

USE OF ANALOGUES TO BUILD TECHNOLOGISTS' CONFIDENCE: NANET

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Outline

- Definition of Analogue
- General information about NAnet
- Different roles of analogues in confidence building for technologists
- Examples of analogue studies for these different roles
- Conclusions

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Definition

- From NANET: "An analogue is a natural, historical or anthropogenic system that permits a study of repository-related processes, including its surrounding environment and the processes that control its evolution"
- Definition has been extended
- Main reason for use of analogues:
 - cover temporal (and spatial) scales not accessible by lab / field studies
 - Industrial: < 150 a
 - Archaeological: >150 a, <10 000 a
 - Geological: > 10 000 a

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The relevance of analogues to radioactive waste management stems from the long timescales that have to be considered. Periods up to a million or more years into the future need to be considered and these are beyond experimental investigation and human experience.

Within the last years the term "Natural Analogue" has got a much wider meaning and includes man-made analogues as well.

The role of natural analogues in the safety case depends amongst others on the time scale to be covered. Therefore, it is useful to classify them by the time period addressed in the study. Here it is referred to

- industrial analogues, which started earliest 150 years ago and result from "disturbances" of the environment caused by input of constructions, materials, contaminants, etc. produced within the Industrial Age,
- archaeological analogues, which cover time frames between the past 10 000 and 150 years and result from man-made disturbance of the environment with the major difference that the materials do not stem from the industrial epoch, and
- geological analogues, which usually cover time frames of more than 10 000 years and in most cases more than million years. These analogues mostly result from natural changes in the geological environment, e.g. in temperature conditions, in geochemical and/or hydrogeological conditions.

NAnet: Background information

- “Network to review natural analogue studies and their applications to repository safety assessment and public communication”
 - 5th EURATOM Framework of the EC
 - Duration: 01. January 2003 – 31. December 2004

- Partners

- ENVIROS, UK (Coordinator)	- NRI, Czech Republic
- NIREX, UK	- CEA, France
- Conterra A.B., Sweden	- ONDRAF-NIRAS, Belgium
- GRS, Germany	- ENRESA, Spain
- GSF, Finland	- CSN, Spain

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The current interest in analogues in different countries is reflected by several recent review projects with emphasis on the application of natural analogue study results in performance assessment. The most recent international review was performed within the 5th EURATOM Framework of the EC by the NAnet project, a network on the review of natural analogue studies with emphasis on the application of analogues in long-term safety assessment and communication. The project ran from January 2003 to December 2004 and involved a network of European organisations, including both users and providers of natural analogue information. Although several reviews of analogues studies have been undertaken before, NAnet was the first international project to involve participants with expertise in undertaking analogue studies in the field; performing safety assessments and the application of assessment models and codes; regulatory and licensing issues; and public communication.

Details about the goals of this network and all results can be found in:

Miller, B.; Hooker, P.; Smellie, J.; Dalton, J.; Degnan, P.; Knight, L.; Noseck, U.; Ahonen, L.; Laciok, A.; Trotignon, L.; Wouters, L.; Hernán, P.; Vela, A.: NAnet Network to review natural analogue studies and their applications to repository safety assessment and public communication. Synthesis Report. EUR 21919, January 2006.

**NAnet: Goals**

- Critical reviews of a large number of analogue studies
 - not comprehensive but representative
 - no new studies
- Analysis, how far information from analogue studies have been used in performance assessments (PA) and for communication issues
- Compilation of quality-approved analogue information, relevant for typical European repository concepts
- Consideration of potential added value from these past studies that may be applied to future safety cases and stakeholder dialogue programs

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The overall aim of the NAnet project was to review the past and present use and understanding of natural analogues, and to make recommendations for their future use. The specific goals are listed on the transparency.

The project covered ‘traditional’ natural analogue studies, such as large-scale investigations of radionuclide transport around uranium orebodies, and process or mechanistic analogue studies such as those examining natural glass and bentonite clay stability. To complete the picture, a restricted range of other studies of natural systems which employ a similar philosophy to analogues was also included in the scope. These included studies which have examined radionuclide transport and retardation processes occurring at the geosphere-biosphere interface and in the surface environment.

NAnet: Approach

- Development of a systematic review structure for NA-studies
 - short description, relevance (e.g. repository concept, process(es))
 - previous application in PA, use for communication
 - focusing on PA-relevant information
- Compilation of available studies and prioritisation
- “Classical analogues” and restricted range of other studies of natural systems considered (more than 70 studies evaluated)
- Development of a structure to easily identify relevant NA studies for PA- and communication experts
 - matrices for processes in different environments (near field and far field)

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One of the primary outputs of the NAnet project has been the compilation of reviews of more than 70 individual analogue studies with relevance for the near-field, far field or biosphere.

