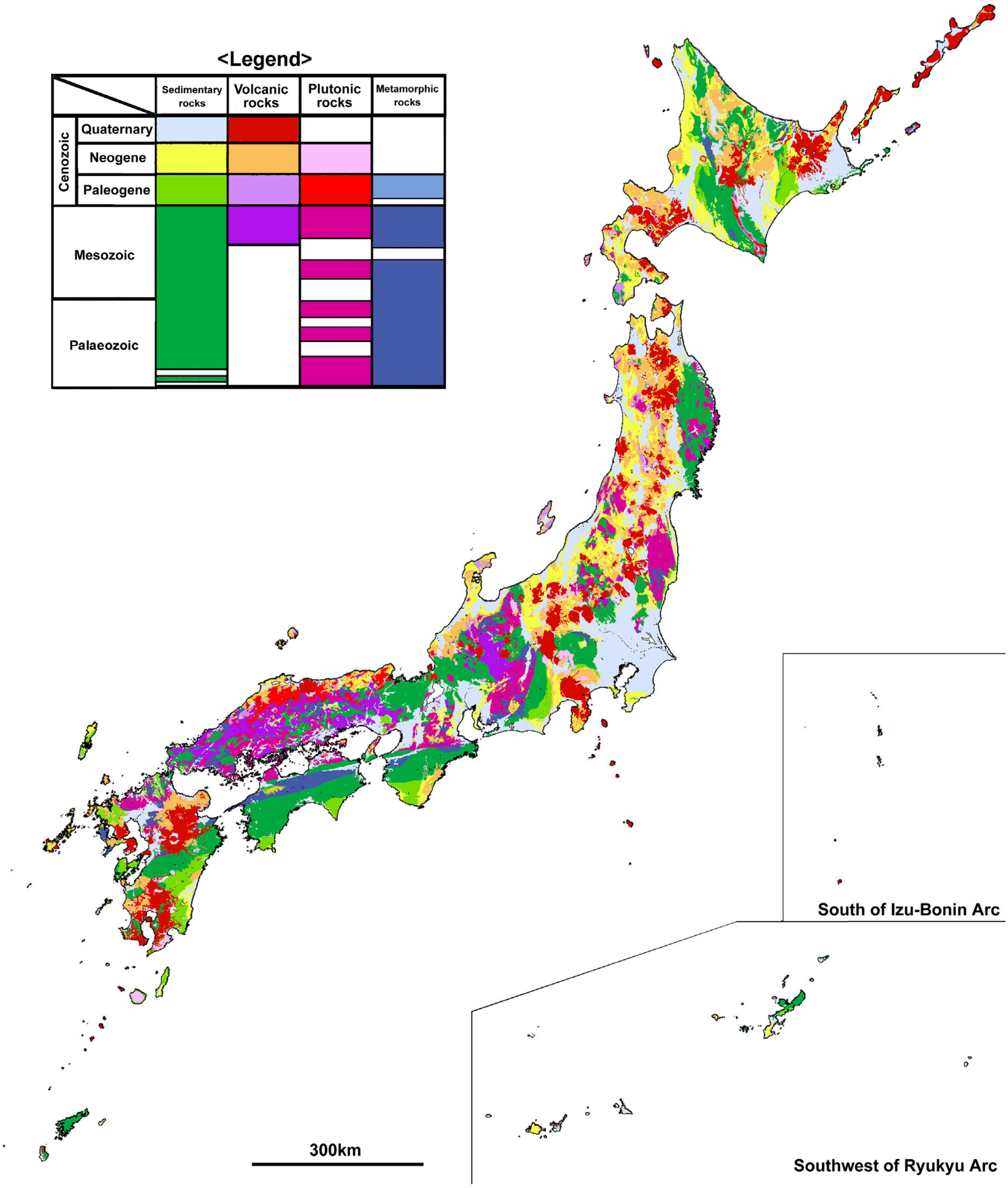


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Figure 7-1(a): Distribution of subsurface rock units (modified from Geological Survey of Japan, 1995).

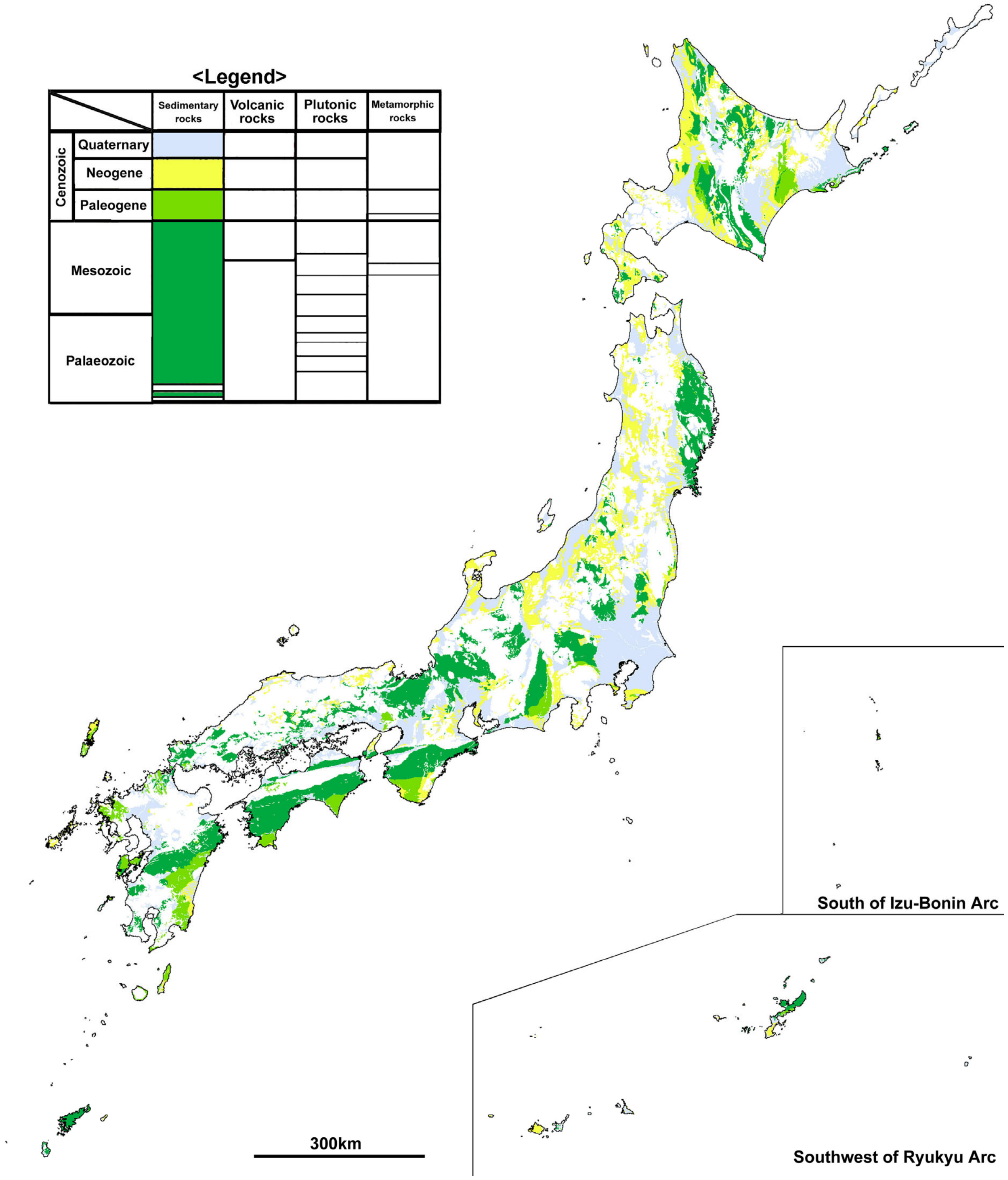

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Figure 7-1(b): Distribution of sedimentary rocks (modified from Geological Survey of Japan, 1995).

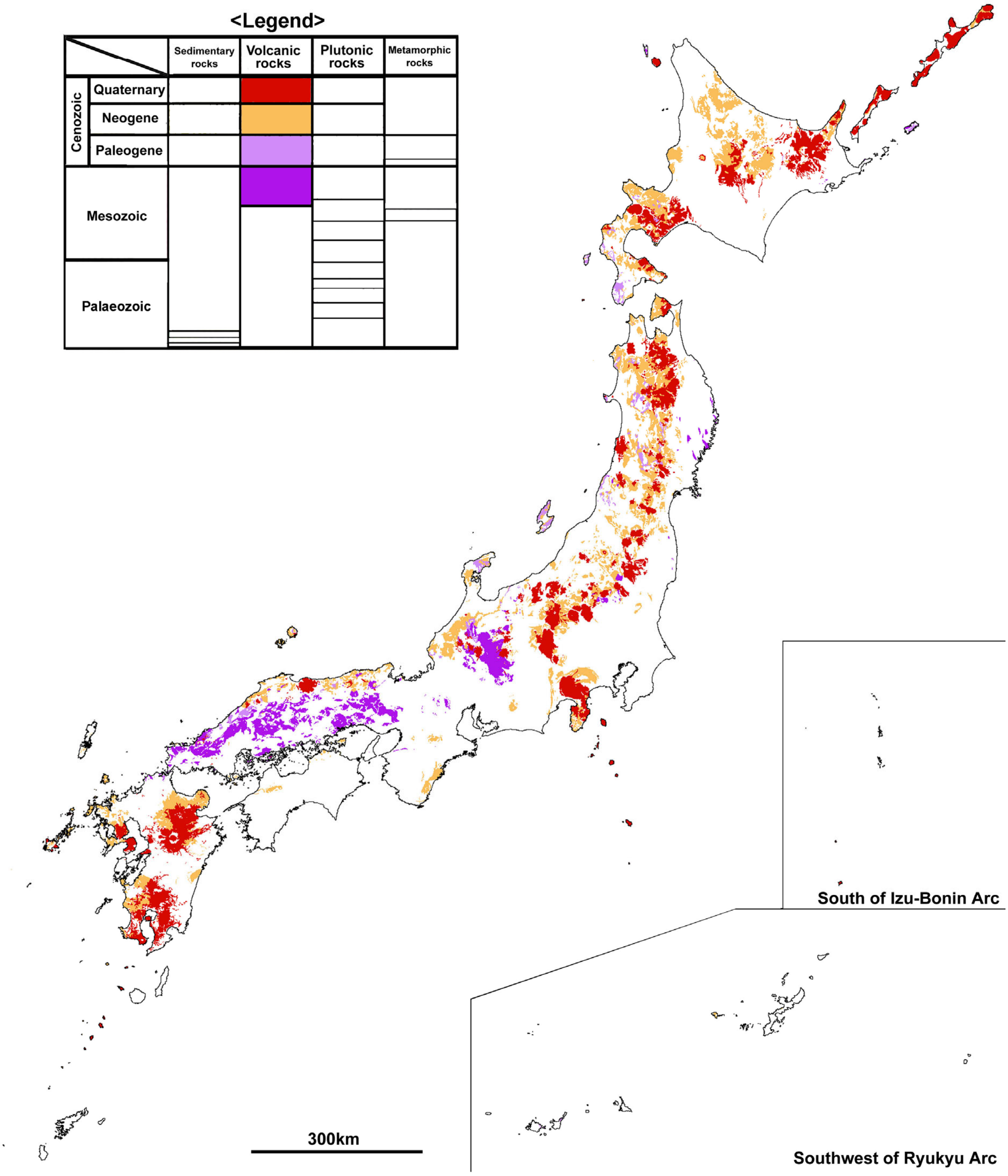

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Figure 7-1(c): Distribution of volcanic rocks (modified from Geological Survey of Japan, 1995).

