SYNTHESIS OF THE WORKSHOP

The workshop was divided into four plenary sessions and a poster session. The first plenary session discussed the general framework to be followed when considering deep disposal in crystalline rocks. The subsequent sessions focused on more specific processes of importance to the stability of crystalline rocks, their response and resilience to natural perturbations and arguments to support confidence in their stability.

Session I – General framework: crystalline rocks as host formations

This session established the general framework for consideration of crystalline rocks as host formations for geological disposal. Presentations provided the perspective from both an implementer and a regulator on the expectations for the functions to be served by the geological formation and their treatment in the safety case.

The questions that were addressed were:

- What are the main functions/roles of the geosphere for disposal at different time scales (especially for crystalline and other hard, fractured rocks)?
- What assumptions relating to such geosphere settings are commonly made in safety cases (uncertainties, time scales, etc.)?
- What are the regulatory expectations concerning the confidence in geosphere stability?

Allan Hedin (SKB, Sweden) presented the safety functions of crystalline rock formations in deep geological disposal and their handling in a safety case, using the example of SR-Can (SKB, 2006) – the safety assessment produced during SKB's site investigation stage at two sites in Sweden. SR-Can is based on initial site data from Forsmark and Laxemar and was under review by SKI and SSI at the time of the workshop. An updated assessment, SR-Site, will support the licence application at one site in 2009. The risk criterion is applicable for 10^5 years after closure and the time scale for assessment is 10^6 years.

For the KBS-3 disposal concept, the three main safety functions of the host rock are to provide a favourable environment for the containment of the spent fuel in canisters, to provide retardation of radionuclides released from a potentially imperfect container and to provide isolation of the waste from the surface environment. The repository should, therefore, isolate the waste from the surface environment, with the granitic host rock contributing to all these functions. For containment, in particular, the role of the geosphere is to provide chemically, thermally and hydrogeologically favourable conditions, and favourable transport and mechanically stable conditions.

Although the dose and risk compliance criteria are the ultimate measures of safety, intermediate measures are also required in order to evaluate the system in a more detailed and disaggregated manner. To do so, a number of safety function indicators (SFI) have been defined by SKB and, from these, criteria developed to represent what can be considered as "good" performance of the system. These are measurable or quantifiable properties of the system, primarily related to the near-field, that

should preferably be fulfilled throughout the one million year assessment period. Thus, these safety function indicator criteria (SFIC) are quantitative limits on the indicators, such that if a safety function indicator fulfils its respective criterion, the corresponding safety function is maintained. The breaching of a SIFC does not mean that the repository is unsafe, but rather that more elaborate analyses and data are needed in order to evaluate safety. It is not necessary, therefore, for all SFIC to be fulfilled to argue that a repository is safe.

A summary was provided of what were considered to be the favourable conditions referred to above (i.e. the requirements on the host rock). These requirements are, in turn, derived from the safety functions of the canister and the buffer. Examples of these requirements are: reducing chemical conditions, high transport resistance, shear movements of less than 0.1 m at deposition holes, and temperatures maintained above the buffer freezing temperature. It was emphasised that these requirements are strongly linked to the repository concept and that, if the requirements are fulfilled over time, this would ensure a stable geosphere for a KBS-3 repository – in particular in relation to the repository's capacity for containment.

It is necessary to assess the thermo-hydromechanical and chemical (THMC) evolution over the one-million-year assessment period. Over the long-term, perturbations in Scandinavia will be caused mainly by climate change. To examine the implications, a main scenario and an alternative climate scenario were considered (more detailed aspects of the effect of future climate change on the stability of the geosphere in the Swedish context were presented in Sessions II, III and IV).

Discussion on this presentation concentrated on SFIC: for example, how it was decided which SFIC are more important when developing a safety case. It was explained that all SFIC need to be evaluated (but that not all have to be fulfilled), and that each needs to be assessed to examine whether the repository still conforms to the dose and risk criteria. Some SFIC are more important in this regard, e.g. those related to canister integrity. Also, pessimistic assumptions have been made by SKB in the evaluation of certain SFI. For example, when evaluating the presence of favourable transport conditions in the geosphere, it was pessimistically assumed that all deposition holes suffer from thermally-induced spalling.

Susan Duerdan (Environment Agency (EA) of England and Wales) presented a regulator's perspective of the confidence that can be placed on geosphere stability and its handling in a safety case, based on the regulations in the United Kingdom (Unite Kingdom). The considerations of the regulator were placed in terms of what was expected to be presented in a safety case, how it would be considered and the associated rationale. It was emphasised that the level of detail in any submission from the waste disposal organisation should be appropriate to the stage of repository development. A full range of Principles and Requirements will need to be considered but, with reference to geosphere stability, it was noted that that UK regulations, in this regard, are not prescriptive. These considerations are related to: disposal layout and construction, site investigations, performance and monitoring, modelling studies and the treatment of uncertainty. Multiple and complementary lines of reasoning and evidence will be necessary to build a robust safety case, information gathered over many tens of years will need to be assimilated, managed and presented, and disposal will not be considered complete until all the requirements established and demonstrated as part of the safety case are met.

With respect to the layout and construction of a facility, factors such as the safety of excavation and operation, repository design, effects of excavation, potential problems and corrective action and the stability of the excavations would need to be considered.