Each analogue study review was documented using a standard review template that includes sections concerned with performance assessment relevance and applications, limitations of the analogue (e.g. dissimilar materials and environments compared to a repository etc), a summary of any particular quantitative information derived from the study, an assessment of the uncertainties associated with the qualitative and quantitative information, an indication of the time-scales covered by the analogue and reference to any applications in communication and links to the primary literature.

NAnet: Example of near field matrix



Near-field matrix		Waste form				Package		Buffer/backfill	
		Glass	Spent fuel	Cement	Bitumen	Copper	Steel	Bentonite	Concrete
Mechan. integrity of barriers	Mech. failure		Oklo (Helium pressure)	Roman cements		Archaeol.	Archaeol.	Orciatico	Hadrian's Wall
	Corrosion-chem. alter.	Iceland basalt	Cigar Lake	Hadrian's Wall	DeadSea bitumen	Kronan cannon	Inchtuthil nails	Caborde Gata	Hadrian's Wall
Nuclide release from barriers	Dissolution	Iceland basalt	Pena Blanca	Roman hot spas		Natural copper nuggets	Disko Island		Roman hot spas
	Leaching	Uranium glass studies	U ore bodies	Maqarin	Lower Saxony bitumens				Roman hot spas
Nuclide migration in barriers	Advection			Roman hot spas				Gotland bentonite	Roman hot spas
	Diffusion			Roman hot spas				Gotland bentonite	Roman hot spas
	Two-phase flow								
Nuclide retardation in barriers	Chemical	Iceland basalt		Roman hot spas			Sorption on oxy-hydroxide	Cigar Lake clay layers	Roman hot spas

One general feeling in NAnet project was that natural analogues have not been used to their full potential. The reason for this may be that, because of the large extent of analogue information that exists in technical reports, papers and other publications, for users it is hard to find information that meets their needs from the large body of.

Therefore, a simple referencing system was developed that enables safety assessors and communication specialists rapidly to find all those analogues that relate to their specific issues and interests.

The referencing system that was devised is based on a simple matrix that has on one axis the range of materials and on the other axis the range of processes that can occur in the repository system. Intersections of the axes identify unique material-process combinations and analogue studies can be listed at the appropriate intersections.

Two generic analogue matrices have been developed, one for the near-field and one for the far-field. Exemplarily the matrix for the near field is shown.

Analogue studies complementary to lab / field experiments

Aspect	Analogue studies	Lab and field experiments
Time frame	Very long periods (tens - billion years)	Short-term (weeks - few years)
Boundary conditions	Often poorly defined	Well-defined, set by researcher
Materials	Only approximate repository materials	Materials actually used in repository design
Systems	Complex, involve coupled processes, → realistic but hard to model	Simpler, facilitate modelling → may be unrealistic
Conditions	Natural conditions, partly slow reaction rates	Reactions often accelerated by raising temperature or use of aggressive reagents

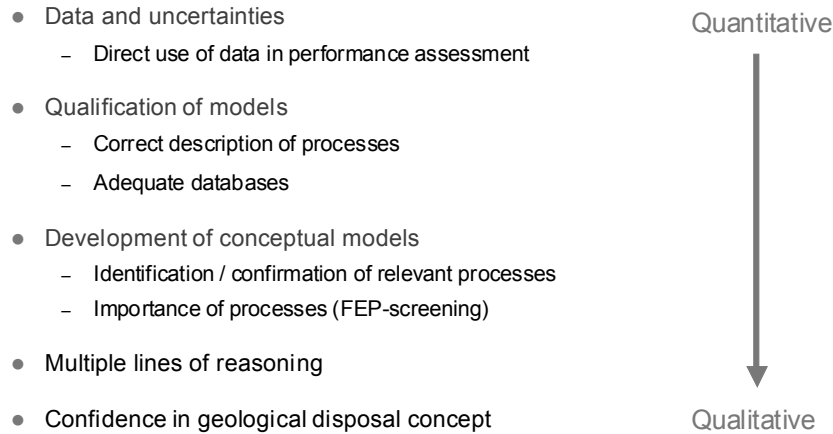
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Although analogues are important for providing realism, it is important to recognise that they do not have a unique role in this regard and should be seen as complementary to other forms of investigations such as field and laboratory experiments. Combining analogue studies with field and laboratory investigations provides a powerful means of investigating the natural processes which will occur in the repository environment because the disadvantages of one method are balanced by the advantages of the other.