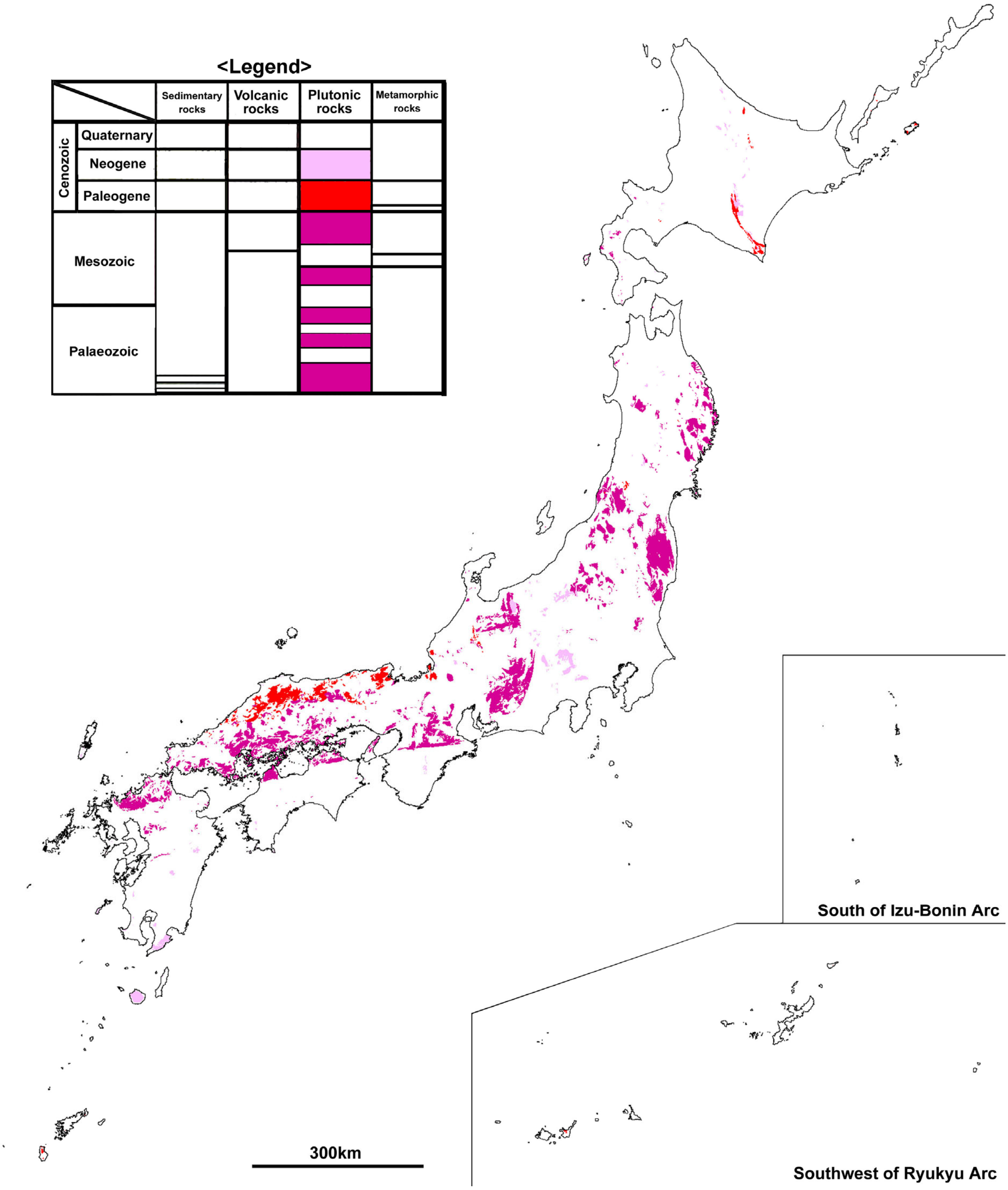

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Figure 7-1(d): Distribution of plutonic rocks (modified from Geological Survey of Japan, 1995).

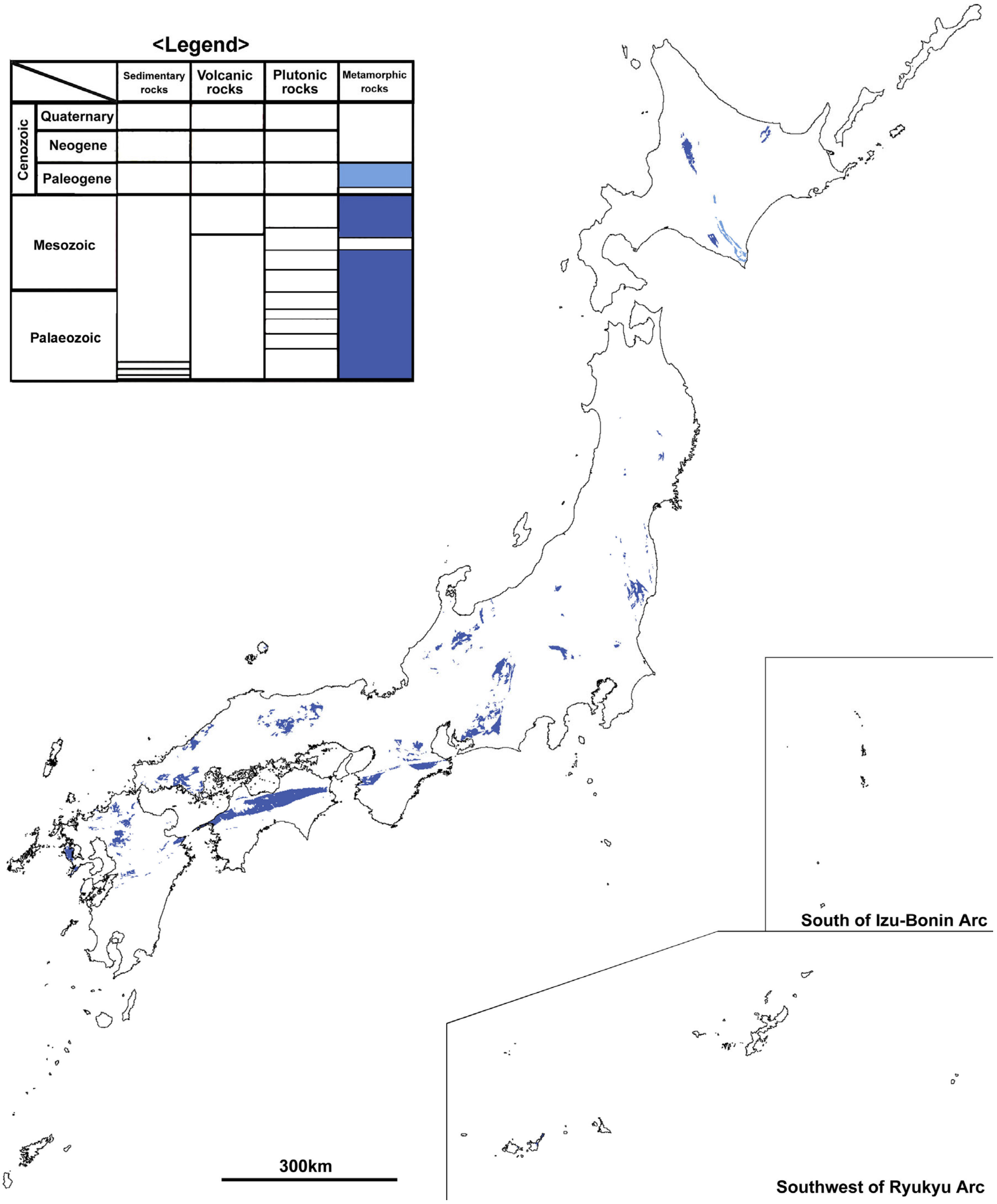

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Figure 7-1(e): Distribution of metamorphic rocks (modified from Geological Survey of Japan, 1995).

7.2 Characteristics of the geological environment in Japan

In general, rock types that have been identified internationally for radioactive waste disposal are classed into crystalline rocks, argillaceous rocks and evaporites. The first category includes granites, high-grade metamorphic rocks and welded tuffs. Argillaceous sediments include mudstones, shales and plastic clays. Correlating these internationally used categories with Japanese ones is not straightforward. For example, Japan has no evaporites.

Japan has extensive areas of exposed and more deeply buried granitic rocks that are geologically and structurally comparable with granitic terranes elsewhere in the world. On the other hand, many of the sedimentary rocks are dissimilar to the predominantly homogeneous clays and shales being considered for HLW disposal in Europe (e.g. the Boom Clay of Belgium and the Opalinus Clay of Switzerland). The majority of these sedimentary rocks have been laid down in tectonically quiet environments and subsequently subjected to only mild structural deformation, compared to the accretionary tectonics affecting many of the sedimentary rocks of Japan.

The sedimentary rocks (pre-Neogene and some Neogene) are characterised by a wide variety of indurated rocks (including volcanic intercalations) that may behave like hard rocks, both mechanically and hydrogeologically. The less consolidated and deformed Neogene formations including effusive volcanic rocks are similar in some of their properties to the argillaceous rocks being evaluated in other countries, whilst the Quaternary formations are semi- or non-consolidated (JSCE, 2001).

It can thus be seen that the geological environment that may arise from our volunteer process may not be directly analogous to those under examination for waste disposal in other countries. They rather reflect the specific geological and tectonic conditions of the Japanese Islands.

8 AVOIDING SEISMIC IMPACTS

To a foreign observer, the active tectonics of the Japanese Islands are probably most manifest in the frequent, large magnitude earthquakes that affect the region. Japanese society has always had to accommodate the potential for seismic disruption, and modern Japanese civil engineering is highly skilled in earthquake-resistant design for buildings, transportation and other infrastructure.

