Structural geology and geophysics as a key to build a hydrogeologic model of granite rock to support a mine

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Abstract. A methodology developed for low permeability fractured media has been applied to understand the hydrogeology of a mine excavated in a granitic pluton. This methodology consists of (1) identifying the main ground water conducting features of the medium, such as the mine, dykes and large fractures, (2) implementing them as discrete elements into a three-dimensional numerical model, and (3) calibrating them against hydraulic data (Martínez-Landa and Carrera, 2005b). The key question is how to identify preferential flow paths in the first step. Here, we propose a combination of several techniques. Structural geology, together with borehole samples, geophysics, hydrogeochemistry and local hydraulic tests aided in locating all structures. Integrating these data yields a conceptual model of the site. A preliminary calibration of the model was performed against short-term (less than a day) pumping tests, which helped in the characterization of some fractures. Their hydraulic properties were then used for other fractures that, according to geophysics and structural geology, belonged to the same families. Model validity was tested by blind prediction of a long-term (4 months) large-scale (1 km) pumping test from the mine, which yielded an excellent agreement with observations. Model results confirm the sparsely fractured nature of the pluton, which has not been subjected to glacial loading-unloading cycles and whose waters are of Na-HCO$_3$ type.

1 Introduction

Low permeability fractured media play a relevant role for enhanced geothermal energy and waste management. Their study is hampered by the contrast between conductive fractures and nearly impervious matrix, which makes it important to account for heterogeneity. Interest and difficulty have motivated a large number of investigation sites, notably in granites, around the world: Stripa (Rouleau and Gale, 1985; Long et al., 1991), Äspö (Tsang et al., 1996; Svenson, 2001b) and Forsmark (Stephens et al 2015, Seroos and Follin 2014) in Sweden; Grimsel in Switzerland (Davey Mouldon et al., 1993; Martinez-

Landa and Carrera, 2005b): Fanay-Augères in France (Cacas et al., (1990)); Mirror Lake in New Hampshire, USA (Shapiro and Hsieh 1991; Day-Lewis et al., 2000); Olkiluoto in Finland (Ko et al, 2015), among others. Most sites are located in zones affected by the last glaciation, which caused severe deformational and fracturing. Instead, sites in Southern Europe have suffered much less tectonics. These include El Berrocal pluton (Guimerà et al., 1995) or Ratones mine (Martinez-Landa

5   et al., 2004), both in Spain. This article is based on work conducted at the Ratones Mine, in Cáceres province of Spain (Figure 1), thereby contributing to improve the knowledge on this type of media.

A generally accepted methodology to model low permeability fractured media has not emerged. Several approaches have been used, but they can be viewed as combinations of two extremes: continuous medium and discrete fracture networks. The former assimilates the domain to a porous medium, which includes the effect of fractures. The hydraulic conductivity field is

10 estimated by geostatistical techniques conditioned to actual measurements of hydraulic conductivity and pressure at observation points (Neuman, 1988; Carrera et al, 1988; Gomez-Hernandez et al., 1999; Day-Lewis et al., 2000; Vesselinov et al., 2001; Svenson, 2001a; Ando et al., 2003; Illman, and Tartakovsky, 2005; Illman, et al., 2009; Selroos and Follin, 2014; Ko et al., 2015; Illman, 2014).). The latter represent the medium by means of fracture networks that are generated statistically. This approach is based on the assumption that fractures behave as preferential flow paths (Long et al., 1987;

15 Cacas et al., 1990; Dershowitz, 1984; Dershowitz et al., 1991; Castaing et al., 2002). A further sophistication from fracture networks models consists of channel networks models, which represent only the conductive portions of the fractures planes (Moreno and Neretnieks, 1993). We have been using an intermediate, mixed, approach that consists of representing matrix and minor fractures as equivalent, possibly heterogeneous, porous medium and simulating deterministically the hydraulically dominant fractures (Martinez-Landa and Carrera 2005b). The main drawback with this approach is that these dominant

20 fractures need to be identified and characterized. Strict characterization is only possible in intensely tested environments. Therefore, one may question the validity of such approach when one needs to predict flow at longer scales. This is especially worrying in view of the apparent ubiquity of scale effects.

The scale effect refers to the apparent increase of hydraulic conductivity or transmissivity as the rock volume increases (Clauser, 1992; Illman and Neuman 2000; Vesselinov et al., 2001). Explanations for scale effects are multiple. Illman et al.,

25 (2004) elaborated a thorough discussion about scale effect and its origin, pointing to other issues such as poorly developed wells (Butler and Healey, 1998) and turbulences in the boreholes (Lee and Lee, 1999). Guimerà et al., (1995) argue that long term pumping tests are performed purposefully in the most conductive intervals, thus implying that they are not representative. Other authors (Day-Lewis et al., 2000; Meier et al., 1998; Sanchez-Vila et al., 1996) attribute it to the connectivity among structures. Certainly, the hydraulic conductivity derived from interpreting pulse tests yields information

30 about the closer vicinity of the borehole. These results in marked differences between values associated to intervals that intersect any conductive structure and those that are open only in the matrix (Martinez-Landa and Carrera, 2005a). In cross-hole tests, pumping must be carried out from intervals in high conductivity zones to maintain a significant flowrate for a long time, but pumping also affects points located in the matrix. If the interpretation of the tests does not take into account the existence of conductive fractures, their effect will lead to a high effective hydraulic conductivity. As it turned out, Martinez-

Landa and Carrera (2005) found that this effective conductivity was appropriate for predicting large-scale tunnel inflows. Yet, such effective conductivity was far larger than any average of small scale hydraulic test, the vast majority of which were sparsely fractured, hence the scale effect.

The above makes it clear that a good representation of fractured media requires identifying the main water conducting features. We contend that this is possible by integrating different types of information (geology, geophysics, hydrochemistry and hydraulics). Accounting for heterogeneity makes it possible to use the models for non-trivial predictions under conditions different from those during calibration. This has been done in previous works (Carrera et al., 1990; Carrera et al., 1993, Carrera ad Martinez-Landa, 2001) but always at scales similar to those during calibration. Still, the best indicator of model robustness lies in its ability to predict changes in flow conditions at scales different from those of calibration. We conjecture that structural geology and geophysics can be used to identify large water conducting fractures that have not been characterized by direct hydraulic tests. By assigning to these the hydraulic parameters of similar fracture types that have been characterized, we would be effectively extending the model scale and potentially modelling a large volume of rock.

The objective of this article is threefold. First, we present a methodology based on the above conjecture and check its predictive capability. Second, we discuss the scale effects observed at Ratones mine. Finally, we contribute to improving the knowledge of low permeability, fractured media at the Iberian Peninsula, in Southern Europe.

