A DFN HYDROGEOLOGICAL SIMULATION FOR THE EL BERROCAL GRANITIC BATHOLIT

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ABSTRACT

In many cases the safety analysis of high level radioactive waste underground storage systems require the fractured rock studies. The performance assessment study of this type of facilities include the development of flow and transport models to predict the evolution of possible contaminants released from the repository to the biosphere.

The rock heterogeneity and anisotropy make very difficult the task to obtain representative data to define its hydrogeological parameters, even though many field and laboratory tests are carried out. That is the main reason why it is necessary to apply statistical methods and to develop stochastic models to simulate the fractured rock medium. The goal is to identify the zones with a high probability to act as fast paths through the geosphere.

The methodology developed in the HIDROBAP project, and some results obtained with its application, in El Berrocal granite batholit, are presented in this paper. The methodology integrates modern tools belonging to different disciplines. A Discrete Fracture Network model (DFN) was selected to simulate the fractured rock block and a 3D finite element flow and transport model has been defined from the DFN model to simulate the water movement through the fracture network system to calibrate its hydrogeological parameters. The obtained results show that this integrated methodology can be a very useful alternative for the hydrogeological characterization and simulation in rock fractured media.

INTRODUCTION

It is known that granitic rocks have good mechanical, thermal and geochemical behaviour and have low permeability in "fresh" areas. Nevertheless, they have some inconveniences, like the presence of fractures (faults, diaclases and joints) which if interconnected can create preferential pathways for fluid flow and so radionuclides transport from the repository to the biosphere. This obviously makes the characterisation of the repository system complicated.

One of the recent methodologies are directed towards the use of stochastic models to estimate the inherent uncertainty in the fracture data interpretation and in the determination of hydrogeological conceptual models. Among these methodologies we can find those that simulate the geological media geometrically.

Discrete Fracture Network models (DFN) generate fractures inside a compact rock mass with an assigned variable permeability. The initial objective of the DFN models is to estimate the hydrogeological properties on local scale from nearly punctual measurements, such as injection test essays, in order to make later estimations of those attributes at a global scale. The experience has shown that this type of models interprets adequately the local scale field measurements (Elorza, 1997). However, it is necessary to get and process many structural data in order to generate the fracture network. This fact limits the scale at which these models can be applied. One solution to increase the scale of the DFN models application can be to develop a filter process to choose the fault network with highest probability to be conductive. The aim is to better define the medium at each scale from a hydrodynamical point of view.

OBJECTIVES

The main objective is to develop and evaluate a methodology based on DFN models for the characterisation and simulation of flow and transport processes in rock fractured media. This methodology must be suitable in the Performance Assessment of underground nuclear waste repositories. The methodology integrates the information obtained from different disciplines (structural geology, tectonic, petrology, geochemistry, geometrical statistic and hydrogeology).

WORKING AREA

The majority of the field data used to develop, calibrate and verify the methodology here developed were obtained by ENRESA and CIEMAT at the experimental site of El Berrocal

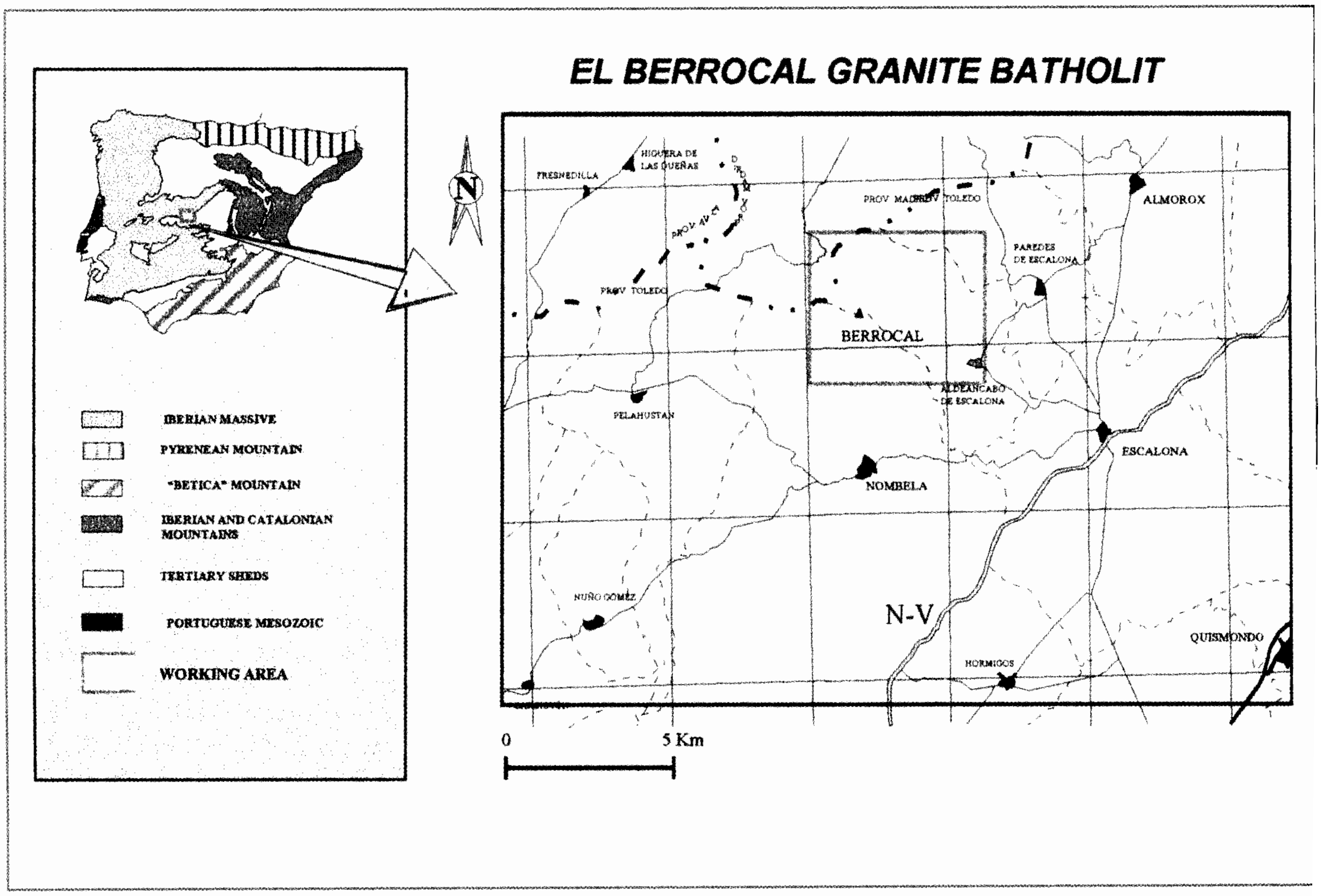

Figure 1. Working area: El Berrocal granite batholit.