All regions of Japan experience seismicity to varying degrees and it is clear that a repository that can provide secure, long-term containment of HLW will experience many, recurrent seismic events. Seismic shaking at several hundreds of metres depth in competent rocks is of limited concern as it is well known to have little structural impact on underground facilities even in the largest events. Thus, the main issue is the potential for shear displacement within the rock mass in which the repository is constructed.

8.1 Location and distribution of earthquakes

Earthquakes in and around Japan are divided into two principal types according to their tectonic environment of their occurrence. Plate boundary earthquakes occur at the interface between the subducting oceanic plate and the over-riding continental plate (shown pink in Figure 8-1). In-plate earthquakes are subdivided into continental plate type (shown yellow in Figure 8-1) and oceanic plate type that takes place within the subducting oceanic plates (shown green in Figure 8-1). The continental in-plate earthquakes are relatively shallow and occur within the upper part of the crust that comprises the Japanese Islands, although most of them occur at depths more than 5 km. Oceanic in-plate types occur at much greater depths beneath the Japanese Islands, although they can be shallow offshore.

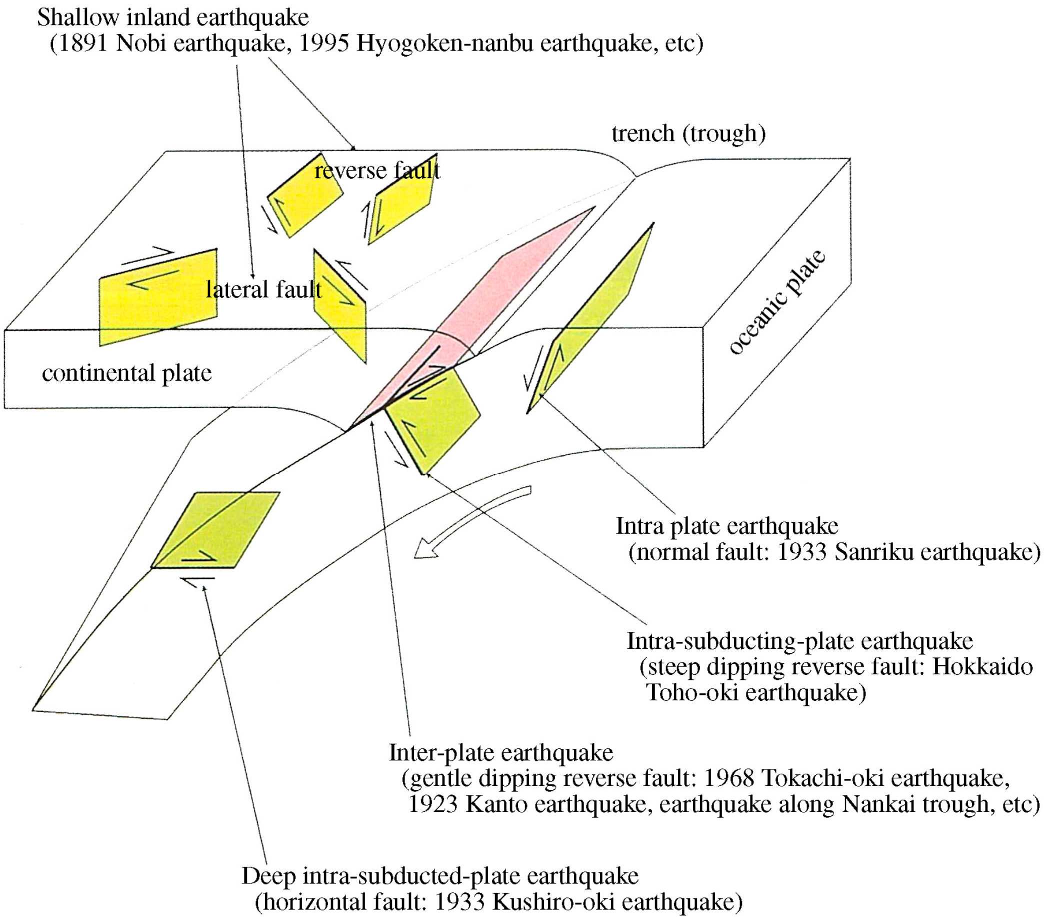

Figure 8-1: Types and sources of earthquakes in Japan (Headquarters for Earthquake Research Promotion, 1999).

Very large (M 7-8) plate boundary earthquakes occur in areas such as the Kuril Trench, the Japan Trench and the Izu-Bonin Trench where the Pacific Plate subducts. Movement along low angle thrust faults along the edge of the continental plate, dragged by the oceanic plate during the progressive accretionary process, is interpreted as the cause.

Plate boundary earthquakes of M 8 also occur in areas such as the Sagami and Suruga Troughs near the Izu Peninsula, and the Ryukyu Trench. Examples include the Tonankai earthquake (1944; M 7.9) and the Nankai earthquake (1946; M 8.0). The historical record shows that there has been this scale of earthquakes periodically, with intervals of between 90 to 260 years (Sangawa, 1998). Lower angle reverse faulting also occur in these areas.

Within the oceanic plates, different types of in-plate earthquakes occur as a result of the movement of the subducting plates. In the offshore area, immediately to the east of the subduction zone, normal fault type earthquakes are common because tension is predominant in the shallower regions where the oceanic plate is pulled down into the upper mantle by its own weight. At depth, on the other hand, reverse fault type earthquakes are frequent, as in-plate compression is dominant in the down-going slab. The Izu Peninsula is overriding the Philippine Sea Plate and the earthquakes in this region belong to the oceanic plate category. Despite the general observations above, lateral (slip) faults are observed in this area, as horizontal stress is predominant, owing to the collision process (Shimazaki and Matsuda 1994). Very deep earthquakes occur at depths of 50-200 km in the subducted oceanic plates with reverse and/or strike-slip fault movements (Headquarters for Earthquake Research Promotion, 1999).

Earthquakes in the continental plates show different characteristics in NE and SW Japan, reflecting the different stress regimes. In NE Japan, where EW stress dominates owing to the subducting Pacific Plate, earthquakes occur on N-S striking reverse faults. In SW Japan, where the Philippine Sea Plate subducts in a NW direction towards the Nankai Trough (Ohnaka and Matsuura, 2002), a NW-SE compressional stress regime is present and lateral strike-slip faulting causes earthquakes.

At depths greater than 20 km in the continental region, the high in-situ temperatures t appear to prevent brittle fracturing from taking place and plastic deformation occurs. Therefore, with the exception of those occurring on the plane of the subducting plates, earthquakes on land occur at depths less than 20 km and mostly greater than 5 km. The recorded distribution of deeper and shallower earthquakes is shown in Figure 8-2(a, b).

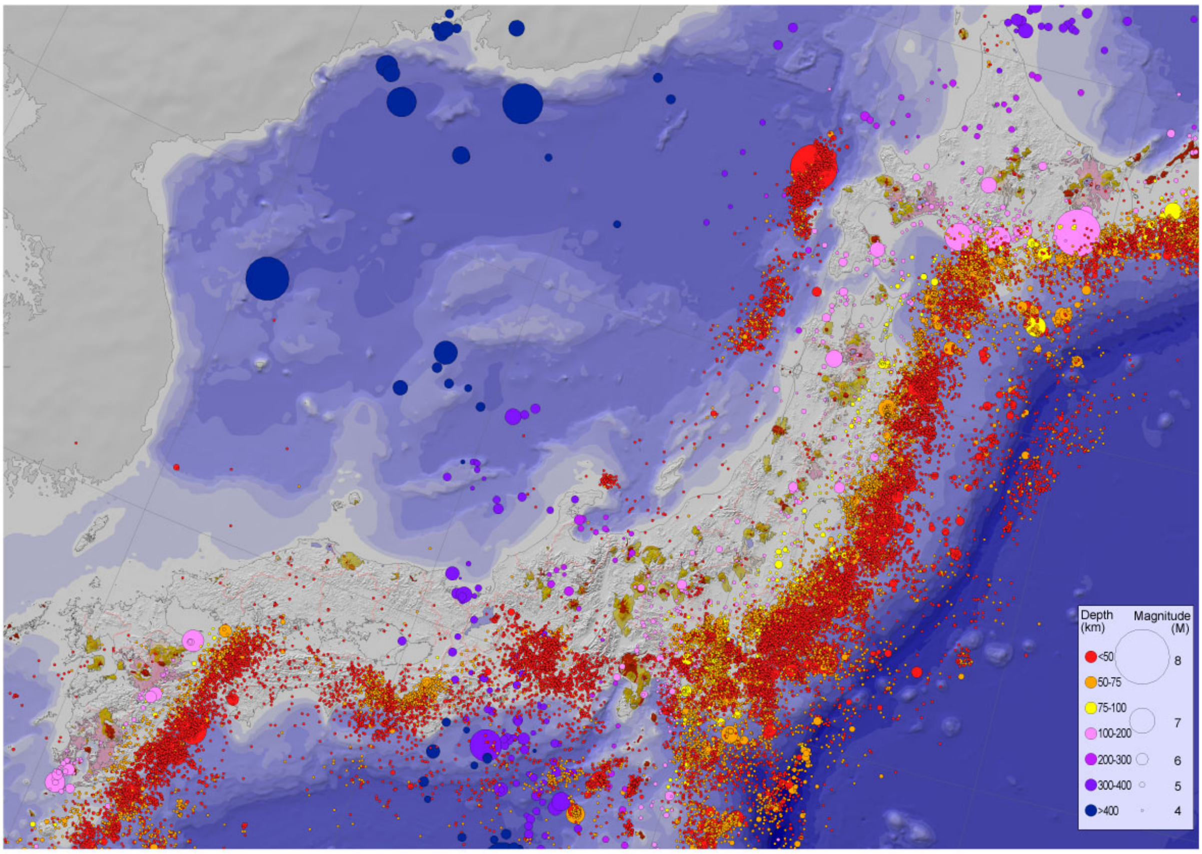

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Figure 8-2(a): Distribution and magnitude of recorded deeper (>50 km) earthquake hypocenters (Editorial Group for Computer Graphics, Geology of Japanese Islands, 1996).