To accomplish these objectives, field datasets from the Ratones Mine (study of the hydrogeology around an old uranium mine excavated in a granitic pluton) are used. Datasets proceed from geochemical, geologic-structural, geophysics and hydrogeological studies that aid in identifying the main structures (heterogeneities), including their position, direction, dip and extent. A three-dimensional numerical model is constructed then, where the matrix and minor fractures are treated as an equivalent porous medium and the identified fractures are implemented as two-dimensional planes embedded in the matrix. This numerical model is then used to calibrate cross-hole tests and to predict the long-scale pumping tests from the mine.

2 Test site

2.1 Geological characterization

The Albalá Granitic Pluton is located in the southwest sector of the Iberian Massif (Central-Iberian Zone of Julivert et al., 1972). The pluton is a concentrically zoned body, elongated in an N-S direction, with porphyric biotite granites in the rim and fine-grained two-mica leucogranites in the core (Fig. 1). Ratones is an abandoned uranium mine, located in the central aureoles of the pluton. Fault zone architecture in the Mina Ratones area has been established on the basis of field geology, structural analysis, seismic experiments, drill cores (SR1 to 5) and sonic well-log data (Escuder Viruete and Pérez-Estaún, 1998; Carbonell et al., 1999; Escuder Viruete, 1999; Jurado, 1999; Jurado, 2000; Pérez-Estaún, 1999; Martí et al., 2002). Surface geology was mapped at 1:1000 scale in a zone that include the block where the seismic tomography survey was to be conducted. The resulting maps include granitic facies, dykes, ductile-brittle shears, fault zones and granitic soil cover (lehm). The 3-D fault distribution obtained for this area is shown in Fig. 2.

The post-Variscan structural evolution of the Albalá Granitic Pluton has been established on the basis of fault kinematics and palaeostress analysis in superficial outcrops (Escuder Viruete and Pérez Estaún 1998; Pérez Estaún et al. 2002). This evolution includes three episodes of brittle deformations related to different stress-field configurations, which cut and reactivate ductile and ductile-brittle late-Variscan structures:

5   - The first episode is extensional and produces the intrusion of Jurassic sub-vertical diabasic dykes, aligned following a NNE–SSW trend. The constant trend of these dykes at regional scale indicates that σ_3 was sub-horizontal and WNW–ESE to NW–SE directed.

- The second episode is characterized in the Mina Ratones area, by the development of strike-slip faults with E-W direction and kilometer thickness.

10   - The third fracturation episode, post-Hercinian, produced the partial reactivation of the previous WSW-ENE to E-W structures and dykes as normal and normal-slip faults. (Escuder Viruete and Pérez Estaún 1998; Pérez Estaún et al. 2002).

The main identified structures in the Ratones area (Fig.1 and 2):

- North Fault (NF); N70ºE to N80ºE trend and 55º-65º S dip, diminishing with depth to 30º-40º.

15   - South Fault (SF); N64ºE to N78ºE trend and 68 and 82º N dip. Subvertical set of parallel fractures, forming a fragile transcurrent shear zone.

- Mineralized 27 and 27' dykes; subparallel and subvertical structures, with a thickness of 0.4-1.8m, composed of a quartz breccia, cemented by sulphides (Escuder Viruete et al., 2003a; Escuder Viruete et al., 2003b).

- Damage zone; defined by small faults and kinematically related fracture sets and joints. The dikes and other

20   fractures (as NF and SF) are hosted in an extensively fractured damage zone of hydrothermally altered granite (fractured belts).

Other relevant brittle structures of minor size are:

- The 474 and 474' Faults; are two high-dip subparallel structures that trend N064ºE to N076ºE. Both structures connect toward the W with the 27 dyke.

25   - The 285 brittle structure; is also a sinistral strike-slip fault with a N052ºE to N060ºE trend and subvertical dip.

Faults 474 and 285 are younger than the NF; they cut and displace it, so that remains hydraulically disconnected.

The last deformational phase gives us that the stress state at the recent evolution was E-W direction. As a result, the North and South family fractures are oriented in the most favourable direction, which makes them the best candidates for flowing flow structures.

30   **2.2 Hydrogeochemical characterization**

Rainwater entering into the rock-mine system is saturated in atmospheric O_2, which causes (1) the oxidation of metal sulfides present in the dykes and mineralized fractures, (2) precipitation of metal oxy-hydroxides and (3) the addition of acid to the

medium. Acidic water causes dissolution of carbonates in fissure fillings, buffering the pH of mine water, and promoting the precipitation of metals released by sulfide oxidation as metal carbonates (Fig. 3).

In parallel, plagioclase weathering promotes kaolinites precipitation in the shallower areas. The albite becomes Smectites clays, giving sodium bicarbonate waters in the deeper areas (400-500m deep, borehole SR5) with transit times of tens of

5   thousands of years (16000 years dated with noble gases).

These sodium bicarbonate waters are typical of granitic water with relatively high residence times. Groundwater circulating through granites in the Hesperian Massif is sodium bicarbonate type, which may be significant for the waste disposal in this type of rocks (Gomez 2002, Gomez et al, 2006). This is different from the chemical compositions of groundwater in granitic formations in other parts of the world as in the Hercinian granitic in the Chardon U mine in France (Beaucaire et al., 1999)

10   and in the Canadian (Frape et al., 1984) and Scandinavian (Blomqvist 1999) Shields, where the major ions are chlorides and sodium.

Hydrogeochemical studies aid to identify water conducting fractures. Water flowing through fractures is chemically marked by water-rock interaction along the flow-path within the medium (Perez del Villar et al., 1999; Gomez et al., 1999; Gomez et al., 2001; Gomez, 2002). This enables to identify some fractures and potential connections. Fig. 4 shows an example of the

15   diagraphies and records of a multiparametric device (temperature, electrical conductivity, pH, redox potential, dissolved oxygen) in borehole SR1, down-gradient the mine. These data are used to identify the intersection with dyke 27, where water flows from the mine, as indicated by chemical parameters and changes in the upwards velocity of flow within the borehole (flowmeter log).

2.3 Hydraulic characterization

20   As discussed above, geology and geophysics give an insight into the physical configuration of the fracture network. Structural geology and geochemistry help in identifying which of those fractures may be water conducting. Simple borehole hydraulic tests (pulse tests, slug test, constant head tests), provide the location of these structures and their hydraulic conductivity. Large scale connectivity can be identified by means of cross-hole tests and hydrochemistry, if there is a chemical tracer in the water.

