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Simulations of Groundwater Flow in Fractured Crystalline Rocks of Northern Switzerland

with 6 figures

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Abstract

The crystalline basement of Northern Switzerland is under consideration as a potential host rock for deep geological disposal of high-level radioactive waste (HLW). Characterisation of groundwater flow through the geological environment at different scales is required to provide input for analysis of the repository safety. Relevant hydrologic input data for solute transport calculations are groundwater fluxes through the repository, flow directions and flowpath geometry. A multi-level approach of equivalent-porous-medium models and stochastic fracture-flow models was followed. An application of the developed methodology is presented. The developed approach may be applicable to a variety of site characterisation programs in fractured rocks requiring assessment/prediction of groundwater flow and transport by numerical modeling.

Zusammenfassung

Das kristalline Grundgebirge der Nordschweiz wird auf seine Eignung für die Lagerung hochradioaktiver Abfälle untersucht. Für die Beurteilung der Langzeitsicherheit eines Endlagers hat die Charakterisierung der Grundwasserströmung durch das umgebende Wirtgestein eine zentrale Bedeutung. Deren Ziel ist die Herleitung von hydrogeologischen Eingabedaten für Transportrechnungen. Relevante Parameter hierfür sind Grundwasserfluss durch Endlager, Fliessrichtung und Fliesspfad-Geometrie. Die hier vorgestellte Methode der quantitativen hydrogeologischen Charakterisierung basiert auf einer Kombination von hierarchischen Modellen, die ein äquivalent-poröses Medium oder generische Kluftnetzwerke beschreiben. Diese Vorgehensweise kann in verschiedenen hydrogeologischen Charakterisierungsstudien überall dort eingesetzt werden, wo Grundwasserfluss in geklüfteten geologischen Formationen untersucht wird.

1. Introduction

Evaluating the safety of a deep-seated radioactive-waste repository requires assessment of groundwater solute (radionuclide) transport through the geological environment. These transport calculations are based on a realistic input provided by an appropriate hydrogeological characterisation.

This paper presents an application of the methodology adopted for quantitative

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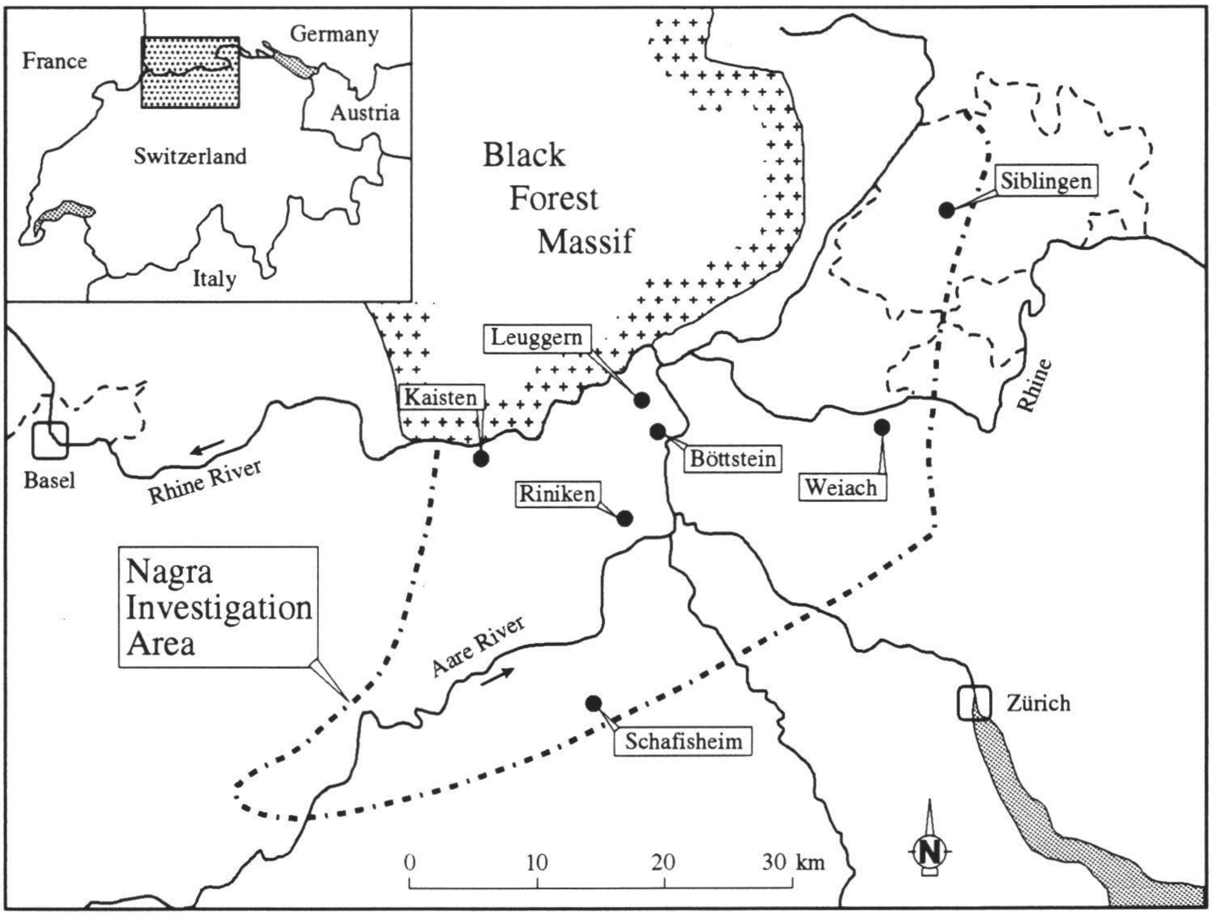