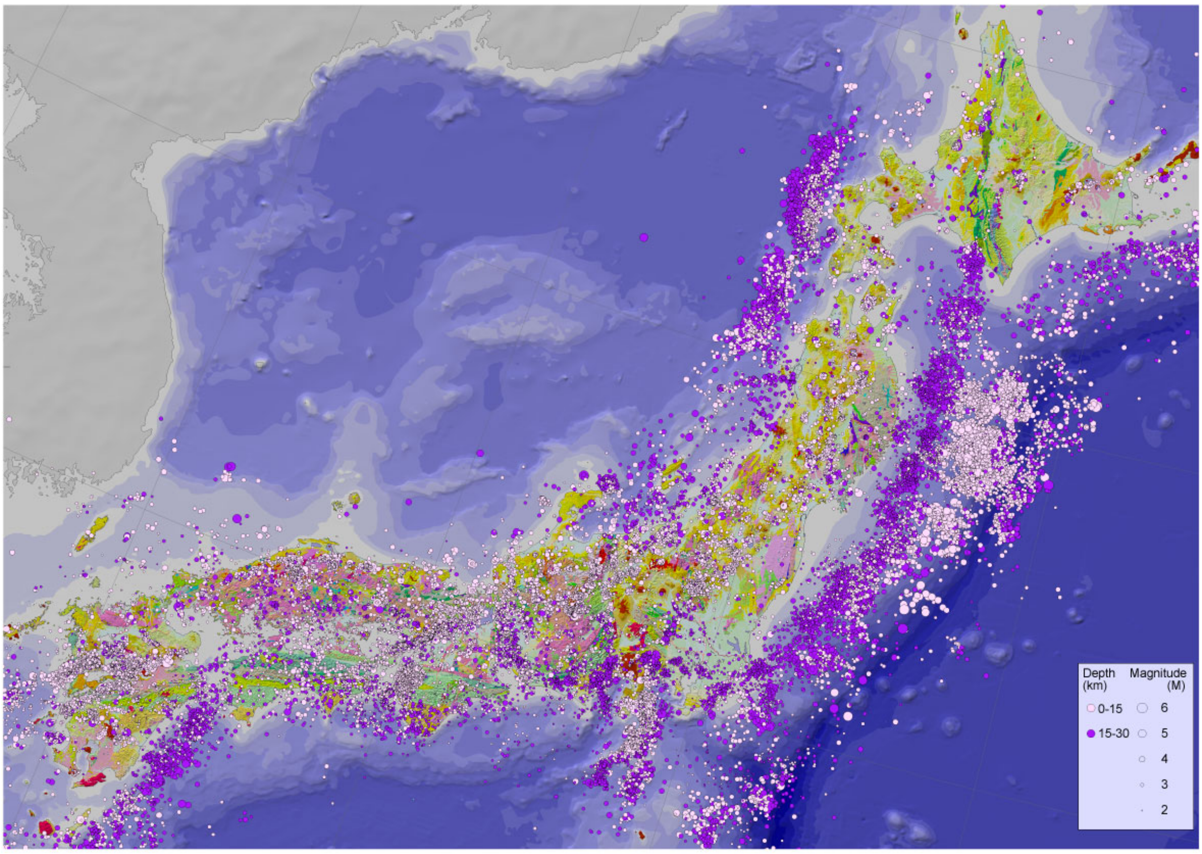

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Figure 8-2(b): Distribution and magnitude of recorded shallower (0-30 km) earthquake hypocenters (Editorial Group for Computer Graphics, Geology of Japanese Islands, 1996).

8.2 Active faults, their distribution and characteristics

In general in Japan, an active fault is an earthquake source fault that reaches the ground surface, causing deformation and displacement to the near-surface topography and geology. To be defined as active, faults need to have been reactivated repeatedly in the late Quaternary (the last few hundred thousand years). Active faults are thus likely to be reactivated in the future.

The onshore distribution of active faults in Japan is compiled as the "Active Fault Map of Japan" (Nakata and Imaizumi, 2002) on a scale of 1: 2,000,000. The same type of map is available on the same scale for offshore areas (Tokuyama et al., 2001). Both onshore and offshore maps are included in the Annexes to this document.

It is considered that the majority of active faults in Japan started their activities at around the beginning of the Quaternary and have been active since then. For example, the Kitayuri fault system in NE Japan "backbone" ridge started to move at about 2.5 Ma (Awata, 1988) and the main faults in NE Japan (central mountain range) started to move at around 1.0 Ma (Awata and Kakimi, 1985; Awata, 1988). However, as shown by the Shoubudani fault in SW Japan (Sangawa, 1977), there are also some faults that have ceased movement during the Quaternary.

It is estimated that the active faults in SW Japan (Fujita, 1993) and in the northern Izu Peninsula established their present movement patterns at around 0.5 Ma (Ito et al., 1989).

For a known active fault, the largest possible future earthquake is likely to be of the same magnitude as previous earthquakes and specific to that fault. This concept is known as the "characteristic earthquake model" (Schwartz and Coppersmith, 1984) and provides the basis for prediction of future earthquakes. Based upon current scientific knowledge, the main characteristics of active faults, except for those that exhibit creep movement, are summarised as follows (Sugiyama, 2001):

- consists of one or more active segments;
- location and magnitude of activity are stable for a period of several thousands (to several tens of thousands) of years;
- the active segment repeats its movement individually or in combination with other segments;
- the intervals of movement of each active segment mostly range between 0.5-2.0 times the average movement interval of the segment;
- displacement of any point in every movement within the active segment mostly ranges between 0.5-2.0 times the average displacement per movement of the point.

The activity of a fault is evaluated by the frequency of movement (inverse of activity interval, R) and average slip (displacement) for a movement, D (Sugiyama, 2001). An average slip rate (S = D/R, in m/1000years or mm/year) is used as an index that expresses the level of fault activity. Table 8-1 shows the classification of faults by this index.

Table 8-1: Classification of active faults by activity and general landform characteristics (Geographical Survey Institute, 1998)

Class	Average Slip rate, S (m/1000 years)	Example faults	General characteristics of topographic displacement
AA	100 - 10	- Faults along Japan Trench - Nankai Trough - Sagami Bay Fault	Visible in a satellite image as a significant topographic feature, equivalent to plate boundaries in most cases.
A	10 - 1	- Median Tectonic Line - Central part of the Itoigawa-Shizuoka Tectonic Line - Atera Fault - Atotsugawa Fault	Topographic discontinuity is obvious in an aerial photo with a scale of 1:40,000 and the strike of displacement is evident. Topographic displacement is highly visible.
B	1 - 0.1	- Tachikawa Fault - Fukaya Fault - Nagamachi-Rifu Fault	Fault displacement can be seen in an aerial photo with a scale of 1:40,000 and the strike of displacement can be defined in some cases. Topographic displacement is less visible.
C	0.1 - 0.01	- Fukouzu Fault - Gomura Fault - Yoshioka Fault	Topographic displacement is barely distinguished in an aerial photo with a scale of 1:20,000. Lineament is evident.
D	0.01 - 0.001		Evidence suggests activity during the Quaternary. However, both topographic displacement and lineament are hard to recognise.

The highly active faults and important active faults from a disaster prevention viewpoint are well studied by trenching surveys and other measures. Inoue et al. (2001) studied the available information on 87 of these faults and found an inverse relationship between average slip rates and intervals of activity (return period) (Figure 8-3). The intervals of fault activity are reported to be less than 30,000 years, although there are other studies suggesting longer intervals; e.g. 31,000 - 36,000 years for the Nagao fault (Sugiyama et al., 2001).

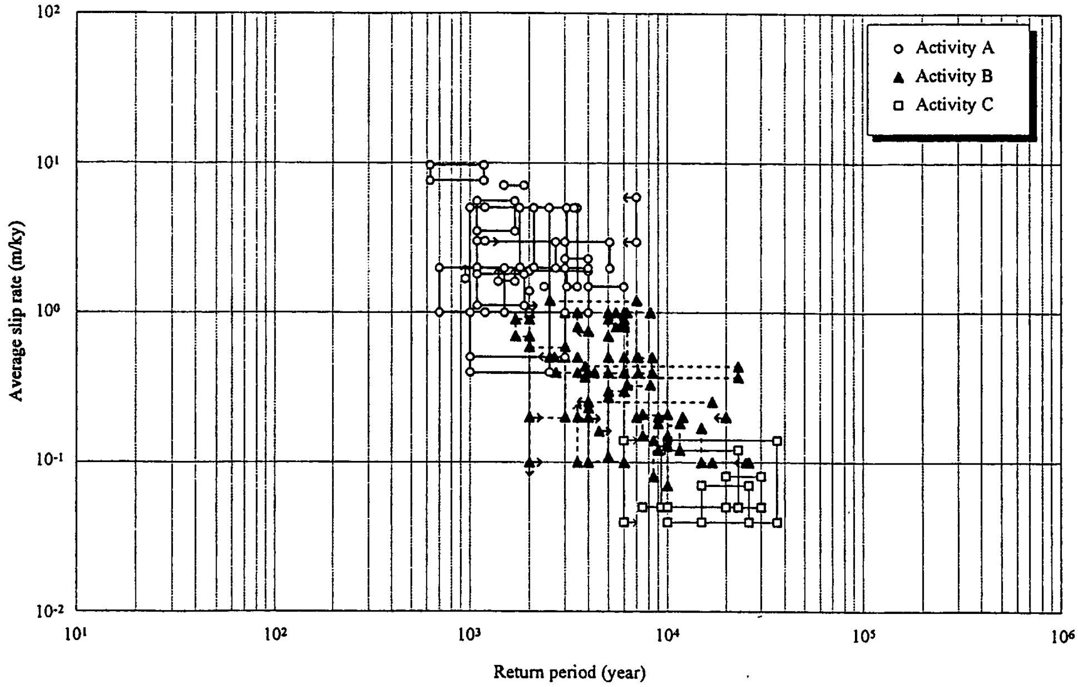


Figure 8-3: Correlation of slip rate of faults and return period of earthquakes on the faults (Inoue et al., 2001) The degree of fault activity is classified as A, B or C (see Table 8-1). The lines between the symbols show the ranges of parameters of individual fault (solid for classes A and C, dashed for class B). The arrows show the estimated direction of ranges for either the average slip rate or the return period.

The distribution of active faults can be considered in terms of the broad tectonic structure of Japan and can be compared with the growing database of GPS (global positioning system, using satellites) shear rate variations across the Japanese Islands. Figure 8-4 shows the pattern of crustal movement observed over the last few years since the establishment of the extensive network of GPS geodetic stations in Japan. The GEONET network was started in 1993 and now has more than 1200 stations providing 24-hour continuous positioning observations at 30 second intervals. The Geographical Survey Institute (GSI) maintains this network.

The data being gathered allow us to calculate strain "budgets" that account for how tectonic stresses are built up by plate movements and are released during faulting, uplift/subsidence and other events causing rock deformation (e.g. intrusion of volcanic rocks and so-called "slow events" with no seismic signature). This type of analysis allows estimates to be made of future earthquake source areas and of accumulated strain energy for such earthquakes (e.g.