25   The hydraulic conceptual model of the system is largely based on the hydraulic extent of the fractures and their connectivity. This is why a hydraulic testing survey was designed. Different types of measurements were used:

   a) Development pumping, carried out in all boreholes SR, consisted of pumping with open borehole to withdraw all drilling materials.

   b) Chemical sampling pumping of NF in borehole SR2, of SF in borehole SR4 and some intervals of SR5. Time,

30   flowrate and interval pressure were measured. These data were used as hydraulic test data.

Also, specifically designed hydraulic tests have been conducted:

c) Pulse, slug and constant head single hole tests were conducted at short intervals in boreholes SR3, SR4 and SR5. The three tests were performed between two packers separated at a constant distance and a system of pipes and valves to allow the injection or extraction of very low water volumes with high precision (Ortuño et al., 2000).

d) Cross-holes tests. Three of them were planned. For this purpose, the boreholes were divided into intervals, which were hydraulically isolated by packers. The position of packers was determined to isolate the structures that had to be tested. Each interval was equipped with a pressure outlet and a water injection/extraction point.

    d.1)   North test: pumping interval S14-1 (first interval of S14 borehole, numbered from bottom to top). Was designed to characterise the dyke 27 upgradient the mine.

    d.2)   East test: pumping interval SR3-1, which intersects the NF, like SR2-2. After pumping for 9 days, there were no responses at any observation point. After interpreting the seismic profiles in a subsequent stage (Pérez-Estaún, 1999; Martí et al., 2002) it became apparent that there is no possible hydraulic connection between these points because the NF is cut and displaced by Faults 474 and 285 (see Fig. 2).

    d.3)   South test: pumping interval SR4-1. Located in the discharge zone of the mine, pumping within the South Fault (SF). This was the only test in which all observation points reacted to the pumping.

The hydraulic characterisation begins with a single hole test (pulse, slug, and constant head). The calibrated parameters give insight into the transmissivity field around the boreholes, and enable to identify the most conductive intervals. Cross-hole tests are then conducted in these ones to identify connectivities.

All hydraulic tests have been interpreted with Theis' method (Theis, 1935). This model assumes that the medium is homogeneous and isotropic, thereby integrating the effect of heterogeneities into the matrix. In cross-hole tests, these preliminary interpretations are done separately for each recorded drawdown curve, which yields a couple transmissivity-storage (T-S) for each observation point (Fig. 5). Note that estimated T's range over one order of magnitude, whereas the estimated S's, which are presumed nearly constant, range over almost five.

These highly variable storativities provide information about the connectivity between pumping and observation points through fractures. A good connection is reflected in a fast response (i.e., high diffusivity, T/S). As discussed in the introduction, the estimated T reflects large scale conductivity. Therefore, the estimated storage coefficient will be low for observation points well connected to the pumping interval (Meier et al, 1998). The dykes and NF and SF are accompanied by systems of minor fracturing that form part of a higher transmissivity zone situated around these structures. Points S10 and SR1-3, which display the lowest S values (Fig. 5) are connected to the pumping point through these fracturing belts. In the 3D numerical model, this connectivity has been simplified by simulating fracture planes referred to as "fracture S10" to connect point S10 to the pumping interval SR4-1, and "fracture SR1-3" to connect point SR1-3 to SR4-1.

The remaining observation points have as lower response (i.e. higher S) to the pumping. Observation points S5 and SR1-2 intersect the dykes 27' and 27, respectively. A priori, it could be thought that these should have a better response to the pumping. Drawdowns between both points are limited by the influence of the mine cavity, which acts as a constant head boundary.

3. Numerical model

A three-dimensional numerical model has been constructed to interpret the South cross-hole test, taking into account the water conducting features. Fig. 6 displays a plan view of the features introduced in the model. The granitic matrix has been divided into two zones, depending on the degree of characterisation of the whole area. On the one hand, the internal matrix

5 represents, in detail, all the fractures identified around the mine in great detail. On the other hand, the external matrix does include all the structures (because they have not been identified). The external matrix has larger hydraulic conductivities than the internal matrix, because it includes the effect of the unidentified fracturing.

The model reaches up to 600m depth to include all measurements (SR5 borehole reached 500m depth) and all units. The most shallow layer is formed by two-dimensional elements and represents the lehm, which consists of altered, disaggregated

10 and washed granite (much like granitic sand) with a high hydraulic conductivity. This layer drains rapidly in humid seasons, so that carries no water in dry seasons. The altered unit reaches 20-m depth, according to geophysics and borehole samples. It is highly weathered, but conserves the granite structure. Its hydraulic conductivity and porosity are higher than those of unaltered granite, due to the decomposition of feldspar. The fractured granitic unit could be identified by geophysics, and corroborated by the hydraulic characterization of a 500m deep borehole (Fig. 7), which was drilled in the matrix, far from

15 the mine. At this depth, there is a reduction in hydraulic conductivity, which was almost constant up to this horizon. In this unit, the granite does not behave like the altered unit, but its fracturing index is high and, therefore, its effective hydraulic conductivity is higher than the non-deformed granite. Finally, the non-deformed granitic unit, contrarily to the other units, has lower fracturing index and effective hydraulic conductivity.

Both, the matrix effective hydraulic conductivity and specific storage, decrease with depth. The upper units (lehm and

20 altered granitic unit) are treated as separated hydraulic conductivity zones. A constant hydraulic conductivity is also adopted in the bottom portion of the model (below 350m) (Fig. 7). The lineal relationship proposed by Stober (1997) is adopted in between. Storativity drops linearly by one order of magnitude between the surface and the bottom (600m deep), based on the results obtained from hydraulic tests.

A zoom in the central part of the model (Fig. 6, right) shows the structures included explicitly in the model. Both matrix

25 zones and fractured belts are simulated by means of three-dimensional elements; fractures are reproduced with two-dimensional elements (lines in the figure); finally, boreholes are introduced as one-dimensional elements (points in the figure).

Structures included in the model (Fig. 8) through two-dimensional elements preserve their azimuth, dip and interception points with the boreholes. In general, they are Subvertical, except for the NF, which is leaned in the surface and cutted,

30 displaced and tilted by fractures 474 and 285. The mine is also treated with two-dimensional elements, because it corresponds to the mining of part of dykes 27 and 27' (planar structures).

3.1 Model calibration of the cross-hole south test

Once the conceptual model is built and the numerical model implemented, a cross-hole test conducted downstream the mine (South test) is calibrated. As initial parameters, those obtained from interpretation of the test with Theis' model are taken. The interpretation model of the South cross-hole test works with drawdowns. That is, initial drawdowns are zero and all prescribed fluxes, but the pumping, are set to zero. The model boundaries have been placed at a distance large enough to impose a zero drawdown condition. Table I summarises the results obtained alter calibrating the test.