As a result, natural analogues should not be viewed in isolation and their key role is to be complementary to other confidence and knowledge building methods such as laboratory studies and modelling exercises. This is one of the main messages from the NANet project: that natural analogue studies should be fully integrated into the mainstream scientific and engineering developmental work in a repository programme, rather than being treated as a separate discipline.

Different roles of analogues

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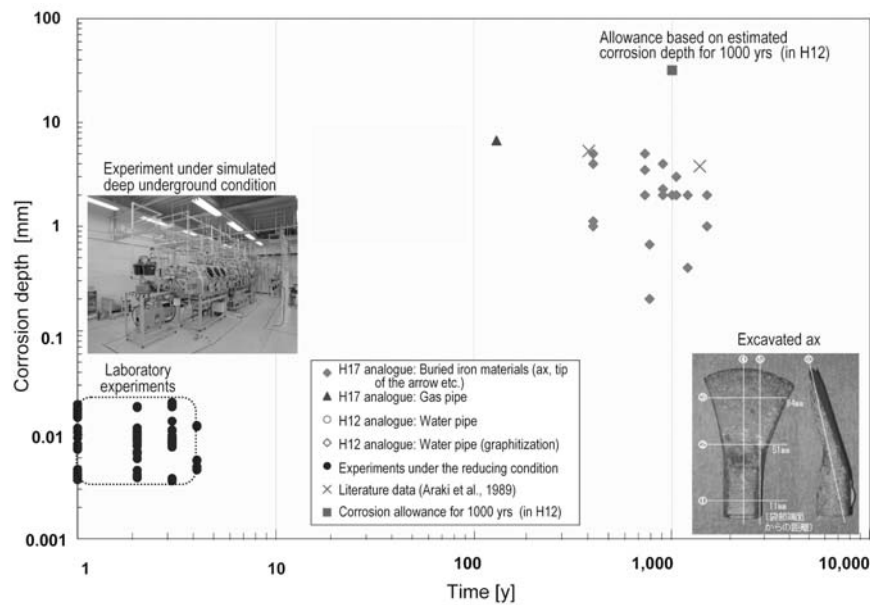
There are different roles analogues can be used for in the safety case. For building technologist's confidence, three roles might be most important.

Data and uncertainties: Approaches to use data, yielded from analogue studies, directly in PA, were only to some extent successful because it proved difficult to extract hard numerical data from complex natural systems where initial and boundary conditions are usually afflicted by a high degree of uncertainty. Nevertheless, there are several examples, where analogue data have been used as upper limits or to confirm results from lab experiments showing the same order of magnitude for the long-term scale.

It is now generally acknowledged that their primary role in support of safety assessment is to provide qualitative information to help develop or qualify conceptual models by identifying which processes are responsible for the evolution of natural systems, how these processes operate and on what spatial and temporal scales, and how these processes are coupled.

In order to illustrate how analogues can contribute to build technologists confidence, examples for the three different roles of analogues are given in the following.

Data and uncertainties: Corrosion of iron materials



Examples where analogue information have been used with respect to data and uncertainties in PA are archeological analogues, in particular those for processes connected with metals used as container material.

The figure shows an example from Japan concerning the corrosion of the container (reference material is carbon steel with thickness 190 mm). The allowance for the corrosion depth in 1000 years is 40 mm indicated by the red dot (from H-12 study). Of course, a lot of investigations are necessary to analyse corrosion processes, which is only possible by lab experiments. Corrosion rates derived from lab experiments are shown in the lower left, covering time scales of four years in maximum. Much larger time scales are accessible by investigation of analogues.

Yusa et al. investigated corrosion of buried gas and water pipes made from various steels and located in a clay-rich burial environment for several hundred up to more than thousand years. The corrosion rate (corrosion depth) estimated from these studies are in nearly all cases equal or below the value applied in the performance assessment study H-12. This analogue gives confidence in the value value for the corrosion rate and therewith in the assumption that container failure earlier than 1000 years after disposal is not expected.