massif (ENRESA, 1996). The work area (Figure 1) is an old uranium mine, which was studied in the European project NI F12W/CT9110080 co-ordinated by CIEMAT. This information has been completed with tectonic, petrologic and emanometric field data collection campaigns at the batholit scale (Figure 3).

HIDROBAP PROJECT PHASES

The HIDROBAP project consists of the following phases:

- Geologic characterisation: Sampling and analysis of the geological, geochemical, petrological and hydrogeological data.
- Geometric analysis and simulation of the fracture network: Construction and conditioning (calibration) of the DFN models to match these data.
- Stochastic simulation of flow and transport: Coupling of the fracture generation model and the flow and transport models.
- Uncertainty analysis and comparison of different models: Evaluating the methodology by comparison with numerical continuum flow models previously developed for the same geographical area (ENRESA, 1996), and developing a sensitivity analysis to ascertain how the different models depend on its input parameters.

Although the latter phase is not finished yet, most of the field data have already been analysed. A DFN model, a discrete fracture generation and fluid flow coupling models have been developed. In this paper, the results obtained from the three first phases of the project are presented.

The work has been performed combining the information from local (gallery mine area and boreholes) and regional El Berrocal scales (E 1:10,000 and 1:2,000). For this, it was necessary to prove a statistical similarity between the geometric data distribution of the measured fractures at both scales (Paredes et al., 1997). Therefore, the information of the hydrogeological characteristics of the fractures defined at a local scale could be extended to simulate the whole batholit.

The Project phases are represented in the a synthetised diagram (Figure 2) and it shows the information interconnection between the different stages and disciplines included in the project.

PROJECT DEVELOPMENT

Characterisation stage

It has been developed at different scales from three points of view: geometrical, kinematical and dynamical. Factors that affect fractured rock water transmission capacity depend on the faults physical and geometrical characteristics, type of movement and recent stress tensor. The macro-scale study has been done with mapping systems, G.I.S. and satellite images. The intermediate-scale study integrates direct and elaborated field data.

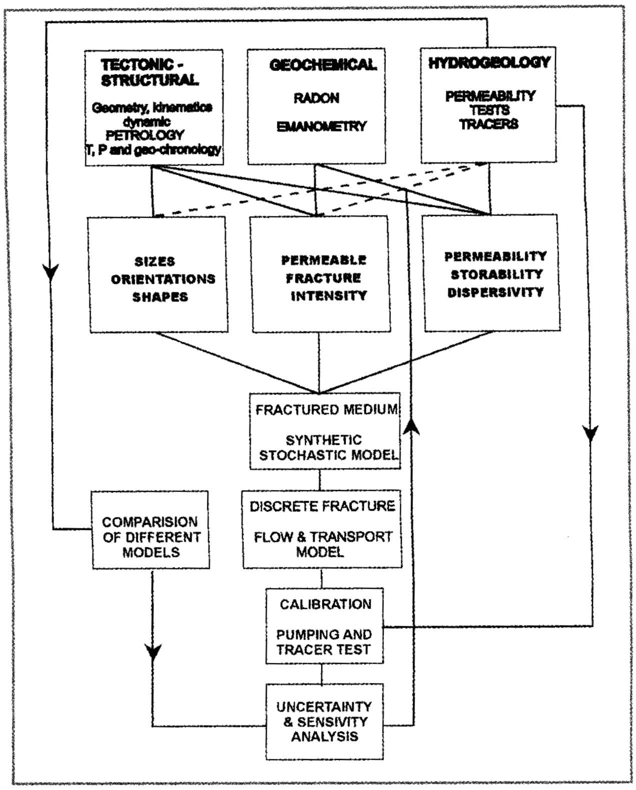

Figure 2. Project phases.

Different techniques have been applied to characterise the granite rock massif:

Fault Population Analysis (FPA) is used to determine the stress tensor related to fault deformation. Although this technique has never been applied to hydrogeology, it offers important information about the three-dimensional tectonic characteristics of the fractures and the rock massif tensional state. The extensional or compressional character of each fault is also determined. FPA technique can define the character of neo-formation or reactivation of faults. All this information can be very useful from a hydrogeological point of view (Zhang et al. 1996).

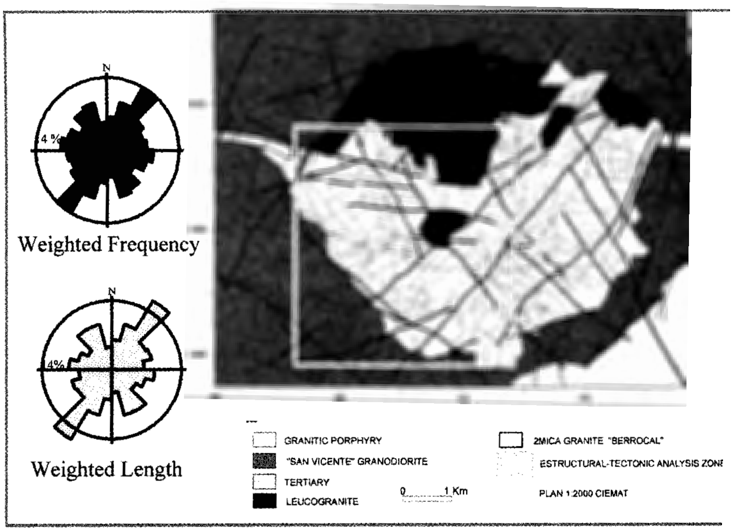

Figure 3. Fracture network: Geological map, rose frequency and fracture rose length distribution.