Wernicke et al., 1998). As discussed later, it also facilitates identification of crustal “blocks” bounded by major fault zones and modelling of their movement and relative stability.

Perhaps the most common observation that has been made since the GPS data started to become available is the way that the measured crustal strains provide direct and “real time dynamic” confirmation of the patterns of plate movement that had previously been inferred from indirect measurements (e.g. rock dating) or infrequent geodetic measurements. The overall pattern that can be seen is one of crustal contraction in northern Hokkaido, E-W contraction along much of the Pacific coast and extension in Kyushu, with various regional perturbations within this pattern.

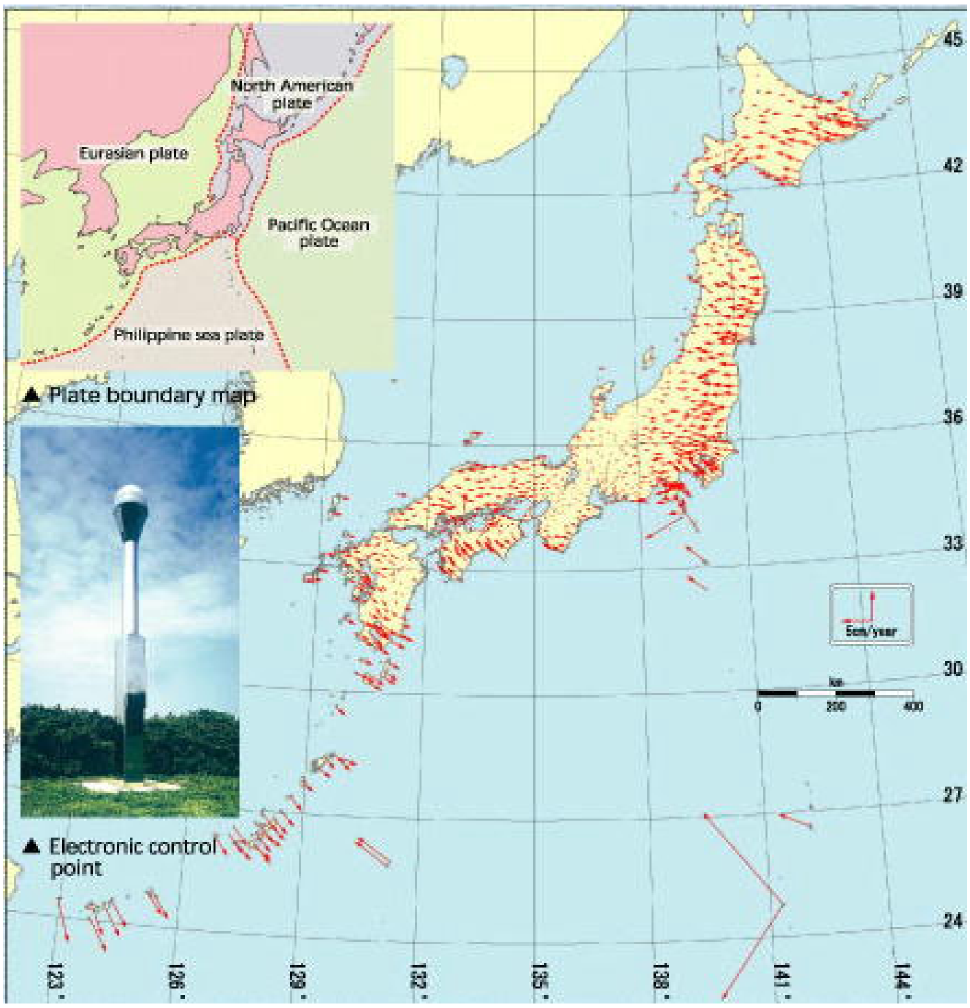


Figure 8-4: Vector map produced by analysis of horizontal crustal movement from April 2000 – March 2001 using the nationwide electronic control points (inset) established by GSI (fixed station: Ohgata, Japan Sea side of NE Japan). The map shows: a) relative crustal movements of the Japanese Islands where tectonic plates (inset) interact with each other; b) the different crustal movements of NE and SW Japan; c) the difference in crustal movements between SW Honshu and Shikoku along the Median Tectonic Line.

Source: GSI homepage (http://www.gsi.go.jp/ENGLISH/ABOUT/OUTLINE/denshi.htm)

Figure 8-5 (Ohtake et al., 2002) shows the broad distribution of active faults, maximum shear strain rates determined from GPS and the major tectonic regions. The areas with higher levels of shear strain rate (> 0.07 ppm/year) are stippled. Also indicated are the subduction zones and collision boundaries of the Pacific and the Philippine Sea Plates as well as the Median Tectonic Line and the collision zone of the Hidaka Mountains. The shaded area indicates a tectonic belt stretching from the eastern margin of the Japan Sea to central Japan, then to the Median Tectonic Line, which corresponds to a zone of active faults, including those with activity level A (see Table 8-1). As discussed in Section 6.1, this tectonic belt appears to form the eastern margin of the Amurian micro-plate within the Eurasian Plate.

It has been proposed that almost all seismic deformation on the Pacific coast of Japan is released by earthquakes occurring along the plate boundaries. As a result, strains observed by GPS on the upper plates do not contribute to the long-term deformation of the Japanese Islands (Taira, 2000). In the Hidaka Mountains collision zone, uplift and seismic movements are due to the formation of thrust faults. From central to SW Japan, strike-slip and reverse faults are dominant and the stress field is in EW compression. Based on the GPS data, there are zones of larger shear strain that form along the Niigata-Kobe tectonic belt in central Honshu.

The active tectonic patterns and distribution of active faults (see also Active Fault Maps in the Annexes) indicate that continued detailed studies are required for further understanding of the fault activities, especially in the following regions:

- the active zone along the eastern margin of the Japan Sea (suspected converging plate boundary);
- the active zone along the Niigata-Kobe tectonic belt;
- the active zone along a few segments of the Median Tectonic Line.
- part of the Izu Peninsula and around the rift zone of the Izu-Bonin Arc;
- the area around the Okinawa Trough.

As discussed later in Chapter 10, at NUMO we are working with national and international experts to develop an approach to integrate all types of information on rock deformation, strain rates, seismic energy release and uplift information to define indices of stability. This will help to assess the stability of specific sites.

We are also evaluating how proximity to active faults could affect a deep repository, and are developing appropriate strategies for setting “respect distances” from such faults. The final selection of respect distances will be highly specific to the site and to the repository concept. The respect distances will be dependent on the regional and local stress history, the geometry and mechanical properties of the rock units, and the history of the faults concerned.

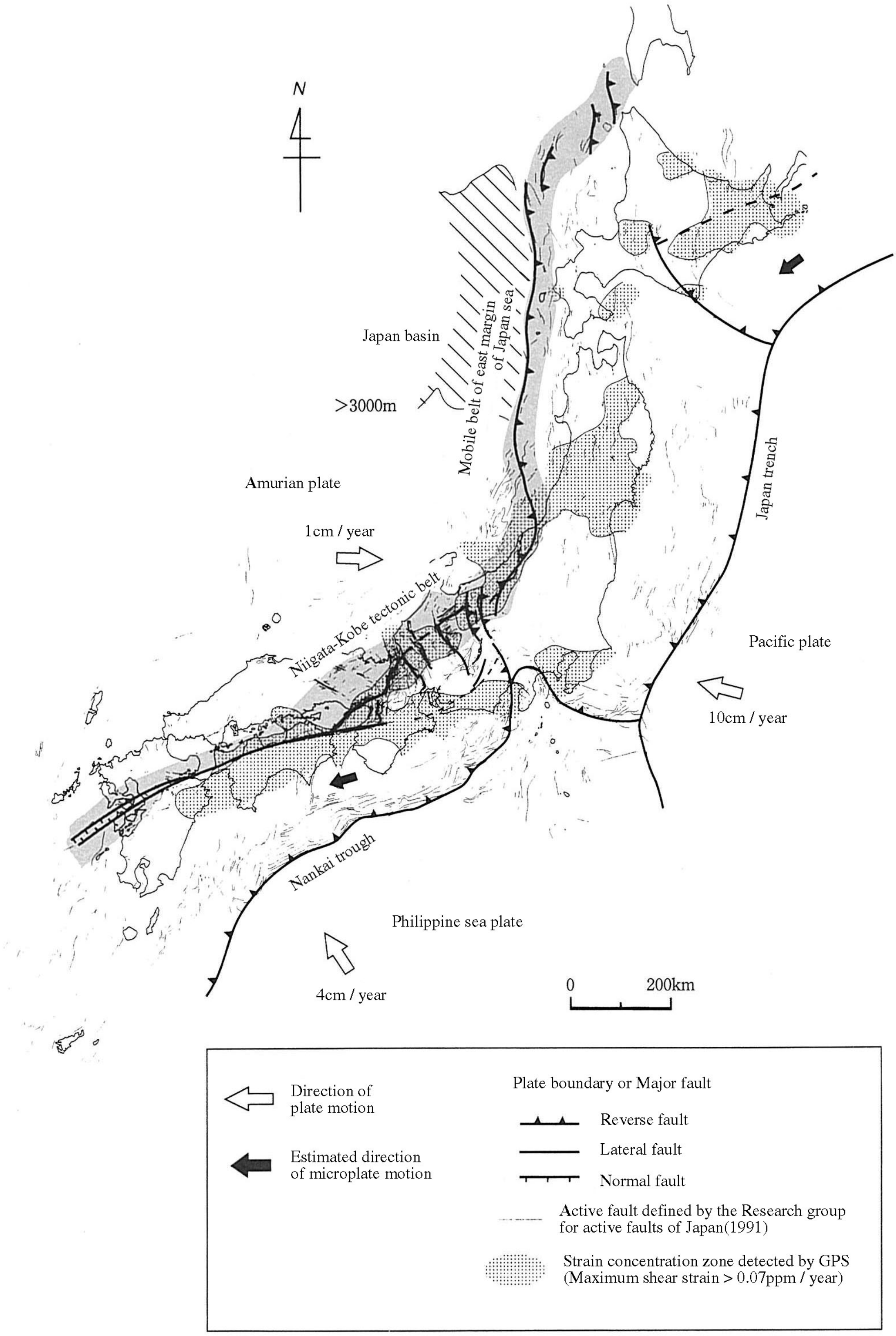


Figure 8-5: Broad distribution of active faults, maximum shear strain rates determined from GPS and the major tectonic regimes of Japan (Ohtake et al., 2002). The distribution of active faults is based on the national-scale map of the Research Group for Active Faults of Japan (1991), and the strain concentration zones detected by GPS are based on the original figure compiled by Sagiya in Association for the Development of Earthquake Prediction (1999).