Fig. 1: Nagra's investigation area in Northern Switzerland with locations of deep boreholes

characterisation of groundwater flow through a block of low-permeable, fractured crystalline rock in the perspective of repository performance assessment. The study was performed in the scope of Nagra's (National Cooperative for the Disposal of Radioactive Waste) crystalline HLW program KRI-1. The synthesis of this investigation program was reported by THURY et al. (1994). The general investigation area with locations of the realized deep drillings are indicated in Fig. 1.

The presented approach is based on hydrogeological characterisation of the crystalline rocks on multiple scales. The first step in characterizing the crystalline hydrodynamic system is the development of a hydrogeological conceptual model as a simple but plausible description of the real system. The conceptual model is then coupled iteratively to numerical models on progressively smaller scales to account for the hierarchy of the relevant water-carrying features. Each model has its specific objectives, but all models are interrelated. The procedure and objectives of each step are outlined in section 2. The evaluation of selected model results that are relevant for repository performance assessment are discussed in section 3. By combining model results from different scales, the groundwater flow in water-conducting features that may occur in the vicinity of emplacement caverns can be determined, and the bulk flux through a block volume of host rock can be estimated. The volumetric fluxes, together with the expected flow direction and path geometry, are the required hydrologic input for the solute transport models.

2. Hydrogeological Characterisation

The first step of hydrogeological characterisation of the crystalline basement is the development of an adequate conceptual model that provides in simple terms a consistent description of the groundwater flow at scales of interest. The second step consists of mathematical modeling of groundwater flow, starting at the regional scale and continuing down to a single-fracture scale. The approach is schematized in Fig. 2.