Figure 3 shows the fracturation network defined in the surface of El Berrocal batholit. Five families are produced in two main tectonic events: extensional phase (Permian? – lower Triassic) and alpine compression (de Vicente et al. 1996).

Petrological analysis has been developed: a) to characterise the micro-fractures to study the rock porosity and fracture patterns at different microscales; b) to define thermal and pressure formation conditions, studying the granite fluid inclusions; c) to determine the exhumation thermal history; stablished with the fission-tracks technique; d) to study the fault rocks geo-chronology using the K-Ar method in fault rocks (Galindo et al. 1994).

Figure 4 represents the second tectonic event that is defined by an alpine compression NNW-SSE. It is possible to represent the horizontal stress trajectory map using the FPA methodology, by determining the directions of maximal and minimal compression and active faults. In the other hand, it is possible to date this tectonic event between 16 m. y. and today using the petrological analysis.

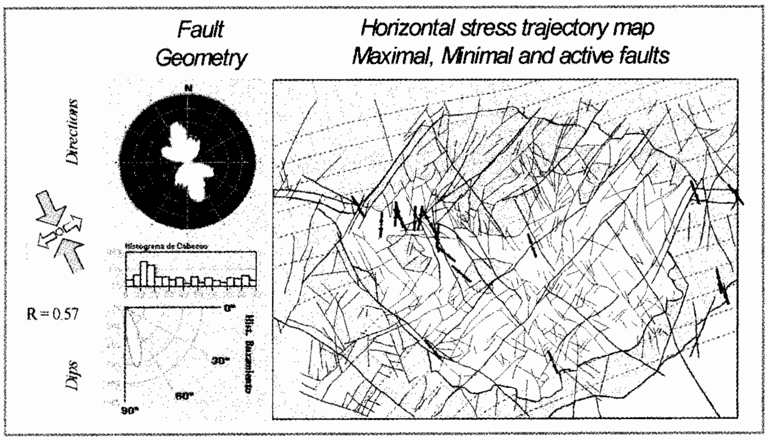

Figure 4. Characteristics of the second tectonic event: Alpine -compression NNW-SSE (16 m.y.-today).

Geochemical analysis. A quantification of gas radon emanations in terms of α-particle counting from the ground through the open fractures (emanometry) (Mazadiego, 1995) has also been realised to a 1000 m x 2000 m area (693 points). Data have been corrected and filtered to eliminate the soil influence. Factorial analysis and spatial correlation have been applied. This method was considered interesting to identify directions of structural weakness planes (Figure 5) and defining areas of different fracture density in covered zones (Figure 6).

In Figure 5 are shown the mean (M3(m)) and the standard deviation (M3(std)) of the background radon emanation measure to represent the prior directions which show a higher autocorrelation in black areas. It is possible to infer that in the left case three prior direction are shown: N-S, N-155º-E and N-60º-E. In the right case three prior directions appear: N-155º-E, N-60º-E and N-30º-E. This last one does not appear before, and the N-S direction disappears.

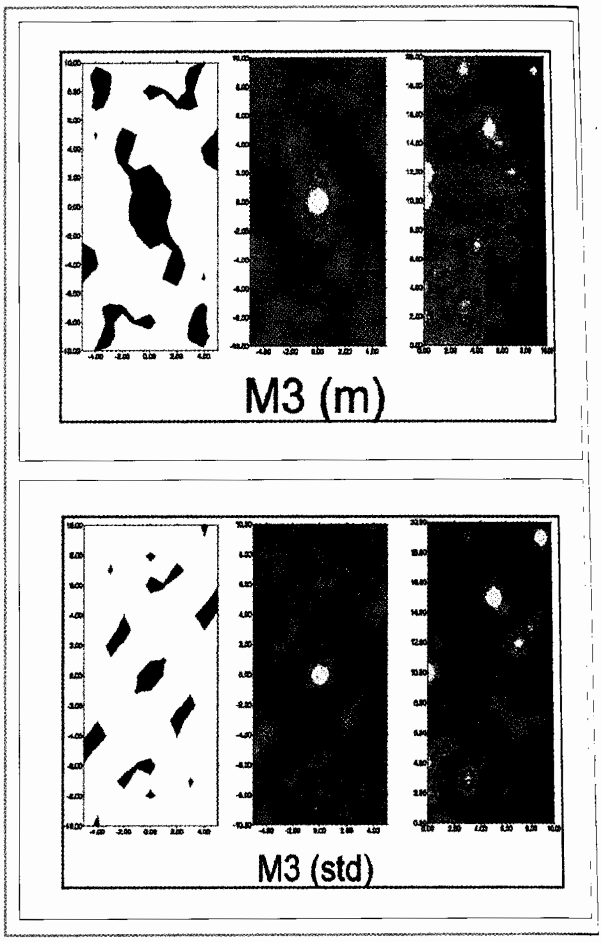

Figure 5. Geostatistical 2-D analysis of emanometrical data.

To deal with the generated information a Geographical Information System (GIS) database has been created with five different work scales: 1:2,000, 1:10,000, 1:500,000, 1:1,000,000, 1:4,000,000. Therefore, faults can be selected by Booleans rules in the geometric characterisation and simulation phase (i.e. open faults + extensive stress + reactivated faults + oxidation evidences). As an example of the capability of the developed database, in Figure 7 are shown the results of a

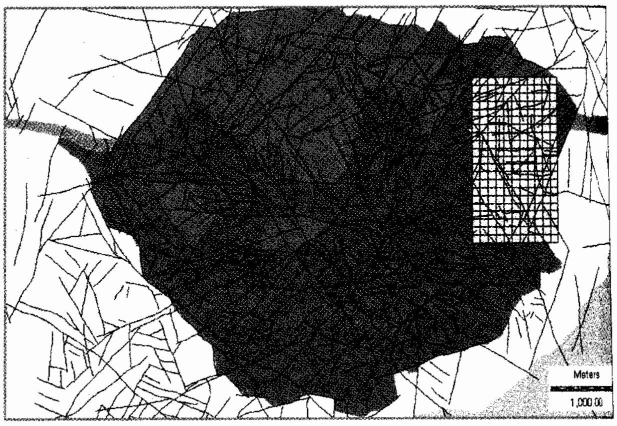

Figure 6. Geochemical monitoring area and emanation intensity (dark squares = high emanation).

selection of open faults and faults where water has been detected during the field study phase. Similarities between the directions of these two sets of faults can be easily inferred. In Figure 8 a 3-D scheme represents the digitalized topography, the fracture network and the maximal and minimal compression stress field, showing faults with extensive character marked with bold black lines.