Active faults develop a “process zone” on either side of their main shear, in which there is more limited displacement along smaller fracture sets. The zone may initially be wide, but, as a fault matures, it becomes narrower. Whilst it is straightforward to avoid the main strands of an active fault and any potential future prolongation along its strike, the main issue with which we are concerned is respect distances to the side of a fault, to avoid potential damage by siting the repository within an active process zone.

Studies have been carried out in Finland and Sweden (LaPointe and Hermanson, 2002; Bäckblom and Munier, 2002), where the potential for large magnitude (up to M 8) post-glacial earthquakes is recognised. The Scandinavian studies have evaluated the respect distances from major fracture zones that would be required to avoid shear displacements along minor fractures that intersect waste container emplacement positions in a repository in crystalline basement rocks, and more work is in progress to refine the estimated quantitative respect distances.

Thus, while we are precluded from having an active fault within a PIA, and can readily avoid them based on the active fault maps, we will need to carry out detailed local studies to assess how far away a repository would need to be located from any nearby active faults. We will also need to carry out careful surveys at each stage of our site investigations to identify the potential presence of deeply buried active faults that have no surface expression.

9 AVOIDING VOLCANIC IMPACTS

After earthquakes, volcanoes are the most prominent manifestation of tectonic activity in Japan. While they may appear to represent a real problem to the integrity of a radioactive waste repository, their future distribution can be predicted with some confidence and their impacts on a repository effectively avoided.

The current pattern of volcanism has become established over the last 14 Ma, since the cessation of back-arc opening in the Japan Sea area and the establishment of the subduction regime for the Pacific Plate. The average lifetime of a volcano is about 0.5 to 1 Ma, thus the distribution of volcanoes over this period, especially in the Quaternary, is the key information for evaluating possible future activity over the next hundred thousand years or more (see Annex for a map of Quaternary volcano distribution).

Broadly speaking, there are two volcanic belts in Japan, one across the Kuril Arc, Hokkaido and NE Honshu and out along the Izu-Bonin Arc - the Eastern Japan Volcanic Belt - and the other across SW Honshu and Kyushu and along the Tokara Islands - the Western Japan Volcanic Belt (Figure 9-1). Two main classes of volcano are identified in Japan. One is the polygenetic volcano where the eruption repeats within the same centre, comprising most of the Eastern Japan Volcanic Belt and the major part of the Western Japan Volcanic Belt from NE Kyushu to the Tokara Islands. The other is the monogenetic volcano which is formed by a single eruptive episode, located mainly in SW Honshu to NW Kyushu. The two classes, polygenetic and monogenetic, have different tectonic origins in terms of their relationship to subduction and melting processes.

Polygenetic volcanoes are predominantly andesitic, associated with magma generation in the mantle wedge above the descending oceanic plate at depths of around 100 km, controlled by decompression melting and slab dehydration. Monogenetic volcanoes are generally associated with alkali basalt extrusion, a product of deeper melting where magma generation is controlled by up-welling and decompression of mantle material and not directly related to the subducting slab.

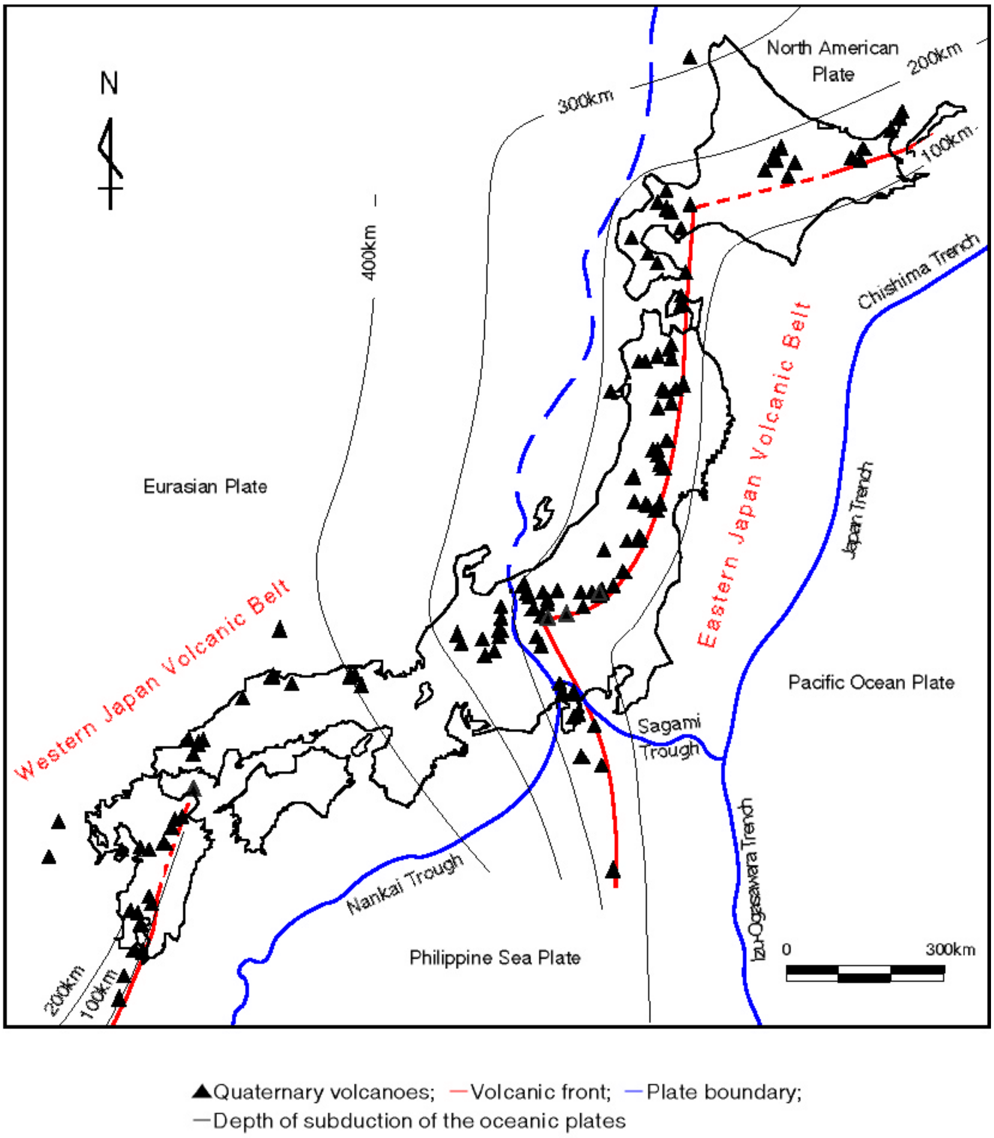
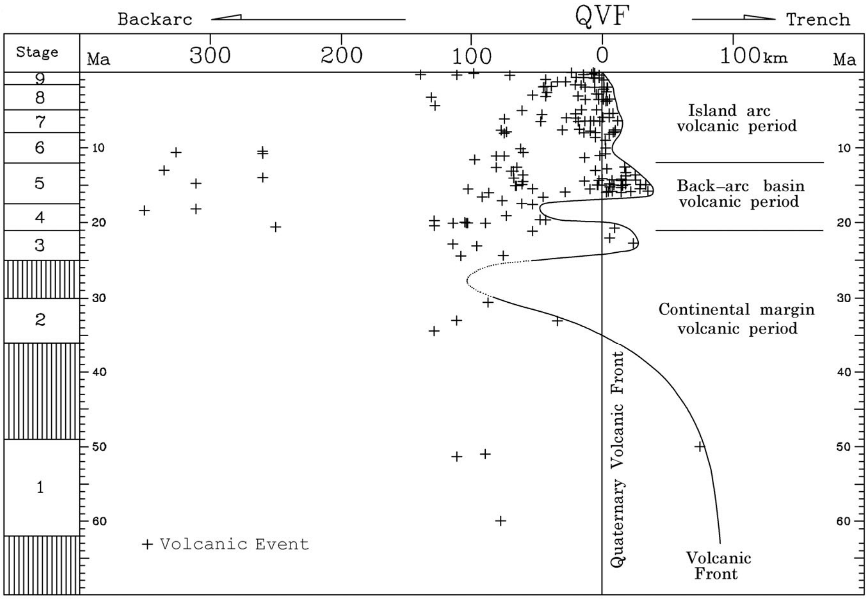


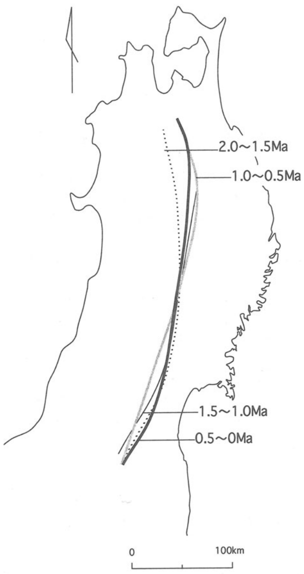
Figure 9-1: Distribution of the two volcanic belts in Japan (JNC, 2000). Quaternary volcanoes in the Eastern Belt and the southern part of the Western Belt are predominantly polygenetic, while the majority of those in the northern part of the Western Belt are monogenetic.

9.1 Distribution of volcanoes in NE Japan

The distribution of active volcanoes in NE Japan follows a well-defined pattern related to the zone of melting associated with the subducting Pacific Plate. Over the last 15 Ma, volcanic activity has been located behind a linear "volcanic front" that runs parallel to the trend of the deep ocean trench (Japan Trench and Izu-Bonin Trench). The volcanic front (Figure 9-2(a, b)) lies along a line that is equivalent to the deep earthquake focal plane with a depth of 100-110 km. All the volcanoes in Hokkaido are situated within 60 km to the northwest of the front. A gap of maximum 50 km exists around the junction of the front and NE Japan Arc (Nakagawa et al., 1995).