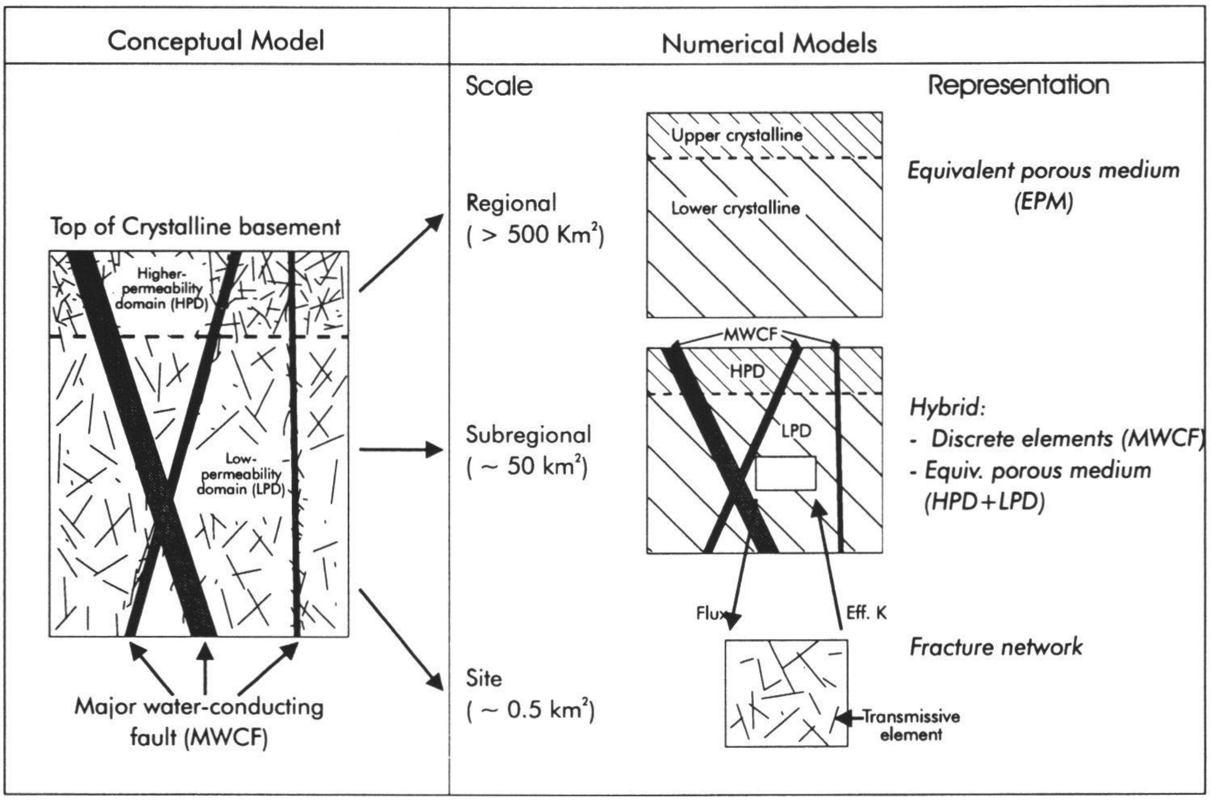

Fig. 2: Hydrogeological conceptual model and relationships to numerical models of groundwater flow

2.1 Conceptual model

At each scale of interest, the conceptual description of the crystalline basement is based on the bi-modal approach: The principal water-conducting elements are considered explicitly, whereas the background rock is averaged as an equivalent porous medium. On the scale of tens of km^2, the conceptual hydrogeological model discriminates explicitly major fracture zones (faults) which are considered as the principal conduits for groundwater flow. These regional and sub-regional tectonic features are referred to as "major water-conducting faults" (MWCF in Fig. 2). The faults are of primary importance for the repository development, because they represent the main active flow system through the geosphere and define the limits of a block volume within which a repository will be sited. Such blocks are composed of a relatively intact "average" rock, designated as "block matrix" by the conceptual model. The block matrix includes all other minor structural features, such as local

faults, fractures, dikes and joints, which are incorporated into an equivalent porous medium at the sub-regional scale, by making the continuum approximation. The conceptual model (Fig. 2) subdivides these "average" crystalline rocks into two hydrogeological units, a higher-permeability domain (HPD) above and a low-permeability domain (LPD) below. The two domains have different geologic and hydraulic properties, as observed directly from Nagra boreholes. The upper domain has an average thickness of about 500 m. The lower domain was identified as the potential host unit on the basis of its favourable hydrologic properties.
At the repository scale, the groundwater flow and transport through a block of the low-permeable host unit, LPD, occurs principally through a complex network of discrete features as described above. In the conceptual model, the variety of these discontinuities - observed in the boreholes as discrete inflow zones - is addressed by the generic term of "water-conducting features". The positions and geometry of these features within a block of low-permeability rock are characterized by statistical means and simulated by stochastic fracture-network models.

2.2 Regional model (continuum approach)

For a first, regional-scale modelling study, all structural features were incorporated into an equivalent porous medium (Fig. 2). The basic assumption is that the flow system, covering an area of 1,200 km^2, represents a large enough representative elementary volume to allow the continuum approximation. The objectives of this modelling phase were a) to test the conceptual framework on regional flow with respect to boundary conditions, identification of discharge areas and consistency with hydrochemical evidence (advective flow particle tracking), and b) to provide boundary conditions for smaller sub-models. Results are reported in VOBORNY et al. (1994).

2.3 Sub-regional model (hybrid approach)

The sub-regional model reproduces explicitly the major water-conducting faults as defined by the conceptual model. The faults are modelled as 3- or 2-dimensional elements. The intervening blocks of "average" rock, i.e., the block matrix, are represented by an equivalent porous medium with effective properties (hence the term "hybrid" or double-porosity model). Therefore, the hybrid approach corresponds to a most consequent transformation of the conceptual model into a numerical grid (Fig. 2). The hybrid model simulates local flow conditions in crystalline rocks assumed to be typical of a selected area of Northern Switzerland; the modelled rock volume is about 6x8x3 km. Because the exact location and spacing of major faults in the study area is not known a priori due to Mesozoic cover, a simplified geometric fault pattern with regular spacings was proposed by structural geology as a probable geometric scenario (THURY et al. 1994). Four principal fault systems are modelled; each system is characterized by its geometry (constant strike, variable dip) and hydraulic properties. Although the hybrid model simulates flow conditions that are deemed representative for a certain study area, the model structure is not site-specific, because the reproduced faults are not related to an exact geographical position.