Hydrogeological characterisation. It is necessary to obtain a precise knowledge of the geologic medium hydraulic properties distribution to study the hydrogeologic behaviour. Those properties are restricted to hydraulic transmissivity of the conductive fractures that constitute the effective flow, circulation and percolation network. The aim is to deduce and assign a transmissivity probability density function (pdf) to each fracture family and employ them to define the hydraulic transmissivity characteristics of the generic structural-hydrogeologic pattern that conceptualises the granitic fractured medium.

The developed methodology consists of three phases, starting from the fracture information recorded at the S-16 borehole by means of the Acoustic Tele Viewer logger /1992) and de visu core interpretation (Pardillo and Pelayo, 1992).

The first one, called *manual analysis*, assumes the fracture families hydraulic transmissivity is an accumulated function of each fracture hydraulic transmissivity function weighted by the fractures number of each family present in each packer (within the S-16 borehole).

Initially, the number of fracture families is determined from tectonical criteria. From that, five families (A, B, C, D and E) were identified.

The second phase is called *automatic analysis*, and consists of the application of a least-squares minimisation method to assign the transmissivities. Starting from the *manual analysis* hypothesis, it becomes an over-determined equation system with n_j equations (number of essayed packers on the borehole) and ***nfam*** unknown transmissivities. The results are taken as the mean transmissivity values of each fracture family.

Eventually, the third phase consists on a *mixed* or *semiautomatic-stochastic method*, which is included in the Oxfilet menu of FracMan code (1995), using the results of the two previous phases. The stochastic method is based on the simulated annealing algorithm that also minimises the residue between the hydraulic transmissivity pdf of each j-family fracture and the user-selected pdf (i.e. lognormal). The results are shown in Table 1.

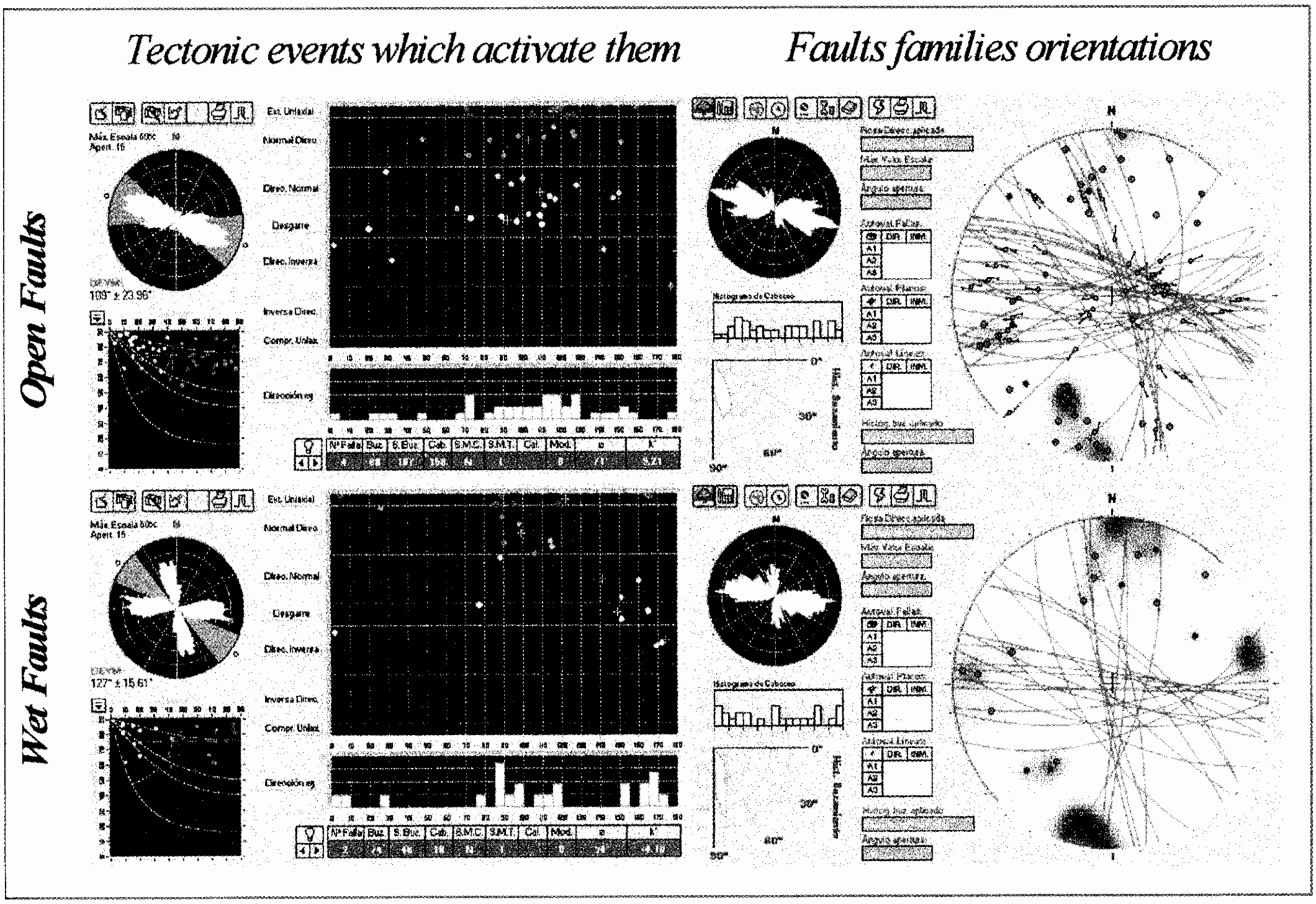

Figure 7. Fault families selection using different hydrogeological considerations.