Table 1: Parameters obtained alter calibration of the South cross-hole test. Units are written in m and sec, but the right dimensions (associated to the scale of each structure in the model) are explicitly defined. Transmissivity values indicate which it changes with depth: the first value holds for the upper 250m (constant parameter), the second value applies to the bottom of the domain –both for the matrix and the fractured belts. The storativity of the "fractured belts lehm" is negligible in the model ($1.0 \cdot 10{-}30$), to prevent the artefact that water might be withdrawn from that zone.

PARAMETERS (m and s)	DIMENSIONS	TRANSMISIVITY	STORATIVITY
Matrix	3D	$2.1 \cdot 10^{-10} / 7.7 \cdot 10^{-14}$	$1.1 \cdot 10^{-8}$
Fractured Belts	3D	$1.5 \cdot 10^{-8} / 1.5 \cdot 10^{-10}$	$1.0 \cdot 10^{-7}$
Mined Dykes	2D	0.1	$2.7 \cdot 10^{-3}$
Dykes	2D	$6.4 \cdot 10^{-7}$	$1.0 \cdot 10^{-7}$
S10 Fracture	2D	$1.07 \cdot 10^{-5}$	$1.0 \cdot 10^{-7}$
285 Fracture	2D	$2.0 \cdot 10^{-5}$	$1.0 \cdot 10^{-7}$
South Fault	2D	$1.9 \cdot 10^{-5}$	$1.0 \cdot 10^{-7}$
SR1·3 Fracture	2D	$1.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$
Lehm	2D	$1.8 \cdot 10^{-5}$	$3.6 \cdot 10^{-3}$
South Fault-Maderos Str.	2D	$1.8 \cdot 10^{-7}$	$1.7 \cdot 10^{-4}$
S10 Borehole	1D	1	$4.3 \cdot 10^{-6}$
S5 Borehole	1D	1	$4.3 \cdot 10^{-6}$
SR4·2 Borehole	1D	1	$4.3 \cdot 10^{-6}$
Altered Unit	3D	$2.6 \cdot 10^{-9}$	$4.3 \cdot 10^{-6}$
Fractured Belts Lehm	2D	$1.9 \cdot 10^{-4}$	$1.0 \cdot 10^{-30}$

DIMENSION--> 1D: K ($m \cdot s^{-1}$), Ss (m^{-1}); 2D: T ($m^2 \cdot s^{-1}$), S (--); 3D: K (m·s-1), Ss (m-1)

Fig. 9 represents the resulting fits. Pumping point is SR4-1, intercepting the SF. Observation points S10 and SR1-3 respond rapidly to the stress, since they are connected to the pumping point through small structures that form the fractured belts (simplified in the model as fracture S10 and fracture SR1-3), which intercept the SF. The remaining observation points are not that well connected with the pumping point. PM is the mine well, whose response is completely damped by this.

5   Observation points S5 and SR1-2 cut dike 27' and 27, respectively, close to the mine.

The pumping withdraws water mainly from the superficial layer (lehm), draining it through the bed of Maderos stream, where water flows sub-superficially. Also, water comes from the mine and the altered granitic unit through the fractures (SF, fractured belts, dykes) towards the pumping point.

4 Scale effect

10   Fig. 10 represents the hydraulic conductivities obtained from all hydraulic tests as a function of the scale. Transmissivities derived from the tests are divided by the length of the pumped interval to convert them into conductivities. The scale of the test is determined by the rock volume affected by each test; it can range between a few centimetres (pulse tests) to some 10's of meters (cross-hole test SR4-1).

As commented above, the tested intervals do not coincide in all types of tests. In the case of pulse, slug and constant head

15   tests, they were conducted sequentially with the same interpretation. But they do not coincide with packed off intervals for the cross-hole tests, which were chosen so as to isolate the main structures from the matrix and minor fractures. However, it is still possible to compare the calibration parameters with the results of homogeneous and isotropic models (interpreted before using Theis model), since larger scale tests also involve the rock volume of lower scale tests.

The dispersion of hydraulic conductivity values for each test diminished with the scale, due to the fact that, when the

20   medium is treated as homogeneous, it includes the hydraulic conductivities of the main structures in the effective conductivity, i.e. it is more homogeneous.

The right part of Fig. 10 shows the hydraulic conductivity values obtained after interpreting the South cross-hole test with a three-dimensional numerical model. This 3D model represents the main features of the medium heterogeneity in an explicit way (fractures, mine and different units of the granite, depending on its hydraulic behaviour). In the next section, the

25   numerical model is presented and their results discussed, but it is included here to compare these results from the perspective of scale effect. Points represented in the Fig. 10, for this cross-hole test, do not represent different results at different observation points, but the conductivity of the main fractures, fracturing belts, altered unit, lehm and matrix. Fracture transmissivities are transformed into conductivities by assigning them a unitary width (dividing by interval lengths). This results in larger conductivity values for the fractures and dykes, whereas the lower values correspond to the matrix elements,

30   whose conductivity depends on the fracturing index.

In sum, the lower values of hydraulic conductivity are associated to pulse tests for points situated within the matrix. These values are consistent with the conductivity estimated for the matrix in 3D heterogeneous model. The increase in hydraulic

conductivity with scale is due to the contribution of fractures to the effective conductivity when interpreting the tests by means of homogeneous models.

5 Blind prediction

A four month pumping test from the mine was carried out with an average flowrate of 0.0025 $m^3 \cdot s^{-1}$. All boreholes were used as observation points (Fig. 11). As for the interpretation of the South cross-hole test, all observations have been introduced as drawdowns calculated from the measurements registered prior the start of the pumping (assumed steady state). The model adopted the calibrated parameters of the analysis of the SR4·1 cross-hole test, and those obtained from the hydraulic characterization for structures not involved on this cross-hole tests. Fractures not affected by any test were assigned the transmissivities of characterized fractures that belonged to the same family, according to structural analysis. Results of the blind prediction (i.e. without calibration) are shown in Fig. 11.

Overall the fit of this blind prediction is excellent. Despite this, it seems that the calculated specific yield for the South cross-hole test model is too high. It can be due to the fact that the whole hydraulic characterization of the zone was done during the winter season and within a wet interanual cycle, so that the entire zone was fully saturated. In the prediction, it can be observed that most of the water comes from the lehm, which is a very conductive layer and has a high specific yield ($3.6 \cdot 10^{-3}$), whilst the altered unit specific yield is set at $4.6 \cdot 10^{-6}$ m^{-1}. The mine pumping was carried out in summer, when piezometric heads are lower and the upper units are unsaturated.