Discussion of this presentation concerned the following issues:

- The extent to which there would be regulatory guidance on identifying and prioritising important issues, as only certain features of the geosphere are important. In this regard, the Environment Agency plan to have continuous dialogue with the proponent, so that there can be agreement as to where the emphasis should lie and the level of understanding and detail required of, for example, a knowledge of parameter distributions.
- Criteria for repository siting and performance: the Environment Agency is not responsible for setting siting criteria, although it has been consulted on proposals.[6]

Session II: Examples of key processes affecting the geosphere for crystalline rock

The session focused on the processes affecting crystalline rock, their potential consequences on host formations and their predictability, with presentations from several national programmes serving as case studies. The questions that were addressed were:

- What are the predominant processes for natural evolution that are relevant for geological disposal?
- What is the predictability of these processes over different time frames: up to 10 000 years, up to 100 000 years, and beyond?
- What are the potential consequences of these processes on the barrier function of the geosphere, including sustaining the integrity of the engineered barrier system?

Neil Chapman (MCM Consulting, Switzerland) presented the International Tectonics Meeting (ITM) methodology of the Nuclear Waste Management Organisation of Japan (NUMO), which considers the likelihood of tectonic activity affecting the stability of a potential repository in Japan. The methodology is designed to provide NUMO with quantitative techniques for evaluating and comparing the geological settings of volunteer host municipalities with respect to volcanism and rock deformation. It is aimed at assessing the likelihood of a site being significantly affected by volcanic events and rock deformation processes within 10^4 years and the potential scale and nature of any such impacts. It proceeds by assembling nationally available data and alternative models of the nature, causes and locations of such processes and events, uses both deterministic and probabilistic techniques to examine their future scale and likelihood and shows them as a function of their type and geographic distribution.

There are two parallel and integrated activities in the programme: the likelihood of volcanism in areas with no Quaternary volcanism and the likelihood, scale and nature of potential rock deformation from such volcanism, with the results of both studies then being integrated. There are also two case study areas, one in an area of predominantly polygenetic volcanism[7] and one in an area that also

6. The UK Government established two expert groups (on the basis of recommendations from the Royal Society, the Geological Society, the Royal Academy of Engineering and the Defra Chief Scientific Advisor) to develop exclusion criteria for repository siting. The two groups were a Criteria Proposals Group (CPG) and a Criteria Review Panel (CRP). Starting in February 2007, the CPG, consisting of nine members, developed the initial criteria proposals. These were then independently peer reviewed by the CRP, consisting of six members. The CPG/CRP's final recommendations are set out in Annex B of "Managing Radioactive Waste Safely: A framework for implementing geological disposal. A White Paper by Defra, BERR and the devolved administrations for Wales and Northern Ireland". June 2008. (available at: www.defra.gov.uk/environment/radioactivity/mrws/pdf/white-paper-final.pdf).

7. Monogenetic volcanoes erupt only once, while polygenetic volcanoes erupt repeatedly.

contains significant monogenetic volcanism. A cladistic approach[8] is being taken to the classification of volcanoes, with the result that statistical and probabilistic analysis can be applied.

The three-dimensional structure of the volcanic system in the area of polygenetic volcanism was outlined and it was concluded that the occurrence of volcanic events was unlikely to be a random (Poisson) process. Different probabilities are being derived, relating to factors such as the recurrence of a volcanic edifice forming in the region of interest. A parallel deterministic approach is also being followed, examining the correlation between possible indicator phenomena, e.g. uplift rate, gravity anomalies and seismic velocity structure in the mantle, etc.

A similar approach is being taken to rock deformation, using independent data sets, the development of alternative models, and the use of expect elicitation and logic trees to produce probabilistic strain maps and allow the comparison of different strain models.

The goal at the end of the programme, in 2009, it to be able to identify appropriate siting confidence levels relating to the level of confidence that can be assigned to the susceptibility of sites to such hazards, for any particular volunteered investigation site.

Questions on the presentation dealt with how this work might address the probability of specific volcanic events (e.g. the presence of a dyke or a volcanic cone) and how it was possible to deal with volcanic events and faults that did not reach the surface (known as hidden faults); also whether the localisation (clustering) of Quaternary volcanic events could also be seen in other parts of the world where volcanism is prevalent. With respect to hidden faults, the consensus appears to be that such structures would need to be considered on a site-specific basis, but that there are theories that relate the likelihood of such faults to the structural setting. With regard to volcanic events, it is possible to develop probability maps for each type of volcanic feature. Both these subjects are discussed in a forthcoming book (Connor *et al.,* in press).

On behalf of **Jens-Ove Näslund (SKB, Sweden)**, Raymond Munier presented the work by the Swedish waste management agency (SKB) on future climate change and its potential impact on the mechanical, hydraulic and chemical conditions in the rock mass, which has taken place as part of the SR-Can project (SKB 2006). SKB's strategy for managing climate-related conditions in safety assessment acknowledges that it is not possible to predict climate in a 100 000 year time frame. Instead, the approach in SR-Can is to identify and analyse moderate climate evolutions, as well as extremes within which the climate in Scandinavia may vary. Knowledge of the general climate variation in Scandinavia has been used to identify characteristic climate domains (temperate, periglacial and glacial) which, in turn, have been used to build a number of selected climate scenarios – such as the base case and greenhouse variants – with additional climate-related scenarios then being developed to examine more extreme effects, e.g. buffer freezing and canister failure due to a large ice load. As expected, the largest impacts on the geosphere and a KBS-3 repository would occur when glacial conditions are likely, in particular when the ice margin passes over a site (when the largest impacts would take place with respect to stress changes, groundwater fluxes etc.). Periods of temperate climate, including the long-term effects of global warming, would appear to be mainly beneficial to geosphere stability in the Swedish case.