Data and uncertainties

- Only few examples where data can be directly used in PA
 - Scope the boundaries of parameters
 - Problem: high uncertainties in initial and boundary conditions

- Example: Iron/steel corrosion
 - archaeological analogues most useful
 - study of more than 40 archaeological artefacts (Johnson et al.)
 - corrosion rates quite uniform (0.1 – 10 $\mu\text{m/a}$)

Gives confidence, that long-term corrosion rates used in PA models are in the right order of magnitude (e.g. NAGRA, JNC)

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A similar use of such analogues stem from the safety assessment of NAGRA for disposal of radioactive waste in Opalinus clay. Based on the results from lab experiments NAGRA selected for their PA study a rate for anaerobic corrosion of $1 \mu\text{m a}^{-1}$ (Smart et al. 2001). This low long-term corrosion rate is consistent with results from natural analogue studies of more than 40 iron and steel archaeological artefacts (Miller et al. 1994), which yield rates in a quite narrow range of 0.1 to $10 \mu\text{m a}^{-1}$, with the higher end of the range likely to be representative of steels exposed to aerated sediments.

→ This is an example, where a high number of analogues with similar results gives confidence in the results.

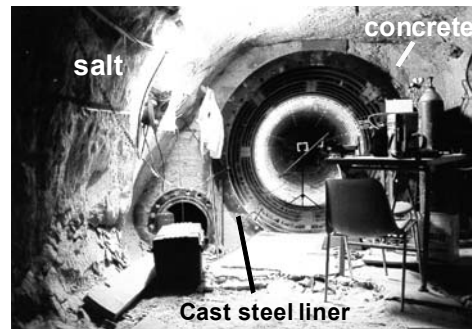
Other examples are corrosion rates for copper derived from ancient native copper at the Hyrkkola site (canister lifetime in POSIVA study) or the penetration depth for matrix diffusion from the Grimsel Test Site, which were used in the Swiss Kristallin-I assessment.

Model qualification: Self-sealing of EDZ in rock salt

PA relevance: increased brine flow through seals via EDZ

- Hydraulic properties (permeability, porosity, ...)
 - Spatial extent
- } Site characterisation
- Development with time → sealing
- } Industrial analogue

Bulkhead drift in the Asse mine constructed in 1914 in 700 m depth



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The second example illustrates the use of analogues for model qualification. The example is an industrial analogue for a repository in rock salt.

Excavation-disturbed zones (EDZs) are formed in all types of rocks as a consequence of the opening of cavities. In salt formations EDZs can extend up to 2 m into the rock salt. These zones represent areas with permeability increased by orders of magnitude compared to that of undisturbed rock salt. In a repository, where low permeable sealings are used as part of a multi-barrier concept, the increased permeability of the EDZ may lead to a reduction of the flow resistance and an increased brine flow through this section. Important for PA are information about the extension and the hydraulic properties of the EDZ and in particular about self healing due to the plasto-viskous properties of rock salt.

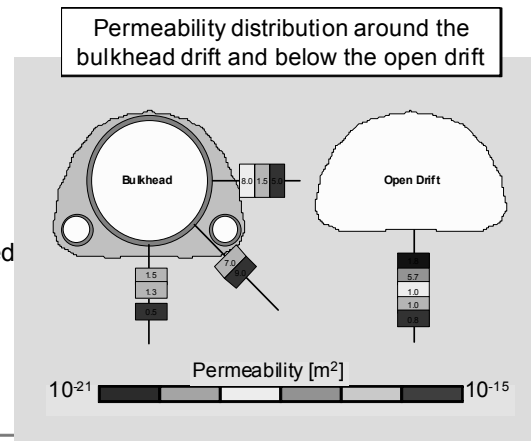
The permeability distribution and the extension of the excavated rock salt was measured at various test sites in the Asse salt mine in Northern Germany, near Braunschweig, by lab and field experiments.

One drift, the so-called bulkhead drift, which was mined in 1911, is especially interesting with regard to the potential long-term behaviour of the EDZ. A 25 m long section of the drift was equipped with a liner of cast steel tubings in 1914, and the void between the liner and the drift surface was backfilled with concrete. This drift can be regarded as a technical analogue for the development of an EDZ in a drift around a bentonite or concrete sealing as foreseen in a repository in salt.