A model calibration has also been completed, but it is not shown, to verify this hypothesis. Numerical results tend to reduce the storage coefficient of the lehm ($4 \cdot 10^{-5}$) and to increase the specific yield of the altered unit ($1.3 \cdot 10^{-4}$ m^{-1}). This artefact is needed to be able to withdraw water from the altered unit, which is the actual storage unit in dry periods.

6 Discussion and conclusions

The main objective of this work has been to demonstrate that structural geology and geophysics techniques, together with hydrochemical and hydraulic data, can help in identifying the main fractures that conduct most of the groundwater flow. Values of transmissivity were estimated at different scales by considering the medium as homogeneous. When plotting these values against the representative field scale we observed a progressive increment of transmissivity with the scale. This scale effect can be attributed to the main fractures because all observations can be explained by incorporating such dominant fractures explicitly into the model. In fact, this model yielded an excellent fit to a 4 months long pump test that provoked responses in all observation points.

The fact that such a long pump test was predicted using only short term (less than a day) tests supports both the use of seismic geophysics and structural geology to identify the dominant fractures and their explicit incorporation into the groundwater flow model (mixed approach).

Results also confirm the conjecture that Southern European granite plutons display low hydraulic conductivity. This, together with the low aggressivity of their sodium bicarbonate groundwater makes them appropriate for hosting nuclear waste.

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References

Ando K., Kostner, A. and Neuman, S.P.: Stochastic continuum modelling of flow and transport in a crystalline rock mass: Fanay-Augères, France, revisited, Hydrogeol. J., 11, 521-535, 2003.

Barker, J.A.: A generalized radial flow model for hydraulic tests in fractured rock, Water Resour.Res., 24(10), 1796-1804, 1998.

Beaucaire, C., Gassama, N., Tresonne, N., and Louvat, D. :Saline groundwaters in the hercynian granites (Chardon Mine, France): geochemical evidence for the salinity origin, Applied geochemistry, 14(1), 67-84, 1999.

Berkowitz, B.: Characterizing flow and transport in fractured geological media: A review, Advances in Water Res., 25: 861-884, 2002.

Blomqvist, R.: Hydrogeochemistry of deep groundwaters in the central part of the Fennoscandian Shield, Geolqgical Survey of Finland, 1999.

Bucher, K., and Stober, I.: Fluids in the upper continental crust, Geofluids, 10(1-2), 241-253, 2010.

Butler, J.J. and Healey, J.M.: Relationship between pumping-test and slug-test parameters: scale effect or artefact?, Ground Water, 36(2), 305-313, 1998.

Cacas ,M.C., Ledoux, E., De Marsily, G., Tillie, B., and Barbreau, A.: Modeling fracture flow with a stochastic discrete fracture network: calibration and validation: 1. The flow model, Water Resour.Res., 26(3), 479-489, 1990.

Carbonell, R., Martí, D. y Trygvason, A.: Estudios Geológico-Estructurales y Geofísicos en Mina Ratones. Informe Final: Geofísica, Proyecto Ratones, ENRESA Internal Report: 10·CJA·IF·02, 1998.

Carbonell, R. y Perez-Estaún, A.: Estudios geológico-estructurales y geofísicos. Tomo II: Caracterización sísmica del entorno de mina Ratones. Proyecto Ratones, ENRESA Internal Report: 10·CJA·IF·03, 1999.

Carrera, J. and Heredia, J.: Inverse Modeling of the Chalk River Block, HYDROCOIN LEVEL 2/Case5A. NAGRA TB 88-14, 117pp, 1988.

Carrera, J., Heredia, J., Vomvoris, S., and Hufschmied, P.: Modeling of flow with a small fractured monzonitic gneiss block, Hydrogeology of Low Permeability Environments, International Association of Hydrogeologist, Hydrogeology: Selected Papers, vol 2, S.P. Neuman and I. Neretnieks, eds. Hannover: Heise, pp. 115-167, 1990.

Carrera, J., Mousavi, S.F., Usunoff, E., Sanchez-Vila, X., and Galarza, G.: A discussion on validation of hydrogeological models. Reliability Engineering and system safety, 42, 201-216, 1993.

Carrera, J. and Martinez-Landa, L.: Mixed discrete-continuum models: a summary of experiences in test interpretation and model prediction, Dynamics of Fluids in Fractured Rock, Geophysical Monograph, AGU, 122: 251-265, 2000.

Castaing C., Genter, A., Bourgine, B., Chilès, J.P., Wendiling, J. and Siegel, P.: Taking into account the complexity of natural fracture systemens in reservoir single-phase modelling, Journal of Hydrology, 266: 83-98, 2002.

Clauser C.: Permeability of crystalline rocks. *EOS Trans AGU*, 73(21), 233-238, 1992.

Davey Mauldon,A., Karasaki, K., Martel, S.J., Long, J.C.S., Landsfield, M. and Mensch, A.: An inverse technique for developing models for fluid flow in fracture systems using simulated annealing, Water Resour.Res., 29(11), 3775-3789, 1993.

Day-Lewis, F., Hsieh, P.A. and Gorelick, S.M.: Identifying fracture-zone geometry using simulated annealing and hydraulic-connection data, Water Resour.Res., 36(7), 1707-1721, 2000.

Dershowitz, W.S.: Rock Joint System. Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, Mass, 1984.

Dershowitz W.S. Wallmann, P., Geier, J.E., and Lee, G.: Discrete Fractured Network Modeling of Tracer Migration Experiments at the SCV Site, SKB Report 91-23, Swedish Nuclear Power and Waste Management Co, Stockholm, Sweden, 1991.

ENRESA: Memoria Cartofrafía Geológica y Estructural. Rocas Plutónicas, Albalá (G111), ENRESA Internal Report (94-G111-IF), Madrid, Vol.II, 249pp, 1996.

Escuder Viruete J. y Pérez-Estaún, A.: Fracturación en Mina Ratones, Informe Final 1: Estructura, Proyecto Ratones. ENRESA Internal Report, 10·CJA·IF·01, 1998.

Escuder Viruete, J.: Estudios geológico-estructurales y geofísicos, Tomo I: Estudios geológicos, Proyecto Ratones, ENRESA Internal Report: 10·CJA·IF·03, 1999.

Escuder Viruete, J., Carbonell, R., Jurado, M.J., Martí, D., and Perez-Estaún, A.: Two-dimensional geostatistical modeling and prediction of the fracture system in the Albala Granitic Pluton, SW Iberian Massif, Spain, J.Structural Geology, 23, 2011-2023, 2001.