8. Cladistics is a systematic method of classification that groups entities on the basis of sharing similar characteristics in the most parsimonious manner.

Discussion of the presentation brought up the following points:

- There are far fewer earthquakes in Antarctica than might be expected for a continent of that size. This conclusion is in agreement with the modelling, which suggests that a thick ice cover reduces the likelihood of seismic events.
- There is a challenge for regulators dealing with the results of modelling that provide very different answers, for example, in relation to the likelihood of excessive stresses and hydrostatic pressures at repository depths and changes in fault stability. It was suggested that the results of the regulatory review (by the Swedish safety authority, SKI/SSI) of SR-Can may shed some light on how regulators may resolve such situations.

Haruo Yamazaki (Tokyo Metropolitan University, Japan) presented work carried out in Japan on uplift rates, determined from the elevation of marine terraces and the associated erosion rates. These marine terraces, which fringe the Japanese coastline, have been formed by the combination of sea-level fluctuations and crustal uplift. It is possible to provide estimates of the amount of tectonic uplift in the future based on the heights of the former shorelines of the marine terraces. The dating of these terraces is possible using a variety of techniques but, in the area studied, use is made of the thickness of volcanic ash on the terrace surface to provide a well-constrained date, at least for many of middle Pleistocene age.

The example used was the Shimokita Peninsula, on which Rokkasho is located (where vitrified HLW is stored for cooling and temporary storage before final disposal, where LLW is currently disposed and where some types of longer-lived wastes will be disposed in the future at a depth of approximately 100 m). The safety case for this additional repository needs to take into account the known uplift and any associated increased erosion that might take place. The uplift rate here (approximately 0.4 m per 10^3 y), has been constant for approximately the last 2 x 10^5 y and is expected to continue at the same rate in the future. An erosion model has been developed, based on the measured uplift.

Discussion of the presentation addressed the relative rates of uplift and erosion. Evidence suggests that erosion does not keep pace with the uplift – leading to the conclusion that uplift, at least in this specific Japanese context, may not be significant for long-term repository safety.

John Cosgrove (Imperial College, UK) and **John Hudson (Imperial College, UK)** gave a two-part presentation on geological and rock mechanics aspects of the long-term evolution of a site in crystalline rocks, from the perspective of structural geology and rock engineering. The structural geologist and the rock engineer use the same mechanical principles to predict the possibility and type of rock deformation, but usually under very different boundary conditions, especially concerning stress, temperature and strain rate.

The first part of the presentation considered the significance of ductile and brittle features and fabrics and their influence on controlling the deformation behaviour of the rock mass. The most important mechanical structure produced by ductile formation is anisotropy in the rock mass, either linear or planar, and, in order to construct a geologically-realistic fracture network model, it is necessary to consider the interaction of the fractures. An understanding of the mechanical principles and processes linked to the evolution of a crystalline rock mass is, therefore, necessary if a realistic assessment of the properties of the rock mass is to be achieved.

The main mechanical stability problems around underground openings were summarised, together with the potential for spalling, where the proportion of, for example, canister holes that could spall can be determined. The influence of rock mass anisotropy on such failure and the many factors that affect the excavation disturbed/damaged zone (EdZ/EDZ) were also considered; for example, rock

mass strength decreases with time when under load. The impact of thermal loading exacerbates the problem of spalling, as does glacial loading.

A novel way of plotting principal stress magnitudes was shown (by plotting each of the principal stresses in turn against the first stress invariant), using data from Australia, illustrating the fact that structures control the principal stress ratios that a rock masses can sustain. Similar relationships are also found in other part of the world. By assuming zero cohesion (i.e. a fractured rock mass in which the fractures themselves are free to undergo displacement) the Earth's crust can thus be shown to be in a state of limiting *equilibria*. This has obvious implications for any future glacial loading, as pre-existing fractures could be reactivated, thereby adversely affecting the mechanical stability and hydrogeological characteristics of the rock mass. The highly variable stress state of a crystalline rock mass was illustrated by the results of the 3DEC modelling[9] of Laxemar, where the influence of the brittle deformation zones was very evident in controlling the orientation and magnitude of the maximum horizontal stress (σ_H).

Discussion of these two presentations addressed how it was possible to obtain knowledge of the relative ages of fractures, with several questions regarding the significance of the 3DEC modelling described above. It is apparent that, as deformation zones are ubiquitous in crystalline rocks, the orientation of σ_H is likely to be variable, with obvious implications for tunnel and canister hole stability, implying a need for data at the local scale. However, these needs are site specific as they depend on the overall stress levels and on the actual occurrence and geometry of deformation zones. Furthermore, the stress orientations resulting from the 3DEC modelling are not validated against measured stress data.