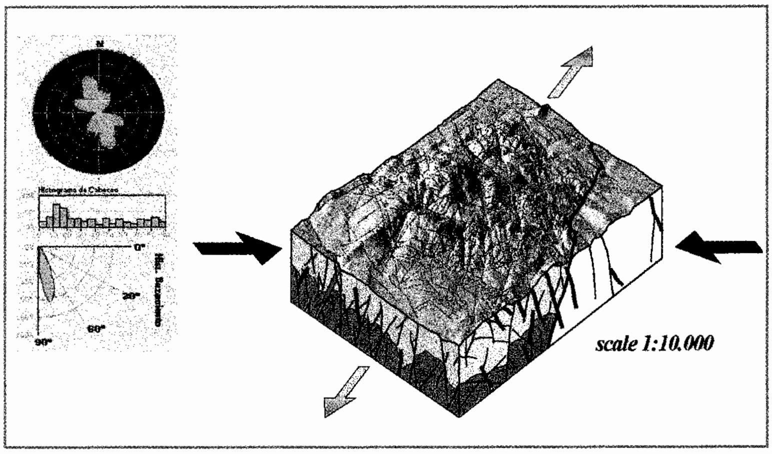

Figure 8. Fault families selection (i.e. faults with extensive character).

Family	A	B	C	D	E
pdf (T)	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Mean (m^2/s)	1.4E-9	1.77E-8	8.65E-9	8.43E-9	1.97E-8
Standard deviation	9.2E-10	1.28E-8	8.55E-9	7.38E-9	1.86E-8

Table 1. Fracture family transmissivity pdf and characteristic parameters.

Geometric analysis and simulation of the fracture network

The objective of this phase is to determine the geometric statistical distribution of each family, needed to construct the discrete fracture network model which represent the batholit, combining the available information: surface information (1:10,000 and 1:2,000) and deep information (S-16 log and gallery).

The orientation, size, spatial distribution and the fracture density of each family are defined using the DFP (Paredes, 1995) and FracMan codes. This characterisation was done in the S-16 borehole and El Berrocal mine gallery domain at two different scales: 1:10,000 y 1:2,000 (Paredes et al., 1997).

Several hypotheses were made to characterize geometrically the fractured medium:

- There are five fracture families, associated to various tectonical events, and so, to different stress tensors.
- The fractures are considered as disks, but they are simulated as regular polygons in 3D.
- Fractal behaviour of the fracture network is supposed, with the implications that this assumption has: fracture patron and fracture density. (One of the fractures analysis result (performed at scales: 1:2,000, 1:10,000, 1:500,000, 1:1,000,000 and 1: 4,000,000) is that there exists auto-similarity patterns in the fracture systems with morphologic representation (Paredes et al. 1997). This could indicates that the process that controls the Península Ibérica morph-structure is the more recent stress field and is scale independent).

As starting point the surface information is analysed adjusting a spherical probability density function (pdf) to the fracture orientations of each family (noted as pdf(α, δ β)). As result, two pdf were shown as the most appropriate: *univariated Fisher* (families A and C) and *bivariated Normal* (families B, D and E) (Table 2). This same analysis has been made with deep information (S-16 borehole) and with all data (surface plus deep information). In these cases the adjusted pdf varies perceptibly for families B, D and E in the sense that Fisher pdf is adjusted better than bivariated Normal for family B and bivariated Bingham better than bivariated Normal for family D and E.

In the second step some scalar pdf are adjusted to the traze size (surface information), using the obtained pdf for orientations, as *lognormal* function, *normal of log* and *Power Law.* The first one and the last one proved to be the best, according to the Kolmogorov-Smirnov test results. Nevertheless, the *Power Law* function is the one that obtained the best fit (significance degree always = 95 %), although its characterisation parameter (exponent) must be strictly superior to 3 (if not, the standard deviation would be negative, and this situation implicates a mathematical aberration). Starting from these functions, FracMan code tries to adjust them to define a pdf of the fracture radius, generating a predefined number of fractures according to these specifications and comparing them to the real data.

Because Box Fractal is the structural geometric model that was adopted, the fractal dimension mass must be calculated through the traceplanes at two different scales. That is why the HETERFRAC Menu of FracMan code is used, to realise a Box-Counting analysis. Once the fractal dimension of each family is calculated, using the Falconer´s hypothesis (Falconer, 1997) it is possible to infer the 3D fractal dimension mass needed to generate the fracture family in the space. And so the simulation support is characterised for every family at two cartographic scales.

Eventually, the fracture density must also be defined to generate a reasonable number of fractures in 3D. It is possible to use three different kinds of fracture densities in FracMan code: number of fractures; P_{32} density, defined like the ratio between the summation of all the fracture areas and the simulation region volume; and, finally, P_{33}, defined like the ratio between the summation of all the fracture volumes and the simulation region volume. However, only the P_{32} fracture density can be considered as invariant, in the sense that is independent of the generation region volume. For this reason, it has been the one that has been used for generating. The problem rest on the non-availability of this fracture density, and in the necessity to define how to obtain it from the measured fracture density within each survey (traceplanes $-P_{21}$ density- and S-16 borehole $-P_{10}$ density). Defining a linear relation between them, it is viable to infer P_{32} as $P_{32} = a \cdot P_{21}$ and $P_{32} = b \cdot P_{10}$, where ***a*** and ***b***