The hybrid model takes an intermediate position between the conventional continuum models on regional scale and the discontinuum models on the blockscale. This approach allows one to characterize the flow regime in low-permeable rocks that is dominated by major discrete features. In this perspective, the objectives of this modelling step were defined as follows:

- to test our understanding of sub-regional groundwater flow (hydraulic impact of major faults?) and to help to discriminate among several plausible conceptual scenarios, and
- to contribute input data required for repository performance assessment: distribution of hydraulic gradients in the environment of a potential repository, and direction and pathlengths of flow in blocks between major faults

In order to reproduce the complex geometry resulting from arbitrarily inclined and intersecting faults in a numerical mesh, a new mesh-generating algorithm *FRACMESH* was developed (HÜRLIMANN 1994). In contrast to purely discontinuum models such as described below, the *FRACMESH* code allows to introduce deterministic fractures or fracture systems of arbitrary geometry into the model **and** to discretize the resulting irregular space ("block matrix") into finite elements. Since the true frequency of large hydraulically active faults is not known, several alternative geometric layouts were investigated by the hybrid model. Starting from the default geometry as suggested by the structural model (the so-called "full" scenario considering the complete fault inventory as being hydraulicaly active), the frequency of water-conducting faults was successively decreased, resulting in increasing size of the "undisturbed" blocks. The geometry with the lowest frequency of faults was defined as the sparse scenario. The two bounding cases are illustrated in Fig. 3.

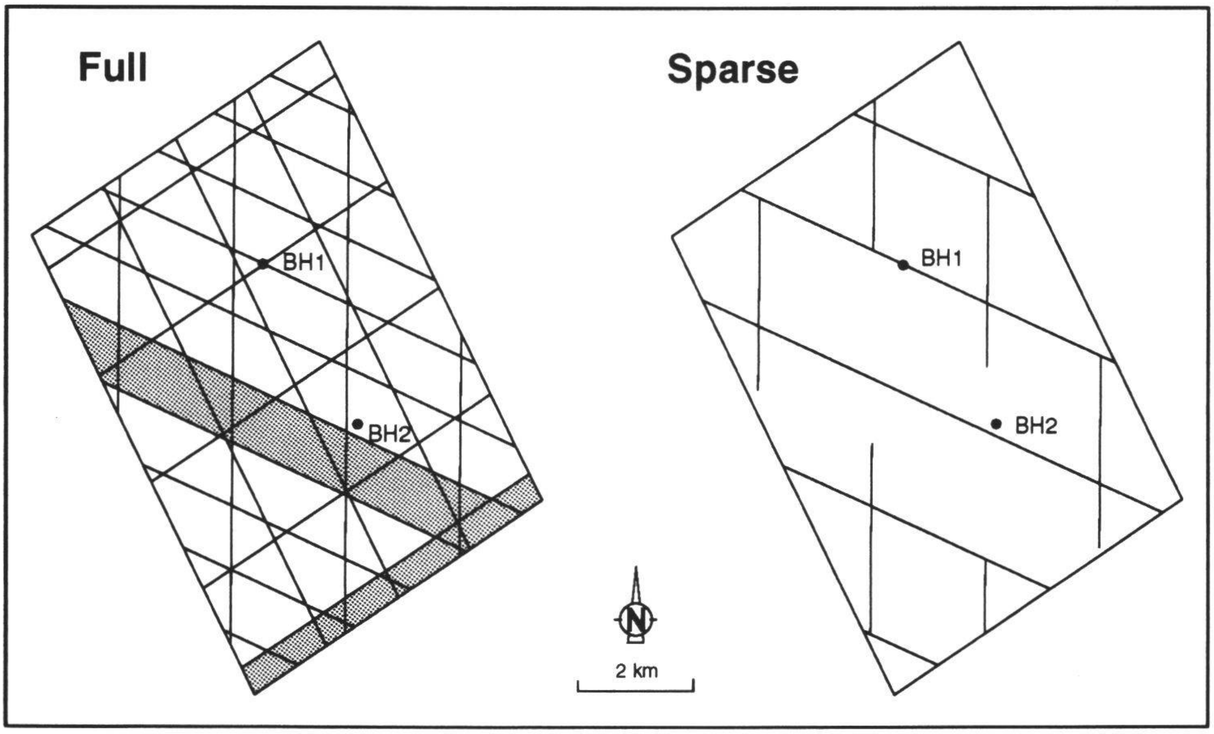

Fig. 3: Two selected geometric scenarios of the hybrid model: full- (left) and sparse scenario (right). BH1, BH2: location of existing deep boreholes