William Murphy (Nuclear Waste Technical Review Board, USA) presented data on the predictability and evolution of a groundwater flow system and hydrogeochemistry, using data from the proposed geologic repository site at Yucca Mountain, Nevada. For example, two studies have identified $^{36}Cl/Cl$ ratios in excess of background in the Exploratory Studies Facility tunnel; these have been interpreted as being due to transport along fast pathways such as zones of fracture concentration, including faults. However, multiple studies conducted over the past decade have not resulted in scientific consensus regarding controls on occurrence and movement of ^{36}Cl in the unsaturated zone.

There is extensive calcite at Yucca Mountain, but groundwater sampled from saturated zone boreholes does not appear to "see" this calcite and displays values of activity[10] which are well below the calcite solubility limit. Microstratigraphic dating of opal was used to determine average mineral growth rates. Because the assumption that the growth rates are indicative of unsaturated zone flow has not been demonstrated, the significance of these data is difficult to interpret.

The Nopal uranium deposit at Peña Blanca, Mexico, is a natural analogue of the proposed repository at Yucca Mountain, having similar geology, hydrology, and climate. Information from Nopal is relevant to the stability and predictability of the proposed repository at Yucca Mountain and comes from studies of the geochemical alteration of primary uraninite and the formation of stable secondary uranyl minerals in the oxidising environment. At Nopal, the secondary uranium mineral uranophane has been immobilised over geological time scales, while primary uraninite has persisted for millions of years as a result of a protective silica coating.

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9. 3DEC is a numerical modelling code from Itasca for advanced geotechnical analysis of soil, rock, and structural support in three dimensions.

10. This refers to the chemical activity: $a = m\gamma$, where a is the activity of the solute species, m is the molality and γ the activity coefficient. Activity is, therefore, the thermodynamic effective concentration.

In conclusion, Yucca Mountain was shown to have complex hydrogeological and hydrogeochemical systems and to be different from other potential high-level radioactive waste repositories in many respects. The hydrogeological and hydrogeochemical data from the site yield evidence of past discharge locations and water table elevations, and at least one zone of very high fluid velocity. Saturated zone geochemical data suggest fracture flow paths isolated from the bulk rock geochemistry. Site hydrogeological and hydrogeochemical computer models are consistent with many properties of the system, including fluid potentials, aqueous chloride concentration, palaeodischarge locations and perched water lenses. However, the models do not completely account for the all available site-specific data.

Discussion of this presentation centred on the extent to which the models adequately captured the uncertainties in the system and how they fed into the development of the safety case. The conflicting $^{36}Cl/Cl$ ratios were identified as a problem that requires further investigation; however developing the understanding and models required may be beyond current scientific knowledge.

General Discussion on Session II

Following these presentations, a general discussion took place based on the three questions posed as the framework for the session. The following points were raised:

- Are the uncertainties in the processes considered here due to our inability to make the correct measurements, or are they inherent in natural systems?
- We understand the processes concerned, especially their bounding values, but perhaps the more rapid processes are harder to understand.
- We can predict reasonably well until the boundary conditions change – but then we are less confident, especially about the subsequent rates of change.

It was concluded that it was relatively easy to link changes in the Holocene (anywhere in the world) with changes in groundwater chemistry, etc., but to go back to earlier times was difficult, specifically where these most recent changes have tended to remove the evidence for earlier changes, i.e. where there have been previous glaciations, of which there have been many during the Quaternary. This problem of overprinting is likely to be less severe where no such ice sheets existed, as long as there are geological features, e.g. mineral precipitates, that are capable of preserving these changes. This suggests that perhaps we can be confident about the stability for the next 10^4 years (which is a critical time period as far as the hazard of the waste is concerned), but that we can be far less certain about extending this to 10^5 years. Crystalline rocks, especially the very old ones in Scandinavia, have suffered from repeated and significant changes and are still relatively stable, a fact that should give us confidence in their future stability. Regarding the level of uncertainty associated with geosphere stability, it was pointed out that, whilst recognising uncertainty was important, it was also important to understand its significance (as illustrated well by the SFIC of SKB).

Session III: Arguments to support confidence in the stability of crystalline rocks as potential host formations

Each presentation described specific national experience focused on the arguments in support of the confidence in geosphere stability, such as:

- the long-term stability of the favourable conditions displayed by host formations;
- the buffering capacity of the formation vis-à-vis perturbations; and
- the predictability and ability to bound the effects of perturbations.

Liisa Wikström (Posiva, Finland) gave a presentation on the lessons that could be learnt from lithological history and ductile deformation regarding the long-term stability of large-scale structures at Olkiluoto, which is the proposed site for the disposal spent fuel in Finland. Evidence was presented that showed the relationships between the shallow-dipping shear zones, the later brittle deformation zones (BDZ) and the alteration, with the location of large BDZs being controlled by earlier ductile deformation and superseded by subsequent alteration. Lithological units are also displaced by both the shear zones and the BDZs which affect the distribution of lithologies on the site.

The largest movement (of 0.23 ± 0.023 mm/year) from GPS (Global Positioning System) measurements is consistent with lateral displacement on a BDZ. Dating of the BDZs shows that they formed about 1.8 Ga, that the illitisation from hydrothermal alteration took place between 1.6 – 1.2 Ga and that at least one of these zones close to the repository site is still active, probably due to the effect of post-glacial rebound (aided perhaps by ridge push). Deformation can, therefore, be shown to be localized over extensive periods of time and this evidence supports the concept that the rock mass lying between these deformation zones is inherently more stable.