Pdf (α,β)	FAMILY A Fisher	FAMILY B Normal bivariated	FAMILY C Fisher	FAMILY D Normal bivariated	FAMILY E Normal bivariated
Mean pole (tr, pl)	190.9, 2.6	332.4, 3.3	223.4, 2.0	249.4, 2.2	286.7, 1.2
Parameter	K = 12.99	K_1 = 10.88 K_2 = 20.81 K_3 = 0.02	K = 17.45	K_1 = 6.07 K_2 = 18.29 K_3 = 0.27	K_1 = 15.38 K_2 = 19.58 K_3 = -0.31
1:10 000					
Pdf (L)	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Mean	175	206	163	92.8	222
Standard deviation	111	137	179	157	131
Pdf (L)	Power Law	Power Law	Power Law	Power Law	Power Law
Minimum	114	114	90	105	120
exponent	3.17	2.86	2.7	3.03	3.04
Fractal dimension	2.642	2.585	2.365	2.072	2.652
Real P_{21} [m^{-1}]	0.001612	0.001883	0.00119	0.0008854	0.002233
P_{32} [m^{-1}]	0.0020493	0.0026	0.002032	0.001614	0.003081
1:2 000					
Pdf (L)	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Mean	19	35.1	27.9	43	42
Standard deviation	12.8	23.3	29.1	19.2	28
Pdf (L)	Power Law	Power Law	Power Law	Power Law	Power Law
Minimum	12.2	18.6	17.7	40	23.2
Exponent	3.09	2.89	2.81	5.28	2.92
Fractal dimension	2.224	2.062	1.9414	1.4332	2.034
Real P_{21} [m^{-1}]	0.006667	0.008806	0.005617	0.0009362	0.007744
P_{32} [m^{-1}]	0.007947	0.009613	0.006505	0.0006885	0.009511

Table 2. Orientation, size, spatial distribution and fracture density.

are both real numbers. With these hypotheses all the P_{32} densities are determined, but those that come from the P_{21} are not comparable with those that come from the P_{10}, because they are reproducing different measure scales of the same reality.

Finally it was also necessary to build a sixth fracture family (family H) predefined as a subhorizontal family, because the posterior interference essays realised in the synthetic generations and designed to reach a similar hydraulic behaviour in the interconnected fracture network around the S-16 borehole showed that a family with conductive subhorizontal fractures was very important. However, the information level available was clearly insufficient for this purpose and it was indispensable to assume new several hypotheses for this reason:

- The fracture plunges are known, because de visu interpretation of the S-16 borehole core by Pardillo (1992), who identified 444 subhorizontal fractures (plunge ≤36º), from which 146, had possible water flow. Nevertheless, the fractures trends are not available, because the registered measures were not taken according to a co-ordinate reference system and they must be randomly assigned depending on the rose direction diagrams of the others families. This was made by means of the distribution of the whole number of H fractures among the knowledge of five fracture family trends, pondering them with the ratio defined as the number of A, B, C, D or E fractures over the sum of all of them. So, the adjusted spherical pdf is a Fisher function, with a dispersion parameter of 14,71 and the mean pole (19,5; 89.5)
- A pdf of the fracture radios must be also defined, according to the non-existence of trace length data associated to this new family. This situation was resolved using a Power Law function, because of its bigger characterisation simplicity (only needs one parameter, in this case exponent equal to 3.01), its capability to integrate the registered information at different scales and the best behaviour of this pdf with the other five fracture families.
- The fractal dimension was calculated using the DFP code (2,82) and not FracMan code (1995), because the available version of this last one can not operate with quasi-one-dimensional data (i.e. boreholes) for this purpose.
- The P_{32} volumetric fracture density was calculated according to the linear relation between it and P_{10} linear fracture density. Moreover, this P_{32} was correlated to depth, as a quadratic function (parabolic).

Stochastic generation of fractured medium

The stochastic fracture network simulation has been developed from the location of one point of the disks (centre or random point over the fracture surface) and the definition of disks sizes and orientation (Figure 9). In this phase each family has been hydraulically classified correlating the results of the hydraulic test carried out in the previous analysis, with the structural, petrological and emanometrical data. The final result of this phase are different realisations of disk set networks, which represent the conductive fractures that control the flow in the El Berrocal batholit (Figure 10) (Paredes et al., 1997).

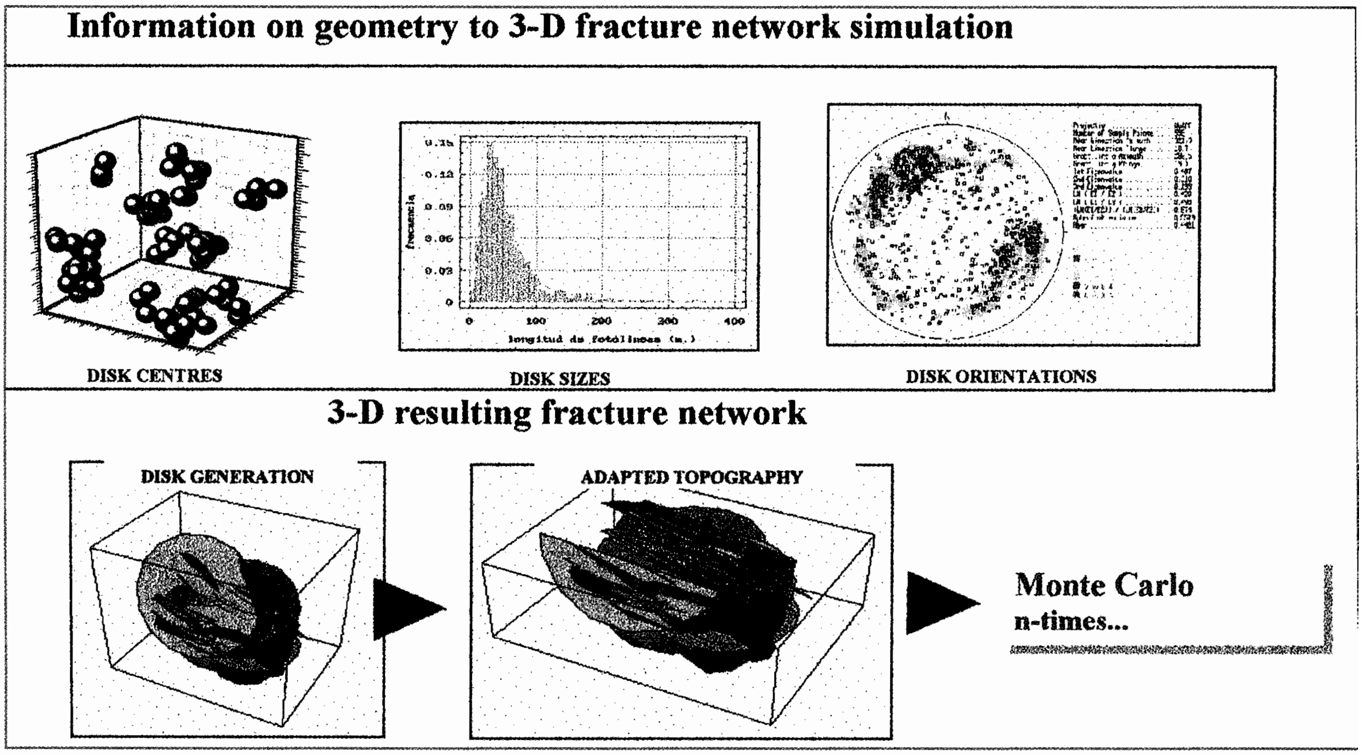

Figure 9. Stochastic generation of the fractured medium.