Escuder Viruete, J., Carbonell, R., Martí, D. and Perez-Estaún, A.: 3·D stochastic modeling and simulation of fault zones in the Albalá granitic pluton, SW Iberian Variscan Massif. Journal of Structural Geology, 25, 1487-1506, 2003-a.

Escuder Viruete, J., Carbonell, R., Martí, D., Jurado, M.J., and Perez-Estaún, A.: Architecture of fault zones determined from outcrop, cores, 3-D seismic tomography and geostatistical modelling: example from the Albalá Granitic Pluton, SW Iberian Variscan Massif, Tectonophysics, 361, 97-120, 2003-b.

Frape, S.K., Fritz, P., and McNutt, R.H.: Water–rock interaction and chemistry of groundwaters from the Canadian shield, Geochim. et Cosmochim. Acta, 48, 1617–1627,1984.

Gómez, P., Garralón, A., Turrero, MªJ., Sánchez, L., Melón, A., Ruiz, B. y Fernandez, F.: Impacto medioambiental de la restauración de la Mina Ratones en las aguas subterráneas. Modelo Hidrogeoquímico, Proyecto Ratones, ENRESA Internal Report, 10·CIE·IF·1·99, CIEMAT/DIAE/54211/7/99, 1999.

Gómez, P., Garralón, A., Turrero, MªJ., Sánchez, L., Ruiz, B., y Melón A.: Estudio del efecto de la restauración de la Mina Ratones en las aguas subterráneas, Proyecto Ratones, ENRESA Internal Report, 10·CIE·IF·1·00, CIEMAT/DIAE/54440/1/00, 2001.

Gomez, P.: Estudio del impacto de la mina de uranio "Los Ratones" (Albalá, Cáceres) sobre las aguas superficiales y subterráneas: modelación hidrogeoquímica, Tesis doctoral, 2002.

Gómez, P., Turrero, M.J., Garralón, A., Peña, J., Buil, B., De la Cruz, B., Sanchez, M., Sanchez, D.M., Quejido, A., Bajos C., and Sánchez, L.: Hydrogeochemical characteristics of deep groundwaters of the Hesperian Massif (Spain), Journal of Iberian Geology, *32*(1), 113-131, 2006.

Gomez-Hernandez, J., Hendricks Franssen, H.J.W.M., Shauquillo, A. and Capilla, J.E.: Calibration of 3-D transient groundwater flow models for fractured rock. Proceedings Model CARE'99, International Conference on Calibration and reliability in groundwater modeling, Zürich, Switzerland. 20-23 September 1999.

Guimerà, J., Vives, L. and Carrera, J.: A discussion of scale effects on hydraulic conductivity at a granitic site (El Berrocal, Spain), Geophysical Research Letters, 22(11), 1449-1452, 1995.

Illman, W.A. and Neuman, S.P.: Type-curve interpretation of multi-rate single-hole pneumatic injection tests in unsaturated fractured rock, Ground Water, 38: 899-911, 2000.

Illman W.A.: Analysis of permeability scaling within single boreholes, Geophys Res Lett., 31(5), 2004.

Illman, W. A., and Tartakovsky, D. M.: Asymptotic analysis of cross-hole pneumatic injection tests in unsaturated fractured tuff. Advances in water resources, 28(11), 1217-1229, 2005.

Illman, W. A.: Hydraulic tomography offers improved imaging of heterogeneity in fractured rocks, Groundwater, 52(5), 659-684, 2014.

Illman, W. A., Liu, X., Takeuchi, S., Yeh, T. C. J., Ando, K., and Saegusa, H.: Hydraulic tomography in fractured granite: Mizunami Underground Research site, Japan, Water Resources Research, 45(1), 2009.

Julivert, M., Fontbote, J.M., Ribeiro, A. and Conde,L.: Mapa Tectónico de la Península Ibérica y Baleares, E. 1:1000000, IGME, Madrid, 1972.

Jurado, M.J.: Estudios geológico-estructurales y geofísicos, Tomo III: Geofísica en sondeos: diagrafías, BHTV, dipmeter y sónicos, Proyecto Ratones, ENRESA Internal Report: 10·CJA·IF·03, 1999.

Jurado, M.J.: Avance sobre evaluación de la testificación geofísica de sondeos adquirida en mina Ratones, Proyecto Ratones, ENRESA Internal Report: 10·CJA·IA·12, CSIC-IJA, 2000.

Ko,N.Y., Ji, S.H., Koh,Y.K. and Choi,J.W.: Evaluation of two conceptual approaches for groundwater flow simulation for a rock domain at the block-scale for the Olkiluoto site, Finland, Engineering Geology 193 (2015) 297–304. http://dx.doi.org/10.1016/j.enggeo.2015.05.003, 2015.

Lee,J.Y. and Lee,K.K.: Analysis of the quality of parameter estimates form repeated pumping and slug tests in a fractured porous aquifer system in Wonju, Korea. Ground Water 37: 692-700, 1999.

Long, J.C.S. and Billaux, D.M.: From field data to fracture network modelling: an example incorporating spatial structure, Water Resour.Res., 23: 1201-1216, 1987.

Long, J.C., Karasaki, K., Davey, A., Peterson, J., Landsfied, M., Kemeny, J., and Martel, S.: An inverse approach to the construction of fracture hydrology models conditioned by geophysical data, *Intenational Journal of Rock Mechanics and Mining Sciences and Geomechanical Abstracs,* 28(213): 121-142, 1991.

Martí, D., Carbonell, R., Trygvason, A., Escuder Viruete, J., and Pérez-Estaún, A.: Mapping brittle fracture zones in 3-dimensions: high resolution ravel time seismic tomography in a granitic pluton. Geophysical Journal International, 149, 95-105, 2002.

Martinez-Landa, L., Alcahud, A., Jordan, J., and Carrera, J.: Modelo hidrogeológico del entorno de la mina Ratones (Albalá, Cáceres), Informe de proyecto: 10·UPC·IF·03, 2004.

Martinez-Landa, L. and Carrera, J.: An analysis of hydraulic conductivity scale effects in granite (FEBEX experiment, Grimsel, Switzerland), Water Resour.Res., 41, W03006, doi:10./2004WR003458, 2005-a.

Martinez-Landa, L. and Carrera, J.: A methodology to interpret cross-hole test in a granite (FEBEX, GTS), doi:10.1016/j.jhydrol.2005.10.017, 2005-b.

Meier, P.M., Carrera, J., and Sanchez-Vila, X.: An evaluation of Jacob's method for the interpretation of pumping tests in heterogeneous formations, Water Resour.Res., 34 (5): 1011-1025, 1998.