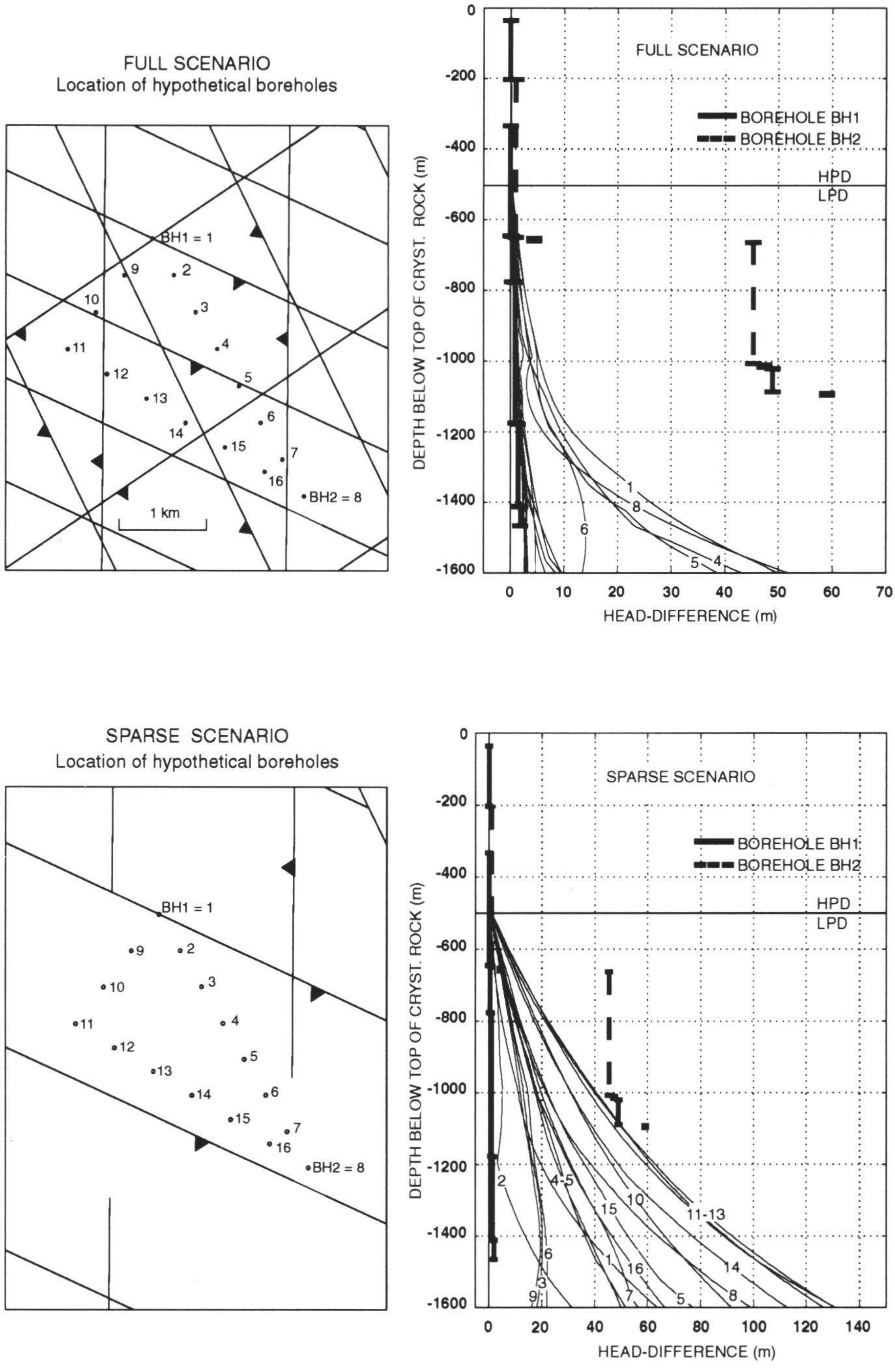

Fig. 4: Calculated vertical head profiles in hypothetical boreholes and comparison with experimental data in existing boreholes BH1 and BH2; full and sparse scenario

In order to assess the impact of fault proximity on hydraulic gradients, vertical head profiles were calculated for a number of hypothetical boreholes that were introduced into the model. As a plausibility check, the simulated head distribution was compared to observed data available from two deep boreholes, designated BH1 and BH2. The random location of these boreholes with respect to the faults in both model scenarios considered is depicted on the left-hand side of Fig. 4. The calculated synthetic head profiles along the boreholes are shown on the right-hand side, together with the observed profiles of BH1 and BH2 (thick lines). A previous evaluation of model results has indicated, that the complete fault inventory of the full scenario results in a well-interconnected hydraulic system, where the overall flow through the model is governed by regional, predominantly horizontal hydraulic gradients within the faults. The small undisturbed blocks are almost completely drained by the surrounding faults. Hence, virtually no vertical gradients are reproduced by this model scenario in the relevant depth range of 500 - 1200 m below top of crystalline basement (Fig. 4 top). In contrast, the sparse scenario results in a substantial reduction of the system connectivity. Under these conditions, the local flow patterns within the intact blocks of low-permeable rock remain preserved, showing an upward vertical flow in the interior and a radial horizontal component along the periphery of the blocks. As a result, the calculated synthetic head profiles in Fig. 4 (bottom) show distinct vertical gradients in boreholes penetrating undisturbed blocks (similar to the observed conditions in BH2) and small vertical gradients in those boreholes that are intersected by a fault (such as observed in BH1). It is evident that the simulated flow field in this case is sensitive to the proximity of major permeable faults. A comparison with experimental data, such as the displayed head profile of BH2 and available hydrochemical evidence, suggests that not all major faults in the structural geological network are hydraulically active; i.e., that the reduced frequency in the sparse scenario is the most plausible alternative (VOBORNY et al., 1994).