It was concluded that, whereas it is not possible to state that the major ductile and large-scale brittle deformation zones are stable, it is possible to state that tectonic processes have been active in a semi-stable manner for approximately one billion years, by repeatedly reactivating existing features which, having been formed, remain inherently weaker (a process referred to as *strain weakening*). In addition, there are no signs of recent large features having been formed in the vicinity of the site, including during the post-glacial period. A corollary is that studies cannot be restricted to existing brittle deformation features, but must also include older ductile and lithological features. This is necessary so as to understand the reasons for the locations and orientations of BDZs and their possible extensions into parts of the rock mass where data may be sparse.

Discussion of this presentation centred on the 'buffering capacity' of such BDZs to accommodate current and future deformation, i.e. due to post-glacial rebound plus ridge push, and further in the future due to ice loading. Posiva's safety concept is not contingent on specific properties of such zones, but on the fact that any major movement will take place only on such zones, with the intervening rock being protected from such movement (see presentations and papers by Hökmark and Follin that discuss related subjects). The GPS data are relatively new, and it is unclear how such information will be included in any future safety case.

Paul LaPointe (Golder Associates, USA) gave a presentation on the evolution of the fracture system in the Fennoscandian shield and evidence for its stability over repository timeframes. He defined a stable fracture system as one in which perturbations produce negligible changes over the time frame and spatial domain of interest, thereby suggesting that abundant new fractures can be produced only by rare events, in which highly anisotropic stresses occur over a large area. The geological events that have affected the Fennoscandian shield (with data from Forsmark and Laxemar), from the time when ductile deformation was still prevalent (>1.83 – 1.7 Ga) to the time when brittle deformation commenced (1.7 – 1.6 Ga) to the time that mineralisation of fractures by epidote occurred (1.4 Ga), were linked to the various tectonic phases (1–5) which could have resulted in fracture sets with specific orientations. It was concluded that the fracture pattern seen today differs little, except in its intensity, from the pattern of the epidote-filled fractures, formed in 1.4 Ga – which is consistent with the premise that the majority of the fracture pattern formed in the Proterozoic. Future deformation, due to continual ridge push and, more importantly, to glacial loading, will add only a small number of near-surface, sub-horizontal fractures. It can, therefore, be concluded that the majority of the fracture system and, in particular, all of the fracture system at depth, is inherently stable and is unlikely to change over the period of interest of a safety case for the repository in Sweden.

Discussion of this presentation considered what additional information on fracture properties had been taken into account, e.g. their transmissivity, and the differences seen between borehole data and surface measurements. The vast majority of fractures at Forsmark are all old in geological terms (i.e. probably in >1 Ga) but their hydraulic properties are to some extent affected by the current stress field. An integrated approach is now being taken by SKB when investigating fractures, with structural geology being linked to hydrogeology, hydrogeochemistry, etc. (see Posiva, 2005 and Andersson *et al.,* 2007 for Posiva's integrated approach with similar rocks at Olkiluoto).

Shizuo Yoshida (Central Research Institute of Electrical Power Industry, CRIEPI, Japan) presented the stability and predictability of a younger crystalline rock system (crystalline rocks occupy 60% of the land area of Japan). He outlined the tectonic history and current tectonic state of Japan – it is not a simple volcanic arc – and the basement rocks formed before the opening of the Japan Sea (30 – 13 Ma), with current tectonic conditions being established 14-15 Ma and conditions at 1.8 Ma being virtually identical to those at present. The volcanic front is unlikely to change for the next 100 000 years, as it has migrated only 10-20 km during the Quaternary, and plate motions are expected to remain the same, so that future faulting is expected to be confined to the 150 major active faults and bulk strain rates to remain as they are at present (and cannot exceed 10^{-14} s^{-1}).

Earthquake data demonstrate that the hypocenters are located at considerable depths (for example over a 20-year period only 0.1% of earthquakes with M>3 occurred at depths <5 km) and the empirical relationship between fault length and earthquake magnitude means that it is highly unlikely that fault displacement or strain will directly affect a repository for 100 000 years in the future (as long as it is correctly located).

An interesting discussion took place comparing the situation in Japan, where displacement is thought likely to occur on known active faults (which can only extend in size relatively slowly), and the situation in Sweden, where approximately 20-30 *potentially* active faults could be present on one investigation site (but would be significant probably only during glacial retreat).

Björn Lund (Uppsala University, Sweden) gave a presentation on the evolution of crustal stress during a glacial cycle, using data from Sweden, in particular the Pärvie fault, a 160 km fault in northern Sweden which shows 10 m of reverse slip and whose movement during glacial retreat is thought to have been associated with a single M_w ~8 event. There is no evidence for such faults further south in Sweden or in other countries that were similarly glaciated, such as Canada.

The modelling approach employed for estimating glacially-induced stresses and the associated fault stability was outlined, firstly using simple earth models, followed by more realistic models of the Weichselian ice sheet. Using these models, the maximum and minimum horizontal glacially-induced stresses for Forsmark and Oskarshamn have been determined.