Self-sealing of EDZ in rock salt

Results

- Typical EDZ still present around the open drift after 85 y
 - 1.5 m extension
 - Max. permeability: $2 \cdot 10^{-15} \text{ m}^2$
- EDZ around bulkhead drift sealed to large extent
 - Max. Permeability $< 10^{-18} \text{ m}^2$
 - microfractures closed but not disappeared



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The figure shows the permeability of the EDZ around the bulkhead drift (left) compared to an open, unlined drift (right). Below the open drift, a typical EDZ is present. It extends about 1.5 m into the rock, and the permeability rises above 10^{-16} m^2 . This confirms the results of a great number of permeability measurements at other test sites in the Asse salt mine. At all test sites with open drifts, an EDZ extension about 1.5 m into the floor and not more than 0.5 m into the walls was observed. Tests using various setups for measurements close to the open surface yielded permeability increases up to values from 10^{-16} m^2 to 10^{-15} m^2 , in comparison to around 10^{-21} m^2 of the undisturbed salt.

Around the lined part of the drift permeability is completely different. Apart from the horizontal borehole close to the drift surface, all permeabilities are less than 10^{-19} m^2 and thus considerably lower than the typical EDZ values. These lower permeabilities are due to a self sealing of the EDZ under a stress state with high normal and negligible deviatoric stress components, which is consistent with the results of supporting calculations. The original permeability of undisturbed salt, however, is not yet attained. Microstructural investigations on cores from both the lined and the unlined part of the drift seem to indicate that this may be due to the fact that the existing microfractures were closed by stress-induced plastic deformation, but did not completely disappear.

Self-sealing of EDZ in rock salt

Conclusions

- EDZ permeability significantly decreased within 85 years
 - Even faster at higher temperatures (expected in HLW repository)
 - Process level models to describe self-sealing under development
- (will be) used to give confidence that
 - models are suitable for calculation of self-sealing of EDZ in rock salt
→ extrapolation to longer timescales (several decades)
 - importance of EDZ for performance assessment restricted
→ considerable effect only expected for first decades of post-closure period

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In case of natural dry rock salt in the Asse mine with about 0.02 wt% water, 90 years under high compressive stress and negligible deviatoric stress were not sufficient to completely heal the EDZ around the bulkhead drift. However, this study clearly shows that a partial healing of the EDZ with permeability reduction of more than three orders of magnitude is observed. The permeability decrease in a HLW repository with temperatures of 100 to 150°C above rock temperature will be even faster. Therefore, this study gives confidence, that the importance of an EDZ in PA is restricted to the first decades of the post-closure period. Further, it is currently used in the EC project THRESA for testing and therewith qualifying the constitutive models describing the sealing process.

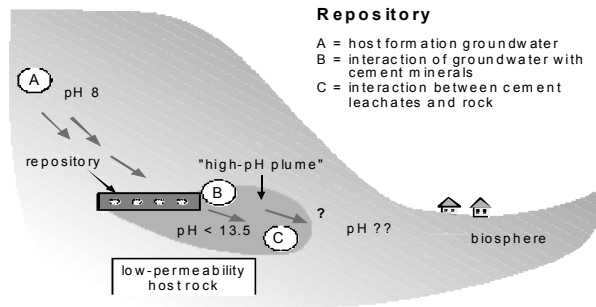
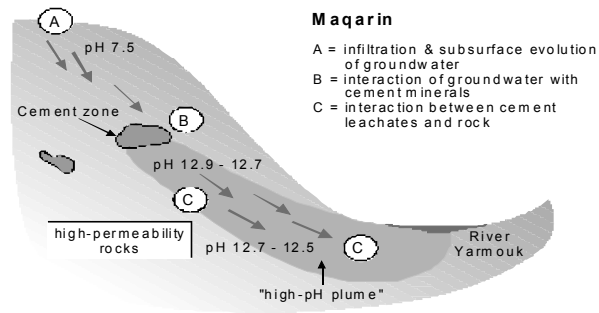
This study shows the worth of an industrial analogue, where the time frame is precisely known and changes of the boundary conditions are of minor importance. It also shows the important complementary role of analogue studies to lab and field experiments.

Other examples are the qualification of thermodynamic models and databases (e.g. in studies from Cigar Lake, Pocos de Caldas, Maqarin) as well as the investigation of natural tracer profiles in argillaceous formations, used for qualification of PA transport codes, showing that the relevant transport process is diffusion. i.e. no significant advective transport on large temporal and spatial scale has occurred.

Development of conceptual models:

Interaction of alkaline waters with host rocks

- Relevant for repositories with cementitious materials
- Analogue site in Jordan (Maqarin)
 - Natural cements from metamorphism of marls / limestone



One nice example where analogue studies have contributed to model development comes from the Maqarin study.