(a)



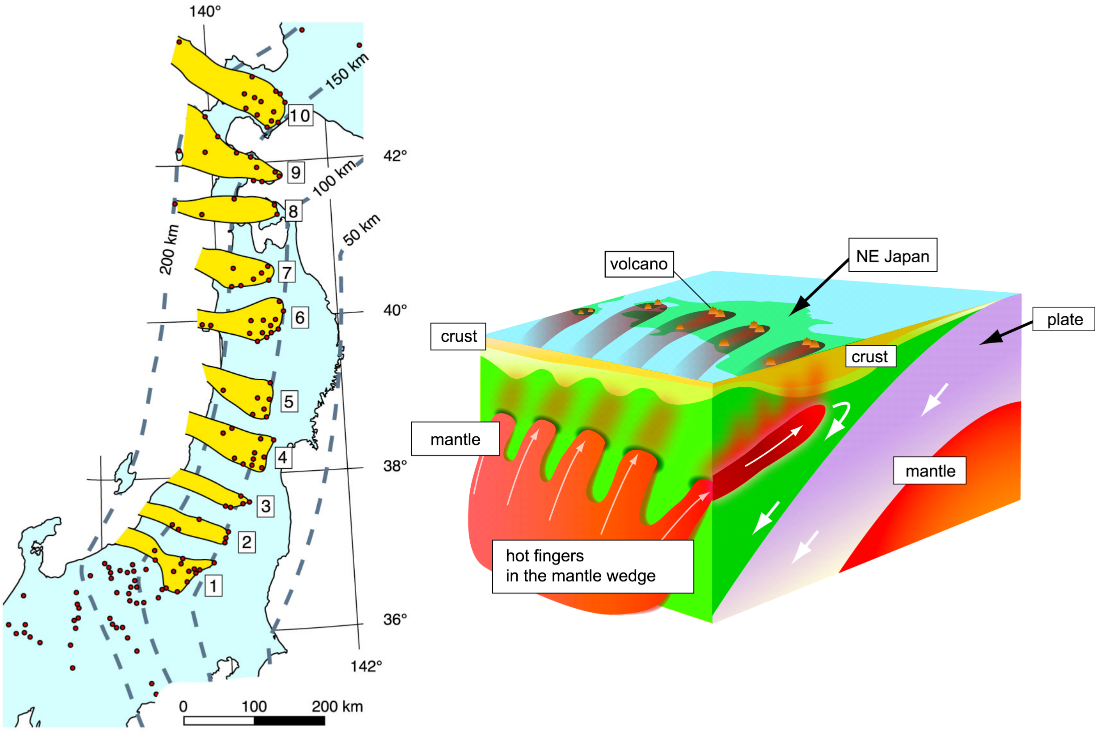
(b)

Figure 9-2(a): Spatial and temporal distribution of volcanic activity around the Quaternary volcanic front (QVF) in NE Japan during the past sixty million years (Yoshida et al., 1995). By definition, activity always occurs to the west of the front. Over about the last 15 million years, there has been no activity further east than about 40 km from the position of the present-day volcanic front.

Figure 9-2(b): Distribution of the volcanic front in the Quaternary (JNC, 2000). The position of the front has become progressively more stable with time. The shift of the front during the Quaternary is limited to 10–20 km at most.

Although the Eastern Japan Volcanic Belt is dominated by polygenetic volcanoes, some monogenetic volcanoes are also found in this region. The distribution of Quaternary volcanoes in this region is characterised by regions of "volcanic clusters" that strike transverse to the arc (E-W direction) at intervals of 50-100 km. This pattern is best seen in northern Honshu. The clusters are separated by parallel gaps, 30-75 km wide.

The locations of clusters are closely correlated with topographic highs (including basement elevations) in the topographic profiles along strike, with local negative anomalies in the gravity profiles along strike and with low-velocity anomalies in the seismic tomography images of the mantle wedge above the subducting oceanic plate. This is postulated to indicate the presence of localised hot regions ("fingers") within the mantle wedge (Figures 9-3(a, b): Tamura et al. 2002; Tamura, 2003). Since the development of the stable subduction regime and the end of back-arc spreading at about 14 Ma, the distribution of volcanic activity in NE Japan has become localised into clusters, suggesting that the evolution of the thermal structure within the mantle wedge across the arc since 14 Ma has reduced the lateral extent of ascending mantle diapirs into smaller fields (Kondo et al., 2004).



(a) **(b)**

Figure 9-3: (a)Apparent clusters in Quaternary volcanic activity in NE Japan (Tamura et al., 2002). Clusters are postulated to be the result of localised thermal anomalies ("hot fingers" (b)) in the mantle wedge overlying the subducting Pacific Plate (Tamura et al., 2002; Tamura, 2003). Dashed lines show depth contours to the surface of the dipping seismic zones.

9.2 Distribution of volcanoes in SW Japan

The Quaternary volcanoes in the northern part of the Western Japan Volcanic Belt are located in SW Honshu and Kyushu, roughly parallel to the subduction zone of the Philippine Sea Plate. They are predominantly monogenetic volcanoes, extruding alkali or high-alumina basalts (Figure 9-4). The Philippine Sea Plate can only be traced geophysically as a coherent slab to a depth of about 80 km and the location of volcanoes in this region is not directly related to plate subduction (Iwamori, 1992). In the central area in Kyushu, the large volcanoes of Kuju, Aso and Unzen are distributed in a line from E to W.

From southern Kyushu to the Tokara Islands, volcanoes are distributed approximately parallel to the Ryukyu Trench. There is a 100 km gap in activity between central and southern Kyushu. No volcanoes occur on land in the area to the south of the Tokara Islands from Ioujima to Iou-Torishima, although seamounts with geomagnetic anomalies are known that may well be Quaternary volcanoes.

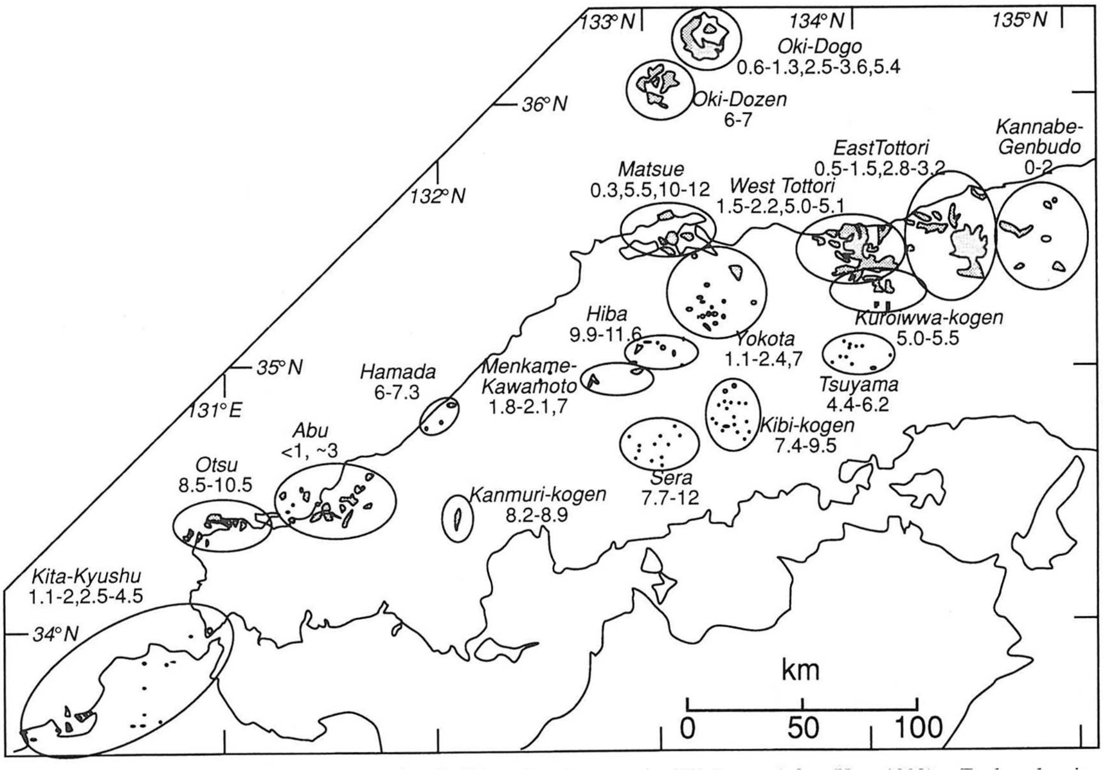


Figure 9-4: Location and age (Ma) of monogenetic volcanoes in the Western Japan Volcanic Belt on the back-arc side in SW Honshu and Kyushu (Uto, 1995). Each group is composed of several to several tens of single monogenetic volcanoes and represents a duration of activity of about 1-2 million years. The ages and the composition of the volcanism are systematically different, even between two neighbouring groups.

9.3 Distribution of future volcanic activity

As discussed above, a clear volcanic front can be defined where no volcanic activity has occurred on its Pacific side during the Quaternary. The front has been stable for periods that are long with respect to the isolation timescale of a HLW repository. However, minor changes have occurred during the Quaternary. In the NE of Japan, Umeda et al. (1999) found that in the period from 0.6 to 1.0 Ma the local trend of volcanic eruption centres changed from NE or ENE to N. In addition, the volcanic front shifted 10-20 km towards the trench side (i.e. towards the Pacific) at the same time (Figure 9-2(b)). In the mid-Miocene the volcanic front was located closer to the trench in comparison with the present location and it took up to 1 million years to relocate by several tens of kilometres.

No type of volcanism in the region to the east (trench) side of the volcanic front is expected for at least the next few hundred thousand years. For repository siting in this region, avoiding future volcanism during the principal waste containment period would thus not be an issue. In addition, our Nationwide Evaluation Factors, discussed in detail in Chapter 4, effectively remove most of the "clusters" to the west of the front from consideration as potential sites, which means that we are only concerned with areas between clusters ("gaps"). On the other hand, the volcanic front is not evident in SW Japan and the groups of monogenetic volcanoes have different periods of activity with no spatial or temporal relationships between groups.

At NUMO, we are thus concerned with the following issues in avoiding volcanic impacts:

- the likelihood of new volcanic eruptions in the "gap" areas to the west of the volcanic front over the next several tens of thousands of years;
- the likelihood of new volcanic eruptions in the areas of monogenetic volcanism in SW Japan over the next several tens of thousands of years.

Together with national and international experts, we are developing a range of approaches to provide reliable estimates of these probabilities, should we need to consider volunteer areas in these regions. In the areas behind the volcanic fronts, these techniques are based upon the well-established patterns of volcano distribution over the last 14 Ma and models of potential causal mechanisms that integrate the most recent geophysical data on the tectonic regime. Both empirical and probabilistic tools are being compared and tested against the large database of volcano age and location. Our eventual approach will be comprehensive, employing many modelling techniques for handling the geological and geophysical datasets, to provide overall estimates of likelihood in different future timeframes.

While the characteristics controlling the distribution of monogenetic volcano groups are less easily identified, it is recognised that globally analogous volcanism is controlled by structural features such as grabens and major fractures on various scales. Relating the spatial and temporal variations of volcanism to particular geological structures is expected to provide a possible technique for predicting future volcanism if we have to consider a repository site on the Japan Sea side of the volcanic front. On both of the two issues above, we are working closely with information and expertise from within Japan and from the broader international community of volcanologists.