2.4 Block model (discontinuum approach)

At the site scale, probabilistic fracture-network models were used to characterize the groundwater flow through a typical block volume of low-permeable rock surrounding the emplacement cavern. At this scale the flow and transport occurs almost entirely through an interconnected network of discrete conductive fractures. Because the explicit knowledge of the position and properties of these features is not available, the properties of all fractures are incorporated into a statistical framework. These discontinuum models assume a purely fractured medium, i.e., the rock matrix is neglected. The required model input parameters are deduced from statistical analysis of borehole data (frequency and properties of water-conducting features). The fracture-network models distribute the bulk flux through a block of typical low-permeable crystalline rock between major faults (hybrid model) to single water-conducting features. The latter are reproduced as planar rectangular "transmissive elements" (TE) in the numerical network model.

The fracture-network modeling of a typical low-permeable crystalline rock of northern Switzerland serves three purposes with respect to input for safety-analysis calculations: 1) to assess the effective hydraulic conductivity of the network (feedback to the hybrid model); 2) to provide a probabilistic analysis of number, trace

length and transmissive properties of discrete features intersected by an emplacement cavern; and 3) to evaluate the flowpath geometry through the host rock (tortuosity).
Once the input parameters defining the fracture network in a statistical form (distribution parameters) have been derived from the boreholes, 20 realizations of the network were performed for each input set. In each realization, the finite-element code NAPSAC (GRINDROD et al. 1991) generates an independent framework of fractures that represents a cube of 500-m side length of the prospective low-permeable host rock (LPD in Fig. 2). Because fracture length is the principal input parameter that cannot be deduced from borehole observations, an adequate parameter study was conducted to cover the likely range of fracture lengths. Multiple networks consisting of 20-m, 40-m, 100-m and 200-m fractures were generated; the areal density and transmissivity distribution of the features were kept constant to ensure consistency with borehole observations. Further networks were considered with log-normal and bi-modal distributions of fracture length. Effective conductivities were estimated by calculating the flow due to unit pressure gradients applied in each coordinate direction.

The results from the stochastic network models showed that network conductivity increased with fracture length even though total fracture area within the model was held constant. The smallest fracture-length cases were typically unconnected while conductivities for the large sizes (100 and 200 m) approached the maximum theoretical value for the equivalent conductivity that can be derived analytically for a system of infinite fractures. As a results of these calculations and after consultation with structural geologists, a base case using typical fracture length of 100 m was adopted for all further models.

3. Hydrogeologic input data for transport calculations

3.1 Procedure

The required hydrologic input data for solute transport models are the hydraulic gradients and flow direction within the host rock surrounding the repository, groundwater fluxes through single water-conducting features intersected by the cavern, and geometry and composition of the flowpaths. The methodology of combining the different model outputs and borehole data to calculate the groundwater fluxes is illustrated in Fig. 5 and discussed in detail by VOMVORIS et al. (1994). The procedure for the derivation of additional transport properties required in the database is described in MAZUREK (1994), whereas the summary of approach and results is given in THURY et al. (1994).

The distribution of hydraulic gradients and the direction of flow in function of the proximity of major faults were evaluated by the hybrid model. The analysis assumed that by considering the full- and the sparse geometric scenario as bounding cases, the full spectrum of possible model results is covered.

The geometric and hydraulic parameters that control the advective fracture flow were provided by the stochastic network models. The principal model output is