Moreno, L. and Neretnieks, I.: Fluid flow and solute transport in a network of channels, J.Contam.Hydrol., 14, 163-192, 1993.

Neuman, S.P.: Stochastic continuum representation of fractured rock permeability as an alternative to the REV and fracture network concepts, In: Custodio,E. et al. (Eds.), Groundwater Flow and Quality Modeling. Reidel, 331-362, 1988.

Ortuño, F., Floría, E., Carretero, G., y Suso, J.: Caracterización hidráulica de Mina Ratones, Proyecto Ratones, ENRESA Internal Report: 10-AIT-IA-04, grupo de hidrogeología de AITEMIN, Toledo, 2000.

Ortuño, F., Floría, E., Carretero, G., y Suso. J.: Hidrogeología de mina Ratones. Proyecto Ratones, ENRESA Internal Report: RAT·AIT·IF·01, grupo de hidrogeología de AITEMIN, Toledo, 2001.

Pérez Del Villar, L., Cózar, J.S., Pardillo, J., Pelayo, M., y Labajo, M.A.: Caracterización mineralógica y geoquímica de las harinas de falla y tapices de fractura del proyecto los Ratones (Albalá, Cáceres), Proyecto Ratones, ENRESA Internal Report: 10·CIE·IF·3·99. CIEMAT/DIAE/54211/6-99, 1999.

Pérez-Estaún, A.: Estudios Geológicos-Estructurales y Geofísicos en Mina Ratones. Informe Final: Conclusiones, Proyecto Ratones, ENRESA Internal Report: 10·CJA·IF·03, 1999.

Perez Estaun, A., Carbonell, R., Marti, D., Aecha, I., Jurado, M.J., Fernandez, M., Marzan, I., Escuder Viruete, J.: Estudios geológico-estructurales y geofísicos en Mina Ratones (Plutón de Albala), Publicación Técnica de ENRESA 0512002, Madrid, 211, 2002.

Rouleau. A., and Gale, J.E.: Statistical characterization of the fracture system in the Stripa granite, Sweden. Int.J.Rock.Mech.Min.Sci.Geomech.Abstr. 22, 353-367, 1985.

Sanchez-Vila, X., Carrera, J. and Girardi, J.P.: Scale effects in transmissivity, Journal of Hydrology, 183, 1-22, 1996.

Selroos, J.O., Walker, D.D., Ström, A., Gylling, B., and Follin. S.: Comparison of alternative modelling approaches for groundwater flow in fractured rock, J. Hydrol, 257, 174-188, 2002.

Selroos, J.O. and Follin, S.: Overview of hydrogeological site-descriptive modelling conducted for the proposed high-level
5   nuclear waste repository site at Forsmark, Sweden, Hydrogeol J, 22, 295–298, DOI 10.1007/s10040-013-1077-x, 2014.

Shapiro, A.M. and Hsieh, P.A.: Research in fractured-rock hydrogeology: characterizing fluid movement and chemical transport in fractured rock at the Mirror Lake drainage basin, Proceedings of the Technical Meeting of U.S. Geological Survey Toxic Substances Hydrology Program, Monterey, Calif., March 11-15, edited by G.E. Mallard and D.A. Aronson (also, Water Resources Investigation Report 91-4034, U.S.Geological Survey), Reston, Va., 1991.

10   Smith, L. and Schwarz, F.W.: An analysis of the influence of fracture geometry on mass transport in fractured media, Water Resour.Res., 20(9), 1241-1252, 1984.

Stephens, M.B., Follin, S., Petersson, J., Isaksson, H., Juhlin, C. and Simeonov, A.: Review of the deterministic modelling of deformation zones and fracture domains at the site proposed for a spent nuclear fuel repository, Sweden, and consequences of structural anisotropy, Tectonophysics 653 (2015) 68–94, doi:10.1016/j.tecto.2015.03.027, 2015.

15   Stober, I.: Ergebnisse geohydraulischer und hydrochemister Untersuchungen im Kristallinen Grundgebirge des Schwarzwaldes und seiner Randgebiete, Túbingen, 1997.

Svenson, U.: A continuum representation of fracture networks, Part I: Method and basic test cases, J.Hydrol, 250, 170-186, 2001-a.

Svenson, U.: A continuum representation of fracture networks, Part II: Application to the Äspö Hard Rock laboratory,
20   J.Hydrol, 250, 187-205, 2001-b.

Theis, C.V.: The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, Trans.Am.Geophysical Union, 16, 519-524, 1935.

Tsang, Y.W., Tsang, C.F., Hale, F.V. and Dverstorp, B.: Tracer transport in a stochastic continuum model of fractured media, Water Resout.Res., 32(10), 3077-3092, 1996.

25   Vesselinov, V.V., Neuman, S.P., and Illman, W.A.: Three-dimensional numerical inversion of pneumatic cross-hole tests in unsaturated fractured tuff: 2, Equivalent parameters, high-resolution stochastic imaging and scale effects, WaterResour.Res., 37, 3019-3041, 2001.