Figure 9 represents the 3-D fracture network generation processes. Each generation would be repeated n-times in the uncertainty analysis phase.

In Figures 10 and 11 are shown the results of two generations, previously defined by tectonic and geometric criteria, in a 3-D blocks that treat to represent the working scales 1:10,000 and 1:2,000. The likelihood degree has been tested positively with statistical, geometric and Baecher analysis. Using a colour code represents all the six fracture families: A blue, B red, C green, D turquoise blue, E khaki green and H violet.

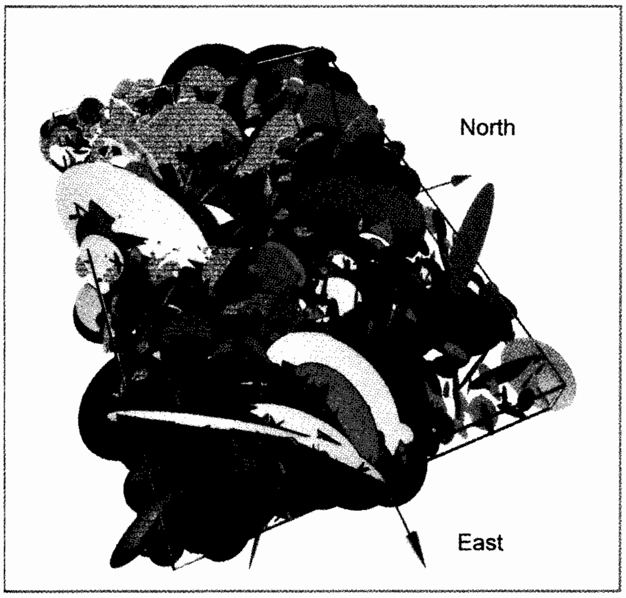

Figure 10. Fracture network at 1:10,000 scale.

Flow and transport simulation

Two different models have been developed: a discrete fracture model (DFN) and an equivalent porous media with individual fractures model (Elorza et al. 1997). In the DFN model each fracture network has a permeability distribution that defines the permeability of the whole domain. The conceptual FRACAS [15] approach has been implemented in the TRANSIN III (finite element code that simulates the flow and transport in 1D, 2D and 3D and includes inverse problem techniques) (Cacas, 1989).

The FRACAS code simulates the underground flow with discrete fracture networks but only resolves the stationary regime. It calculates the flow between two conductive fractures that intersect. Such is the final result that other system could substitute the interconnected fracture system defined as a tube system, which simulates the connections. This alter approach has been included in TRANSIN III.

The verification of this implementation has been carried out with different synthetic examples at local and regional scales. All of them consist basically of the sequence FracMan generation —> FRACAS conductive fracture network analysed —> TRANSIN III flow simulation. The results of one example are shown in the next Figures 12 and 13. Figure 12 (a) corresponds with the fracture network generated by FracMan and intersected by two synthetic boreholes, which represent the S-14 and S-18 boreholes (interference essays (ENRESA, 1996); (b) is another sight of (a); (c) is the conductive fracture network resolved with FRACAS and with the two synthetic boreholes; (d) is another sight of (c). In Figure 13 groundwater flow has been simulated in a rectangular parallelepipedic domain with

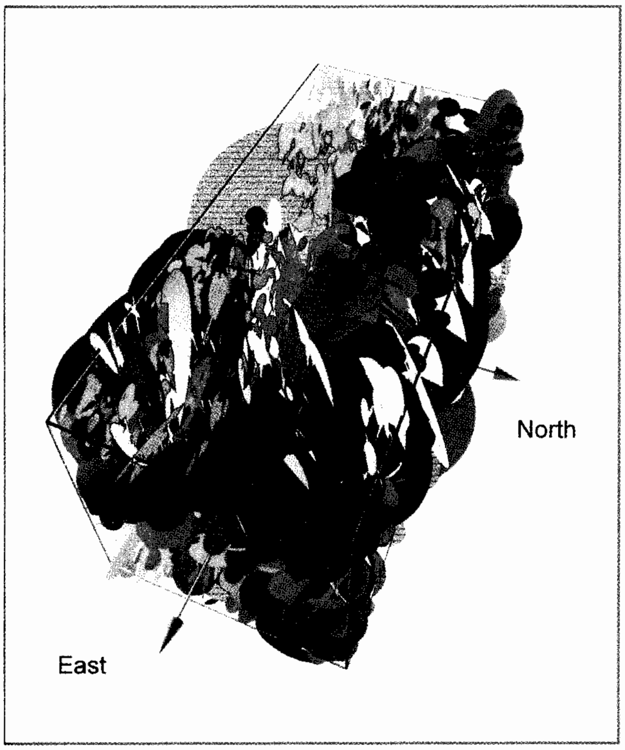

Figure 11. Fracture Network at 1:2,000 scale.