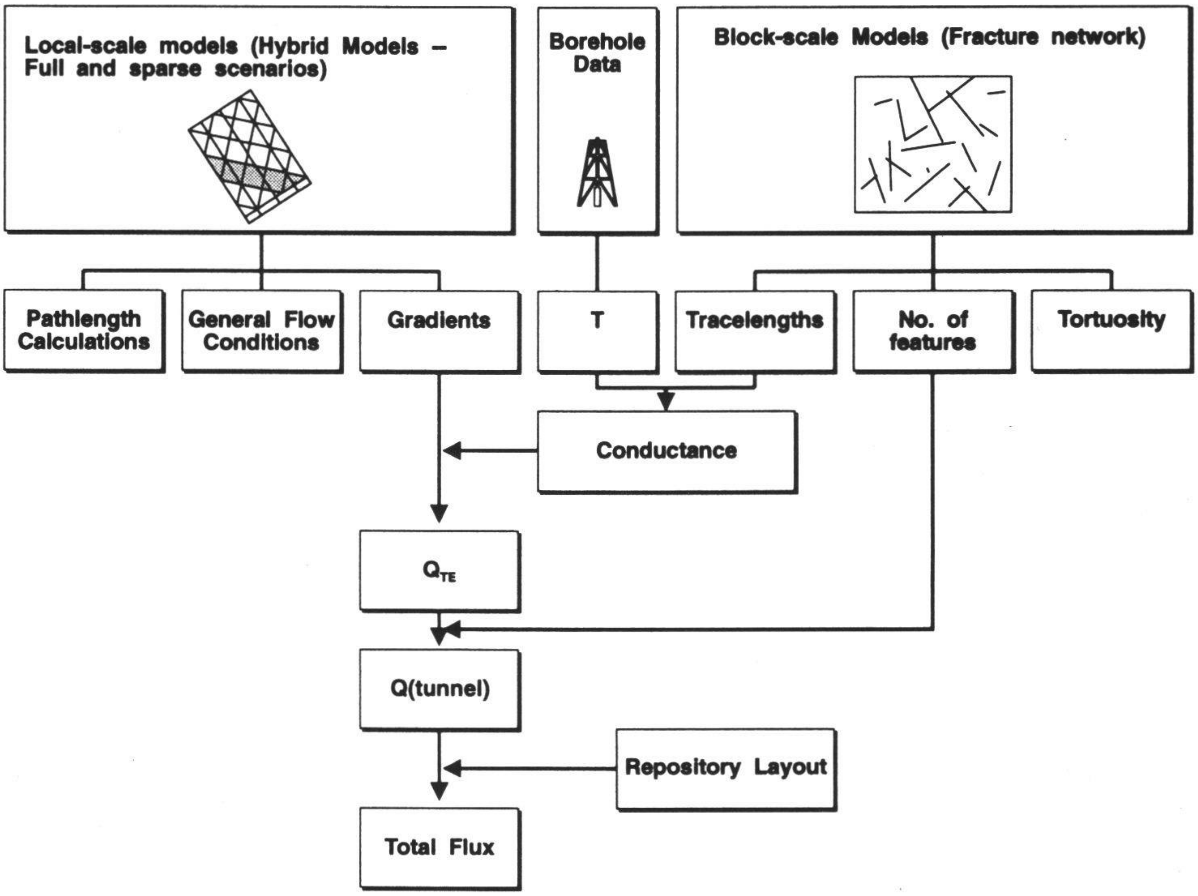

Fig. 5: Procedure for the derivation of the hydrogeologic input required for transport calculations

statistical information on the number, geometry and transmissive properties of discrete planar features that carry the flow through the fractured host rock. For this purpose, a tunnel section of 500-m length and 5x5 m cross-section was introduced into the network models in order to reproduce a hypothetical emplacement cavern.

3.2 Geometry and hydraulics of fracture flow

For each of 20 network realisations, trace maps of the intersected planar features in the tunnel were calculated. Each single features intersected by the tunnel is characterized by its trace length, L [m], and transmissivity value, T [m^2/s]. The latter is assigned individually to each fracture by NAPSAC by sampling from a pre-defined log-normal distribution (input). The product of L and T is defined as conductance, C [m^3/s], which quantifies the capacity of a geometric feature to carry flow. As a direct output of NAPSAC, the conductance is calculated for each intersected feature, resulting in a log-normal distribution.

In the next step, the conductance distribution is multiplied by the distribution of hydraulic gradient (obtained from the hybrid-model) to calculate the groundwater flux, Q_i, through a single water-conducting feature, TE. By applying the gradient distri-butions resulting from both the full and sparse scenarios, the full range of flux distributions is obtained. Fig. 6 shows the corresponding histograms for both cases. These fluxes through a single water-conducting feature can be further up-scaled to