Research is continuing in several areas (e.g. on the introduction of pore pressure and on the effects of the accumulation of tectonic strain) and there are considerable uncertainties associated with the modelling, which will be investigated by examining extreme conditions. The models do predict that some fault instability may be expected during deglaciation at either of the sites.

Discussion centred on the Pärvie fault, particularly regarding what evidence there was to prove it was a end-glacial fault (there is extensive evidence, including liquefaction of sediments and displacement of glacial till), and what its form was at depth (it is likely to be listric or gently-dipping – and a seismic survey will be carried out as part of this research programme).

Eric Smistad (Department of Energy (DOE), USA) gave a presentation on developing confidence in stability and predictability for the geological setting of the proposed repository at Yucca Mountain. The licence application for Yucca Mountain, to be submitted in 2008, must demonstrate that the site provides a reasonably stable and predictable repository environment. Data supporting this position comes from numerous field and laboratory studies on the geological, hydrogeological, geochemical, isotopic, and climatological aspects of the site.

The climate models use data from the Yucca Mountain area and from analogue sites to estimate future climate states. This allows comparisons to be made between the percolation flux at the repository horizon for present-day and future climate states. Infiltration changes are effectively damped by the presence of a non-welded tuff high in the sequence (known as PTn), in which there is matrix-dominated flow. Fracture coating studies, using calcite coatings, are used to demonstrate the amount of water that has passed through the unsaturated zone. Data from calcite and opal fracture fillings can be used to provide spatial and temporal data on palaeopercolation fluxes.

The conclusion is that, although future climate states may bring greater precipitation and lower temperatures, the infiltration model and the hydrogeological properties of particular formations show that only limited amounts of water can be recharged. Specifically, the mineral precipitates suggest that steady rates of deposition have occurred over the last 10 Ma, regardless of significant changes in climate. The slow, steady growth rates of 1-5 mm Ma^{-1} observed throughout the repository horizon confirm its stability and suggest that it is approximately steady-state.

Discussion of this presentation considered the following matters:

- DOE was sufficiently confident that the PTn does offer this important damping effect, based on knowledge of its properties.
- There was discussion as to the chemical process that leads to calcite deposition. It was suggested that its deposition could be due not to the downward transport by water, but to evaporative processes, perhaps associated with gas flow from depth.
- The temporal resolution of the opal deposits is 4 000-5 000 years, so there could be events taking place on the shorter time scale that would not be recorded.

General discussion on Session III

Below is a compilation of the discussion that took place at the end of Session III:

- There was a running theme in this session on the importance, or possible lack of importance, of active faults. The approaches being taken in Japan and Scandinavia with regard to active faults both appear to be conservative (even extremely conservative in the case of Sweden) but, because of the very different tectonic settings, the effect of such features is quite different. There was some uncertainty as to whether the 150 major active faults in Japan referred to by Yoshida really represented all the active faults, or whether there were others, perhaps smaller active faults that are hidden (possibly below Quaternary cover). If so, it is not clear what would be the consequences of their possible presence.
- Questions were raised regarding the strain that is expected to build up between active faults in Japan (see Chapman *et al.,* this report) and how it was expected to dissipate.
- The stability of mineral fracture fills was introduced. These can become unstable due to chemical changes (e.g. dissolution of fracture fills), which could then influence the hydrogeological regime. This has been considered in SKB's and Posiva's programmes, though it appears to be significant only in the near-surface zone.

Session IV: Response and resilience of crystalline rock to natural perturbations and geosphere evolution (buffering)

Presentations in this session described the experience and conclusions of national programmes regarding the response and resilience of crystalline rocks to natural perturbations. The questions that were addressed in this session were:

- What is the stability of key transport processes and parameters (fracture networks, mineralogy, rock-matrix diffusion)?
- What kind of analogues should be used to support confidence (e.g. other types of formations and coming from other industry, e.g. mining or tunnelling/hydroelectric power)?
- What kind of arguments could support the THMC buffering or absence of buffering? (N.B. repository-induced effects are excluded).

Harald Hökmark (Clay Technology AB, Sweden) presented information on the reactivation of fractures in response to seismic events. A canister damage criterion of 0.1 m displacement is used by SKB for fractures that intersect canister holes. Such a displacement can be related to the moment magnitude of an earthquake and to its surface rupture length and, when combined with the process for rejecting potential canister holes, means that potential earthquake faults are either too small to give shear displacements >0.1 m or too large to avoid detection during repository construction. Only secondary fracture shear displacements can, therefore, be significant.

Dynamic 3DEC modelling of the repository region, with explicitly modelled fractures, showed that, at a distance of 200 m from a fault (associated with an earthquake of M_w 7.5), only one fracture slipped more than 0.1 m and at a distance of 1 000 m, none slipped more than 25 mm. It is expected that only 1-2 fractures with diameters >300 m will intersect any of the 6 000 canister holes in a Swedish repository. Therefore, it is very unlikely that any should slip >0.1 m. The seismically-induced shear was associated in the models with slip velocities in excess of those found in large earthquakes, suggesting that the results are also likely to be overestimates.

In the discussion following the presentation, it became apparent that an exchange of information between SKB and researchers in Japan would be useful, as Japanese researchers have considerable experience of earthquake effects, which could contribute to confirming or adjusting some of the assumptions made in the model.