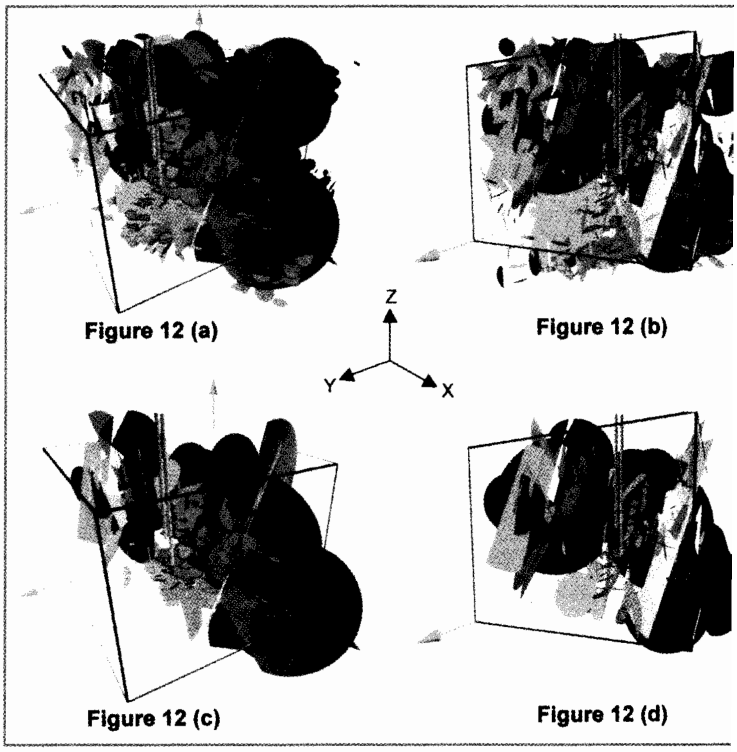

Figure 12. FracMan fracture network and FRACAS conductive fracture network.

null flow through its lateral faces and with an imposed gradient between its upper and lower faces. The piezometric distribution obtained permits to infer the imposed gradient and to know how the fracture network heterogeneity induces an irregular flow.

From those results the equivalent conductivity was calculated for every axis direction, starting from the flow rate between two perpendicular faces to the flow direction, with an imposed hydraulic gradient and null flow in the others faces. For this calculus the coupled FRACAS-TRANSIN is used again, modifying the boundary conditions to impose the hydraulic gradient in the correspondent faces and the null flow in the others. The temporal regimen is permanent, and it is not necessary an observation point for this reason.

The equivalent hydraulic conductivity components was calculated using the initial transmissivity parameters (Table 1) and also from the estimated transmissivities deduced from the interference essay interpretation. The equivalent conductivity anisotropy is very similar in both cases. The results are exposed in Table 3.

Equivalent conductivities	Initial transmissivities	Estimated transmissivities
K north-south	9.556 E-13	3.336 E-10
K east-west	1.053 E-12	4.358 E-10
K vertical	4.432 E-12	8.900 E-10

Table 3. Equivalent conductivities (m/s).

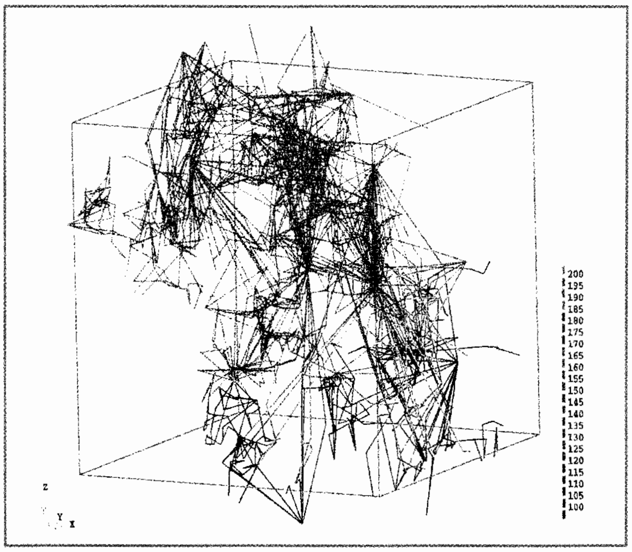

Figure 13. TRANSIN III flow model. Calculated piezometric levels.

It was possible to deduce with both models (DFN and continuum medium) that the horizontal hydraulic conductivity components (north-south and east-west) are smaller than the vertical component, and with the same magnitude order.

It would be also very interesting to compare the medium equivalent conductivities and the fracture family hydraulic conductivities with the El Berrocal batholit permeabilities at different spatial scales (Guimerà et al. 1995) (Figure 14).

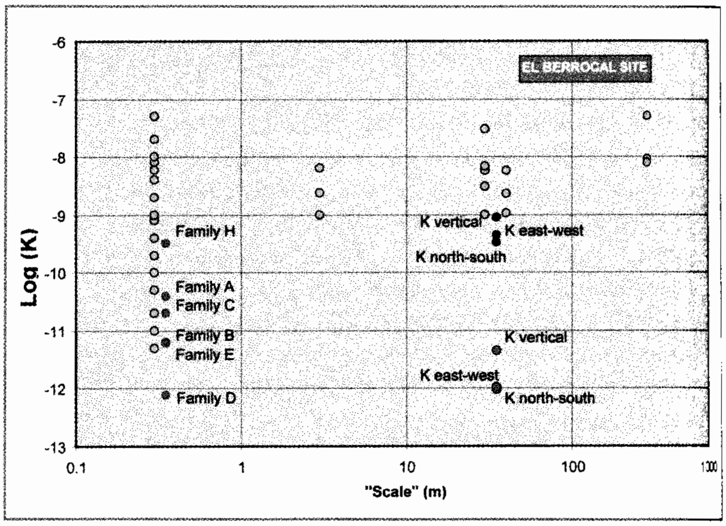

Figure 14. Comparison of scale dependent hydraulic conductivities (m/s).

The conductive network fracture family hydraulic conductivities are in the El Berrocal variation range, but in the inferior values. Moreover, the calculated equivalent conductivities that correspond to the FracMan transmissivities are smaller than the continuum medium permeabilities in three or four magnitude orders.

For these reasons, it seems appropriate not to use the DFN assigned transmissivities to calculate the continuum medium equivalent conductivities, except if they are recalibrated using hydraulic essays. However, it is very useful to employ the DFN assigned transmissivities such us methodology to define the continuum medium conductivity anisotropy.

SUMMARY

Results obtained up to now confirm the great possibilities of the proposed methodology to characterise and simulate groundwater flow and transport in a fractured media. It has been possible to integrate structural and petrologic techniques with the classical hydrogeologic ones. It has been developed a multidiscipline methodology, which is applicable in Performance Assessment Analysis of deep geological repositories and, in general, in Safety Analysis of those waste repository sites located in fractured rocks.

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