The Maqarin natural analogue site is a unique location for examining the mechanisms of processes associated with cementitious repositories, particularly when cement pore fluids will be dominated by the dissolution of portlandite and calcium silicate hydrate gel phases.

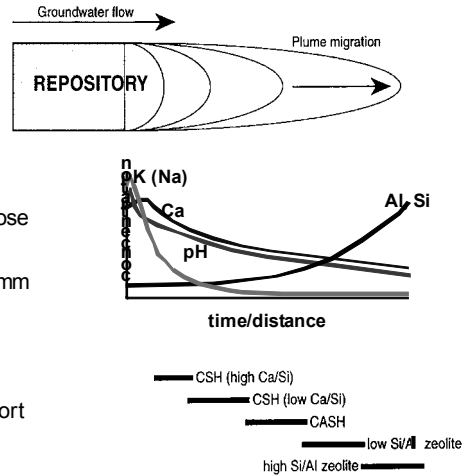
The hyperalkaline groundwaters in the area are the product of low temperature leaching of an assemblage of natural cement minerals produced as a result of high temperature/low pressure metamorphism of marls and limestones.

Interaction of alkaline waters with host rocks



Main Findings

- Conceptual model largely consistent with observations at the analogue site
 - long-lived hyperalkaline fluid conditions (tens of thousands of years)
 - Sequences of secondary minerals very close to those predicted by coupled codes
 - Diffusion-controlled alteration rims: 2 -20 mm
 - mostly positive reaction volumes
→ fractures sealed by precipitation of secondary phases
 - sealing of small fractures occurs within short timescales (years to hundreds of years)



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The Maqarin site now provides a consistent picture explaining the origin of the hyperalkaline waters, the persistence of some of the hyperalkaline springs/seepages, and the sequence of alteration occurring when such waters react with various rock-types. Thus the Maqarin study has contributed to model development, especially by the following observations:

- hyperalkaline pore fluid conditions generated by minerals analogous to those envisaged for cements are long-lived,
- sequences of minerals predicted by thermodynamic and coupled modelling are similar to those observed in hyperalkaline alteration zones at the site,
- diffusion controlled alteration rims occurring in time frames of more than ten thousand years are restricted to only 2- 20 mm, and
- small aperture fractures will be self-healing due to positive volumes occurring by reaction of rock with the alkaline plume.



Interaction of alkaline waters with host rocks

Conclusions

- Increase of process understanding
- Confirmation of findings from experiments and modelling
→ “Demonstration of realism” in the model

gives confidence in

- application of coupled codes to describe transport and interactions of the plume with the host rock
- results used in PA (e.g. reduction of porosity)

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The study has strongly contributed to process understanding, especially on the long-term scale. When the conceptual model for interaction of hyperalkaline fluids with rocks is applied in a safety assessment, confidence in the model is enhanced because the realism in the model can be demonstrated.

This example also indicates that it is largely the qualitative information from analogue studies that is most useful in the development of conceptual models.

Other examples for analogue information used for model development are the improvement of conservative radiolyses models by information from Cigar Lake, the development of conceptual models for glass corrosion, the use of permafrost data in development of iceage scenarios, and the development of a source term conceptual model for YMP from Pena Blanca analogue site.

Overall conclusions

- Increased application range for analogues identified in NAnet
- Multitude of analogue information was structured in matrices
- Approaches and data for integrated level and process level models
 - from laboratory (partly from field) experiments.
 - a number of experiments with well defined boundary conditions necessary
- Technologists' confidence in the adequacy of process-level and PA models underpinned by analogues
- Analogue studies complementary to experimental studies and modelling

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Within the NAnet project an increased application range of analogues was identified. In order to provide analogue information in a most efficient way all analogue information from the review was structured in matrices for the near field and far field of a repository system.

It is clear that approaches and data for modelling of processes on integrated level and process level are derived from laboratory and partly from field experiments. Usually a number of experiments with well defined boundary conditions are necessary. This task can not be done by analogue studies. They should be seen as complementary to experimental studies, because they are important to give confidence that the models are adequate.

Analogue studies contribute to technologists confidence by increasing the understanding of processes that control the evolution of the repository system over time. Qualitative information from analogues is of increasing importance, since it can help to develop or confirm conceptual models by identifying which processes are relevant, how these processes operate and on what spatial and temporal scale.

Not always very long time scales are needed. Some processes are only important on time scales of several tens or hundreds of years, which is still longer than the duration of lab and field experiments. Here, industrial analogues, where initial and boundary conditions are rather well known and materials are similar to repository materials, are very valuable.