Petteri Pitkänen (VTT, Finland) presented information on the buffering offered by the rock at Olkiluoto against the intrusion of groundwater of undesirable composition (from a repository perspective). The major chemical parameters considered in this investigation were salinity, pH, redox and sulphide, with additional information being provided from other sources, such as the mineralogy of facture in fills. Favourable hydrogeochemical conditions appear to be prevalent at depth in crystalline rocks that have been studied in Finland, Sweden and Canada. However, it is also necessary to determine whether the hydrogeochemical and hydrogeological systems are sufficiently buffered against external changes, in particular those associated with future glacial cycling. Key to understanding the extent of this buffering are the knowledge of past changes and an understanding of how they have affected the hydrogeochemical system. Known changes were linked to the groundwater types found at Olkiluoto to explain the origins of the salinity, the groundwater mixing that is evident, the depth-dependence of groundwater types and the inferred infiltration of glacially-derived groundwaters (that is limited in extent).

Buffering of the Olkiluoto ground waters against oxygen and low pH waters was demonstrated. The existence of SO_4 reduction, although in principle unfortunate from a repository perspective (as the presence of the resulting sulphide increases the anyway very slow rate of corrosion of the copper canisters) provides further evidence of chemical stability. Uncertainties remain and the supporting observations are not unambiguous, but it was concluded that the groundwater system at Olkiluoto is adequately buffered and will remain so for the foreseeable future, i.e. probably many tens of thousands of years.

Discussion of this presentation focussed on the boundary between the SO_4 and CH_4 zones, the methane flux and the buffering processes. It was emphasised that the hydrogeological system (with a small number of transmissive, sub-parallel, low angle hydrogeological zones) was more of a buffer against the injection of dilute glacial meltwater than the hydrogeochemical system.

Mahrez Ben Belfadhel (Nuclear Waste Management Organisation (NWMO), Canada) presented NWMO's understanding of the groundwater flow system in the Canadian Shield and its evolution during the Quaternary. He outlined NWMO's current remit, their decision to pursue Adaptive Phased Management and their geoscience work programme, with an illustration of NWMO's approach to assessing long-term climate change, including future glaciation and permafrost evolution.

Predictions of future glaciation are based on a dynamic simulation of the last Laurentide glacial cycle, resulting in predictions of transient features such as ice sheet geometry, ground surface temperatures, permafrost evolution and basal ice sheet meltwater production. The investigation of the effect of these changes on the groundwater system in the Shield employs the Mean Life Expectancy (MLE) as a performance measure, where the MLE represents the average travel time for any subsurface particle to discharge to the biosphere, honouring both advective and diffusive dispersive processes. This modelling suggests that the dimension of the flow system, when combined with the salinity and permeability distributions assumed, provides a system in which solute transport at depth may be diffusion-dominated.

Preliminary THMC modelling results (as part of the European Commission's DECOVALEX – THMC programme[11]) suggest that glacial loading increases the hydraulic heads by approximately 33% of the normal stress applied by the ice sheet. It also suggests that only a small fraction of glacial meltwater recharges to depths of several hundred metres, limited by the depth-dependent salinity. Palaeohydrogeological studies and numerical simulations suggest that dissolved oxygen migration is limited to depths of approximately 100 m.

Discussion of the presentation centred on the statement that diffusion-dominated transport existed at depth and whether this was due to the boundary conditions or to the very low hydraulic conductivity assumed. NWMO's assessment is that it is due to both of these. Concerns were raised about the adequacy of modelling groundwater regional scale models in the crystalline basement rock, since data on hydraulic properties usually can only be obtained from a limited area and may not necessarily represent the entire model volume. It was agreed that large scale numerical models can provide useful insight into the processes and factors controlling the evolution of deep groundwater flow systems.

11. DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments in waste isolation) is an international, multi-disciplinary, interactive and co-operative research programme in modelling Thermo-Hydro-Mechanical-Chemical (THMC) processes in fractured rocks and buffer materials and their role in performance assessment for radioactive waste disposal.

However, the results obtained from such models need to be treated with caution when transferred to site-specific conditions.

Sven Follin (SF GeoLogic AB, Sweden) gave a presentation on the hydrogeology of the Fennoscandian shield, in particular the development of an understanding of the evolution of the groundwater flow system since the last glaciation, using the example of Forsmark. Having introduced the modelling strategy and the development of a Site Descriptive Model (SDM), he illustrated the deformation zones and fracture domains present at the site and their relationships with the stress state and their transmissivities. An integrated approach, using both hydrogeochemical and hydrogeological data, was being taken to the investigations and the modelling (using data from single-hole hydraulic tests, interference tests, natural groundwater levels and hydrogeochemistry). Two vertical bounding shear zones, bounding the tectonic lens at the site, with gently-dipping deformation zones within the lens, provide the main controls on the flow system. One gently-dipping deformation zone in particular, Zone A2, provides an important boundary between a more fractured and more transmissive rock mass above and a considerably less transmissive rock mass below, with few conductive fractures and a fracture network system close to the percolation threshold. Heads at shallow depths display a small range of values, indicating a well-connected fracture network.