10 UPLIFT, EROSION AND ROCK DEFORMATION

Uplift and subsidence are vertical displacements of the crust that occur due to flexure deformation, block movement, faulting or the isostatic adjustment associated with glaciation/de-glaciation and sea level change. Uplift and subsidence in Japan includes both regional-scale events associated with the tectonic regime of the NW Pacific and very local vertical displacements due to faulting and folding.

The evidence for these movements is seen in near-surface geographical and geological features such as fault scarps, palaeo-erosion surfaces and river/marine terraces. Modern geodetic surveying methods, including the use of the wide network of fixed GPS stations, combined with cosmogenic isotope (^{10}Be, ^{14}C, ^{26}Al and ^{36}Cl) and apatite fission track measurement techniques that reveal exposure times of rock surfaces and rates of uplift, are extremely powerful tools for characterising crustal movements and erosion rates.

A rough estimate of uplift and subsidence during the Quaternary can be made using the elevation of mountains and the base level of erosion (e.g. Ohmori, 1987). Evaluation of river and marine terrace development has a higher level of accuracy, owing to developments in tephrochronology and radiometric dating. It is possible to date the formation of erosion surfaces formed over the last 0.15 million years with an accuracy of a few thousand to ten thousand years. Geological approaches use sedimentation rate and sedimentary environment data to estimate uplift and erosion. Although accuracy is low, due to local variations of sedimentation and erosion, this method can deal with much longer timeframes (Naruse, 1990). Current uplift and subsidence over a period of 5 to 50 years can be measured using advanced surveying technology.

In addition to uplift and subsidence, some regions of the upper crust in Japan are also undergoing progressive deformation by folding and flexuring, as a result of lateral tectonic stresses. Active flexuring is typically found in areas along the Japanese Sea coast (both onshore and offshore) with thick Neogene basin fill sediments. It has resulted in folding and flexural slip faulting throughout the Quaternary. The issue of concern is the rate of flexuring in such regions, and whether it would be sufficiently high to have adverse impacts on a repository.

Rates of vertical crustal movement in Japan vary widely. The highest uplift rates are observed in central Honshu. Ota and Omura (1992) categorised vertical displacements into four groups:

(1) Short wavelength monoclinal flexure: active flexuring with a half wavelength of 20-30 km, as seen in the low-lying terrace facing the Japan Sea from Southern Hokkaido to NE Honshu.

(2) Block tilting bounded by active (reverse) faults: small tilted blocks bounded by faults with lengths of 10-30 km: as seen in the Noto peninsula (on the Japan Sea coast of central Honshu).

(3) Slow, long wavelength movements: gentle undulations with a wavelength of more than 100 km: as seen in the NE Japan Pacific coastal region.

(4) Coseismic, earthquake block tilting (from the coast to inland): 30-50 km wide zone such as is seen in the coastal area facing the Pacific Ocean.

For our Site-specific Evaluation Factors (see Chapter 4), we have chosen to reject areas that exhibit evidence of uplift of more than 300 m in the last 100,000 years (equivalent to an average rate of 3 mm/year). Because the Act states that the repository must be located at a depth greater than 300 m, this criterion is intended simply to avoid the potential for exhumation of the repository over the containment period. However, uplift rates are not necessarily constant over such periods of time and we will need to compile and integrate a wide range of data to evaluate past and future movements in volunteer areas throughout the PIA and DIA stages.

In this respect, an aspect of importance is the relationship between slow, interseismic uplift/subsidence and coseismic uplift/subsidence in Pacific coastal regions (Category 4 of Ota and Omura, above). For example, an extensive region of the Pacific coast of SW Honshu, Shikoku and Kyushu experiences a progressive and high uplift rate up to 5-6 mm/year, but this can be counteracted by coseismic subsidence during major plate boundary earthquakes. In the 1946 Nankaido earthquake, the coastal area of Shikoku subsided locally up to 700 mm, while other parts of the island only 80 km away were uplifted by similar amounts (Savage and Thatcher, 1992). Thus, long-term patterns can be more difficult to estimate in areas subject to coseismic movements.

NUMO scientists, together with national and international experts, are thus developing an approach to evaluating uplift and deformation that can be applied throughout the site investigation period. We are using the full range of geodetic and tectonic indicators to estimate strain budgets and indices of stability for rock blocks that can be applied on a regional and local basis. Several existing datasets provide a measure of crustal strain or crustal strain rate. These will be compared and quantitatively integrated to evaluate regional variations in rock deformation using as many different measures as possible to assess the confidence limits for deformation distribution. The measures include:

- strain release on active faults in major earthquakes;
- strain release as diffuse, distributed seismicity that cannot be correlated to a particular fault;
- GPS measurements of crustal deformation, defining the deformation budget available (using the residual of the GPS-derived strain field after large-scale tectonic strains have been removed);
- levelling surveys, coastal terrace mapping and dating;
- distribution and elevation of river terraces inland from the coast (particularly useful in detecting blind thrust and folding deformation styles);
- elevation of marine rock types above sea level.

The approach being developed will provide deformation index maps showing zones with equal or similar rates of rock deformation, as identified by the various datasets. Each zone will have strain rate, seismicity and rock deformation characteristics, which, in combination with the other data above, will provide a basis for evaluating potentially favourable and unfavourable siting characteristics.

11 CONCLUSIONS

At NUMO, we have used a systematic approach to developing Siting Factors so that they will first meet the requirements of the law and then provide a logical, comprehensive and progressive basis for the staged identification of a suitable site for a repository, in particular:

- our Nationwide Evaluation Factors (NEF) eliminate clearly unsuitable areas (susceptible to volcanic eruption and active faulting) in a very simple, first-pass, sifting process using national-scale maps;
- our Site-specific Evaluation Factors (SSEF) look into tectonic and other site suitability aspects in more detail;
- our Favourable Factors (FF) will allow us to assess much wider aspects of site suitability and to compare alternative areas, should we have several volunteers that qualify with respect to the legal evaluation factors.

The Siting Factors are thus intended to go beyond the strict requirements of the law, to help us in our discussions with communities and to guide our decisions with respect to future site characterisation. The level of detailed information that will be required to apply the Siting Factors increases at each step of the siting programme. The earliest application, based only on available literature data, is at a high-level – a process of sifting to exclude areas that are obviously unstable over the next few tens of thousands of years. As we move into the SSEF and FF, we will need progressively more information and more detailed levels of analysis and will need to use these factors at both the PIA and DIA stages. We will also be developing our preliminary list of FF in more depth and detail. The factors will cover a wide range of geological, geographical, environmental and socio-economic matters – issues that are being dealt with in comparable fashion in most national repository programmes worldwide. However, the earliest application of the factors concerns tectonic issues (future volcanism and faulting), which are not as obviously significant in many national siting programmes as they are in Japan.

The nature of the waste means that we need reasonable assurance that tectonic stability will be maintained in the deep geological environment of the repository for the next several tens of thousands of years. It is well known that the tectonic environment of Japan is complex and active. We need to understand this environment in order to find a suitable and stable repository location. The Japanese Islands lie at the junction of four major tectonic plates and the interactions of these plates, by subduction, collision, lateral movements and accretionary processes, drive the seismic, thermal and volcanic activity that characterises the region. Such mechanisms are not unique to Japan – several other regions of the world are in island arc environments and there are many examples of island arc tectonics in the geological record, stretching back over hundreds of millions of years. Over the last decades, earth scientists have built up a broad understanding of the geometry and driving mechanisms of such tectonic systems by combining geological, geophysical and geochemical observations. The latest satellite geodetic measurement techniques allow monitoring of crustal movements to test and calibrate models of the deformation of the surface in response to tectonic strain.

Compelling models exist for the controls on the distribution of earthquakes and volcanoes and for the controls on crustal deformation. These have been developed and tested by integrating a large database of varied information. The main conclusions that have been drawn on stability are:

- the fundamental structure of the present plate system around the Japanese Islands was established at approximately 15 Ma when the spreading of the Japan Sea back-arc basin ceased;
- the directions of plate movement have not changed since 2.5 Ma for the Pacific Plate and 1.5 Ma for the Philippine Sea Plate;
- the movement of the plate system around Japan has been in a steady state since 15 Ma;
- it takes more than 1 million years for a significant change to take place within the plate system and it is unlikely that any rapid change would occur within the relatively short time-period of 0.1 million years;
- it is therefore reasonable to extrapolate the knowledge about the main tectonic controls and patterns over at least the last 0.5 million years to predict the long-term stability of the geological environment for at least the next 0.1 million years.

Nevertheless, at NUMO we need to adopt a cautious approach and we are aware that there are significant local-scale variations and features overprinted on the broad tectonic picture. We are thus developing state-of-the-art techniques to help us make site-specific decisions on several critical issues that may arise as we evaluate volunteer areas. The three main issues related to future stability are:

- the likelihood of new volcanic activity to the west of the volcanic front and in regions of monogenetic volcanic activity, which will help us decide whether some areas might be at unacceptable levels of risk from volcanic impacts over the next hundred thousand years or so;
- appropriate "respect distance" from active faults in various geological and stress environments so that we can locate repository structures such that they will not be adversely affected, even by repeated seismic activity and rock displacements, over the next hundred thousand years or so;
- overall indices of stability that integrate a wide range of information on crustal deformation, including folding, uplift and subsidence, which will allow us to identify stable rock blocks.

As we evaluate volunteer areas for these key aspects of stability, we will also be looking at the FF that we are developing. These all concern characteristics of the natural and human environment of an area that will help determine whether a repository can be constructed and operated with sensible use of resources and to the satisfaction of the local community with whom we shall be working. Our staged site selection process means that both the FF and the SSEF will need to be utilised throughout the PIA and DIA stages with a progressively increasing level of detail in the evaluation.

Sites that are not automatically excluded by the Nationwide Evaluation Factors will be weighed against the SSEF and the FF. The process begins with simple review and analysis of the available literature information, prior to nomination of a volunteer area as a PIA. All areas not excluded by the SSEF are likely to be nominated. Preliminary site characterisation studies will then begin. These will gather more data, and more repository-specific data, to allow the more detailed assessment of both sets of factors. This process will continue as we select DIAs from among the PIAs and the site characterisation work becomes more intensive.

We expect that there are many sites that could host a repository in Japan, despite the active tectonic environment. However, not every volunteer area will be suitable and we will reject those that do not meet our strict requirements, whatever the local support might be. We are at an early stage of our programme. Beyond the simple, first order, legal siting requirements that have been given to us, the factors described here and the way in which they will be deployed can be expected to evolve as we develop methodologies for assessing information and as we consider appropriate repository design concepts for real environments. We thus intend to provide regular updates on how we are developing and applying our site evaluation techniques.

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