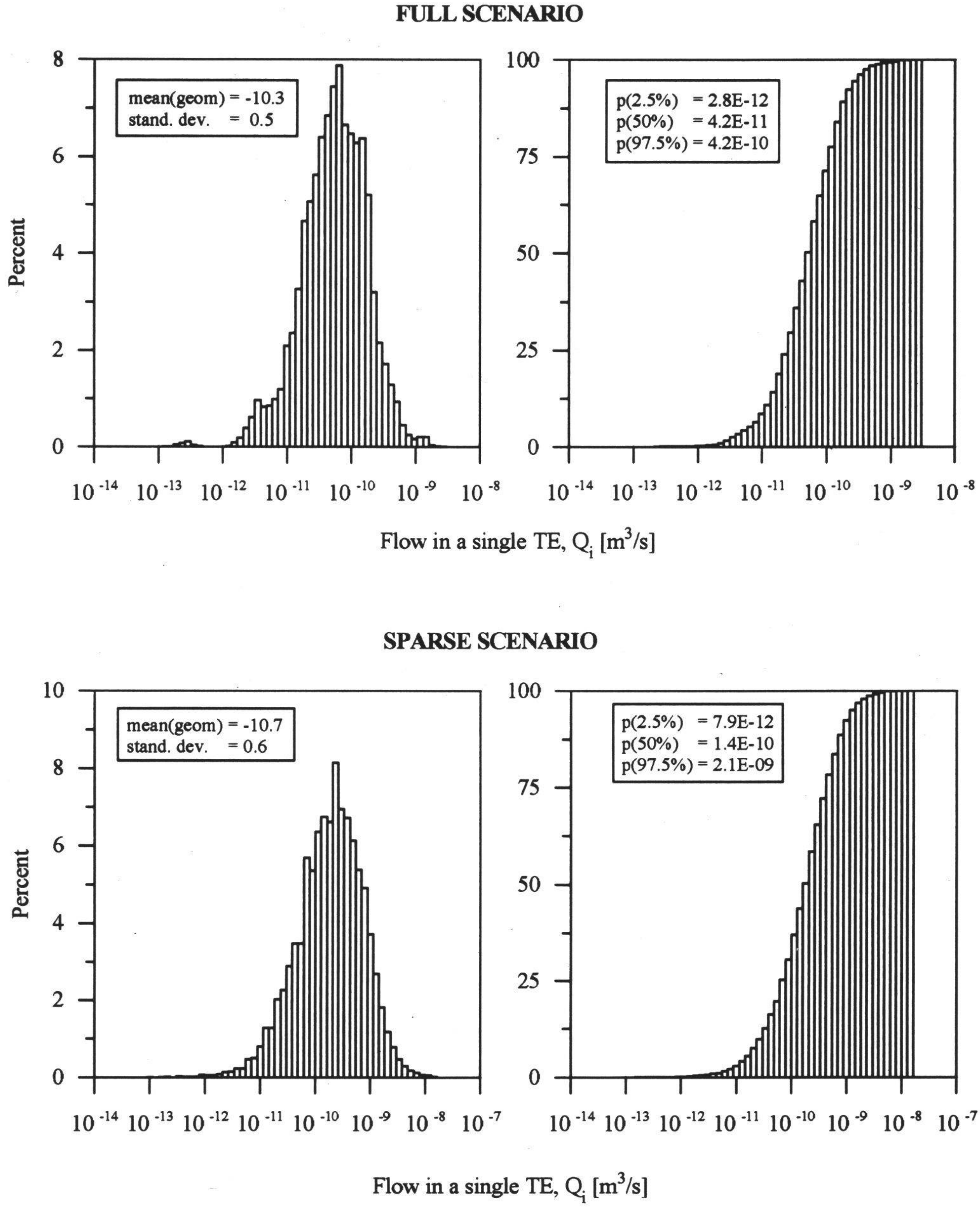

Fig. 6: Calculated distribution of volumetric flow in a single fracture, Q_i [m³/s], full- and sparse scenario

the total flux through the tunnel section by multiplication with the number of intersected features.

The above step of deriving groundwater flux through a single fracture involves several simplifying assumptions all of which are conservative with respect to estimated fluxes, i.e., they yield higher values:

- The gradients and conductances are independent; in "real" networks, in fact, they are inversely proportional,
- all water-conducting features intersected by the tunnel represent an outflow,
- each single fracture has a constant transmissivity (aperture), i.e., the spatial variability along the flowpath is neglected.

It is deemed that this conservative approach accounts for the considerable uncertainty attached to the input data and the conceptual model.

4. Conclusions

A comprehensive hydrogeologic characterisation study of the crystalline basement in Northern Switzerland has been performed with the objectives to: i) improve our qualitative understanding of the hydrodynamic system; and ii) to derive a quantitative input required for solute-transport calculations. The presented approach is based on conceptualization of flow through fractured rocks at various scales, which is iteratively supported (and improved) by numerical models on multiple levels. The development of the hydrogeological conceptual model is the most critical step in the chain of modeling, since it has to provide a simplified yet realistic description of the system that, in turn, must be in balance with a variety of field observations.

Numerical models on progressively smaller scales are utilized to characterize advective groundwater flow through the geological environment of a potential deep repository. In addition to the standard continuum models (regional scale) and discontinuum models (block scale), a hybrid (or double-porosity) model was employed at the intermediate scale to evaluate the impact of major permeable faults on the local flow regime in undisturbed crystalline blocks. Comparison of model results with available experimental data was used to discriminate among several plausible conceptual hypothesis of groundwater flow in fractured crystalline rock. Uncertainties in the conceptualisation and data interpretation are captured through appropriate parametric studies and consideration of different (bounding) conceptual scenarios.

A simple method of combining the results from different scales to derive the required hydrogeologic input for solute-transport models is presented. The methodology may be applied to a wide range of underground waste disposal and engineering problems requiring assessment of advective transport through a low-permeable fractured geological environment.

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