The hydrogeological models simulate the evolution during the Holocene, using conservative hydrochemical constituents (e.g. chloride and bromide); a key reactive constituent in the model is magnesium. In a similar manner to Olkiluoto (see Pitkänen), combining a knowledge of past climate change and hydrogeology shows that groundwater mixing is controlled by the gently-dipping transmissive zones. There are differences in the chemistry of the water in the fractures and the matrix, showing that the system is not in equilibrium. The improved understanding of the initial hydrochemical conditions of the groundwater system at the start of the simulation period (8000 BC) is believed to have had a considerable impact on the confidence in the Site Descriptive Model in general and for the description of the future groundwater flow and chemical transport in Forsmark in particular.

Discussion of this presentation considered the following matters:

- The matrix pore water was collected (from drill core, using a variety of techniques, including diffusion experiments and leaching) and analysed at the University of Bern.
- It is unclear whether such tectonic lenses (together with the associated stress decoupling and the resulting implications for groundwater flow) are more common than is realised. This may be because there is limited experience of investigating such tectonic lenses; in fact, the Forsmark area and the site of the Canadian URL may be the only two such structures that have been studied in detail.
- No overpressures have been found at Forsmark and the system is sensitive to tidal effects and barometric changes, implying that the hydraulic conductivity of the rock mass is sufficiently great.
- It is apparent that the fracture system has not changed much over time (see LaPointe), but that changes in the stress conditions could influence its connectivity and transmissivity. However, assessment of the field data suggests a weak link between these properties and the current stress field.

Tony Milodowski (British Geological Survey, UK) presented information on a study of the impact of Quaternary changes on deep groundwater systems, using the results from Sellafield in the UK; much of the work has been carried out as part of the PADAMOT[12] project. The various drivers for changing the groundwater system and the potential impacts were outlined and the mineralisation and fracture history explained, in particular the distribution and crystal morphology of late calcite.

Changes in crystal growth fabrics provide a record of groundwater salinity and redox, which can be studied using cathodoluminescence, and He-LACE (Helium-flushed laser-assisted carbonate extraction) and ion microprobe studies have been used to measure changes in δ18O and δ13C to examine changes in recharge chemistry. Using such data, it is possible to demonstrate certain features, such as the penetration of oxidising groundwaters to depth (with no evidence of oxidising waters at potential repository depths, based on the lack of a negative Ce anomaly) and the vertical movement of the saline transition zone. An examination of present-day fracture porosity (the basement rocks and much of the overlying sedimentary sequence have fracture-controlled flow) shows that it is dominated by secondary porosity and by the extent to which fracture filling minerals have been removed in the past. A west-to-east evolution of the flow system is evident (with some evolution over time), with anhydrite and carbonate dissolution having occurred in the uppermost part of the site (in the transmissive sandstones); anhydrite dissolution and secondary porosity formation in the basement rocks; and anhydrite and gypsum precipitation, with associated loss of porosity, in the west. The changes to the fracture pore network (which, in turn, determine the hydraulic conductivity of the network) are, therefore, dynamic and irreversible – and the next climatic cycle will not necessarily be associated with the same flow paths and mineralogy/chemistry.

Discussion of this presentation considered the following matters: The negative Ce anomaly, indicative of oxidising conditions, is also found in Scandinavia, but only at shallow depths due to post-glacial recharge, not at depths of 400-500 m. At Sellafield there is a barrier to flow, in the form of a less permeable formation overlying the basement, so that its presence and the increase in salinity with depth have the same effect.

Tsuyoshi Nohara (Japan Atomic Energy Agency, Japan) gave a presentation on the hydraulic and hydrochemical response to seismic events. He showed how coseismic groundwater level changes could be correlated with earthquake magnitude and epicentral distance, using data from Tono and Kamaishi, where the hydrochemical changes due to such events have also been monitored. The reasons for coseismic changes have been investigated by studying the relationships between strain and changes in groundwater head, modelling the volumetric strain associated with faulting, comparing changes in strain with specific earthquake events and measuring changes in groundwater head and estimating the changes of hydraulic conductivity over time.

Research towards the development of an evaluation technique for such events includes examining the recurrence intervals of different types of earthquakes (e.g. interplate and inland shallow earthquakes) and the likely future values of volumetric strain. Trenching studies of active faults, making use of datable tephra deposits, geomorphological studies of river basins and data from the high density GPS network, are being used to examine the recurrence intervals of faults. Geochemical changes due to seismic activity are being investigated using data from the alteration zones and the mineralisation associated with faults.

12. PADAMOT is the research project on "Palaeohydrogeological Data Analysis and Model Testing" conducted in the 5th Framework Programme of the European Union. PADAMOT investigates how minerals and groundwater at a number of sites have evolved through past climate changes and what their compositions record about the sensitivity of groundwater conditions to climate at various depths, in order to improve understanding of long-term safety for geological repositories..

The conclusions of this research were that the changes in groundwater flow accompanying fault activity are generally small, that groundwater heads in a confined aquifer correspond to changes in volumetric strain in response to fault movement and that fault movement can be associated with an initial increase in permeability, followed by a groundwater table decline in the recharge areas, accompanied by a rise in the groundwater table in discharge areas. The overall conclusion is thus that the changes associated with earthquakes are limited in their extent.

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Session IV

Response and Resilience of Crystalline Rock to Natural Perturbations and Geosphere Evolution (buffering)

Poster Session