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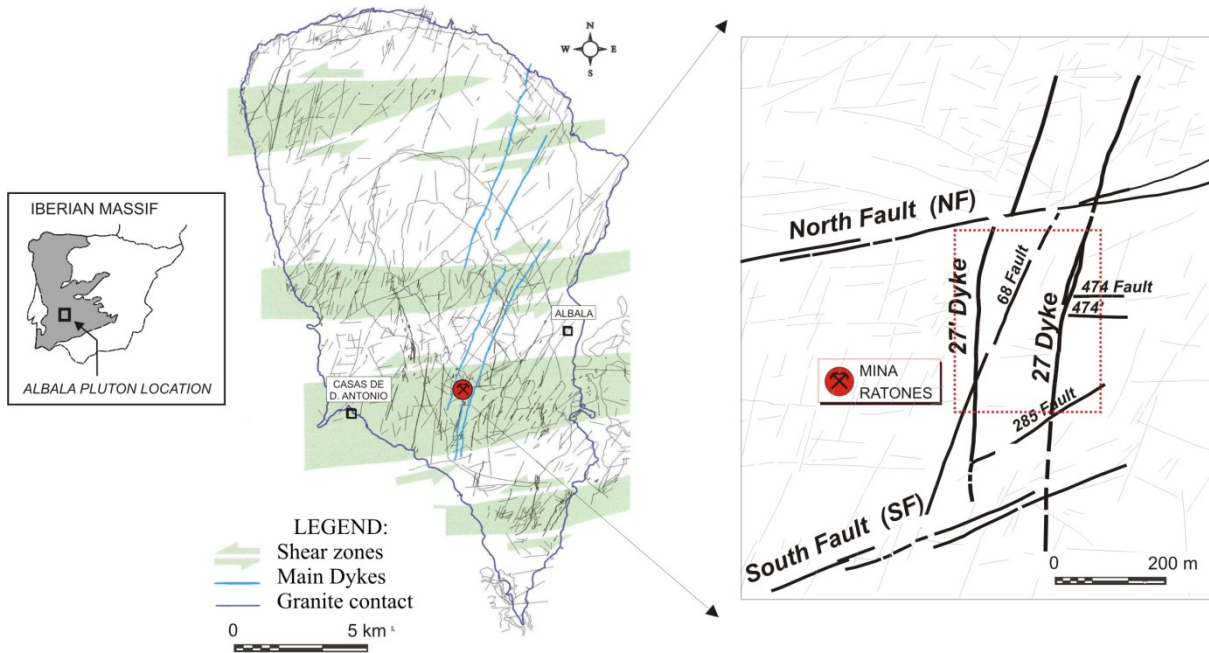
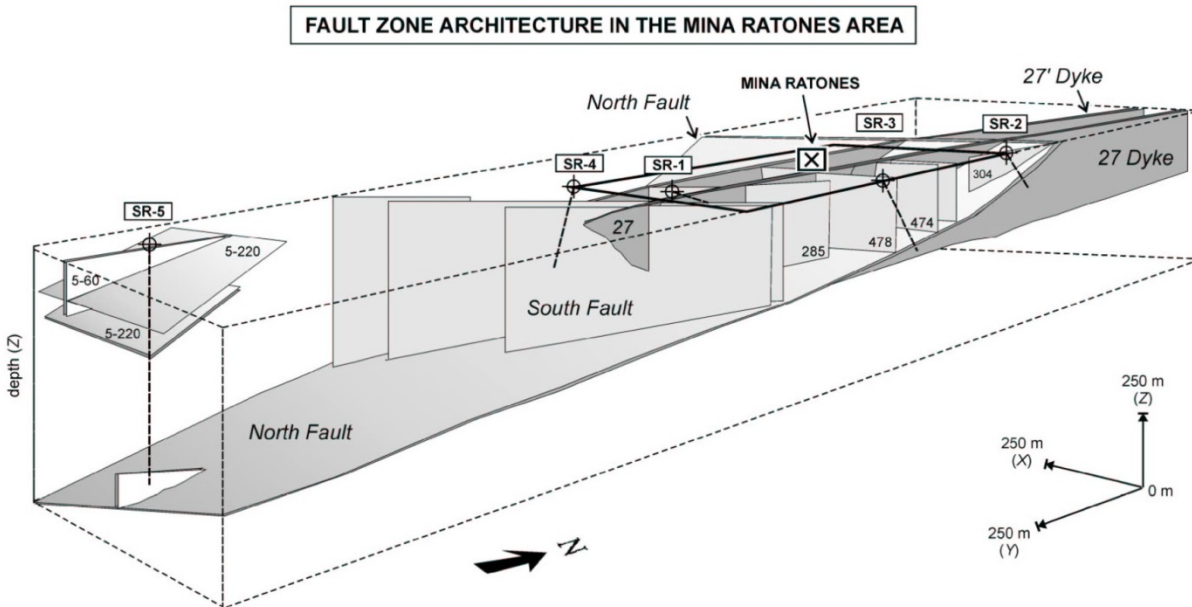


Figure 1: Geological map of Albalá Granitic Pluton with location of the Mina Ratones area (ENRESA, 1996; Escuder Viruete and Pérez Estaún, 1998).

5   **Figure 2: Fault zone architecture of Mina Ratones area obtained from structural, seismic, core and well log data (Escuder Viruete and Pérez Estaún, 1998; Carbonell et al., 1999; Escuder Viruete, 1999; Pérez Estaún, 1999, Escuder-Viruete et al, 2001). The main identified structures are the NF, the SF and the 27 and 27' Dykes. Other relevant brittle structures of minor size are 474 and 285 Faults.**

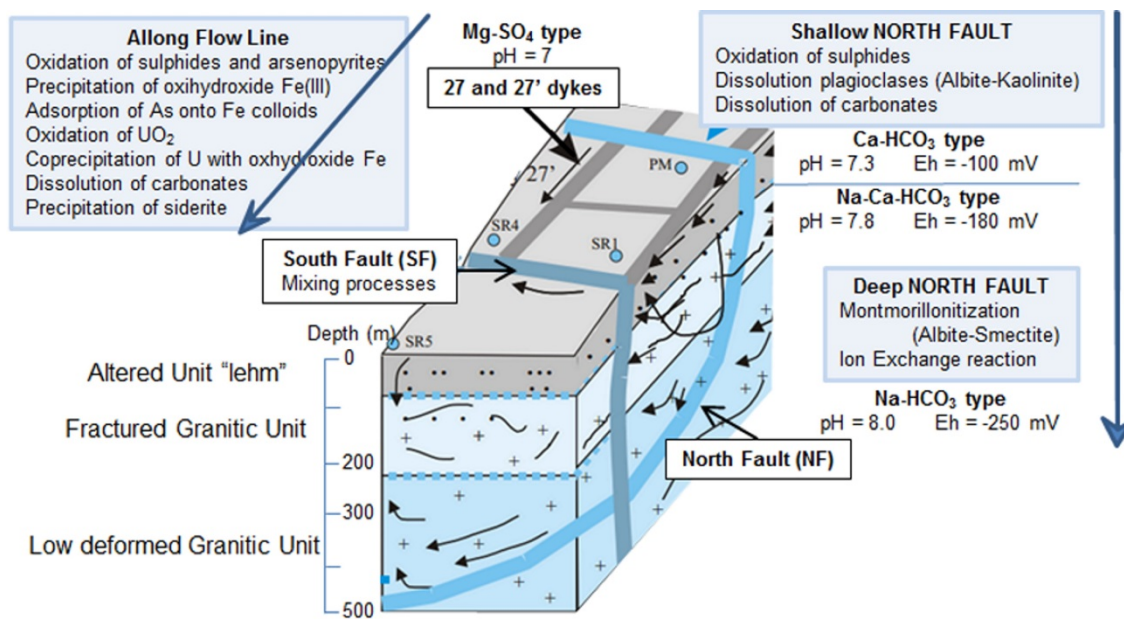



Figure 3: Groundwater hydro-geochemical behaviour model of the Aquifer-Ratones Mine system (modified from Gomez, 2002)

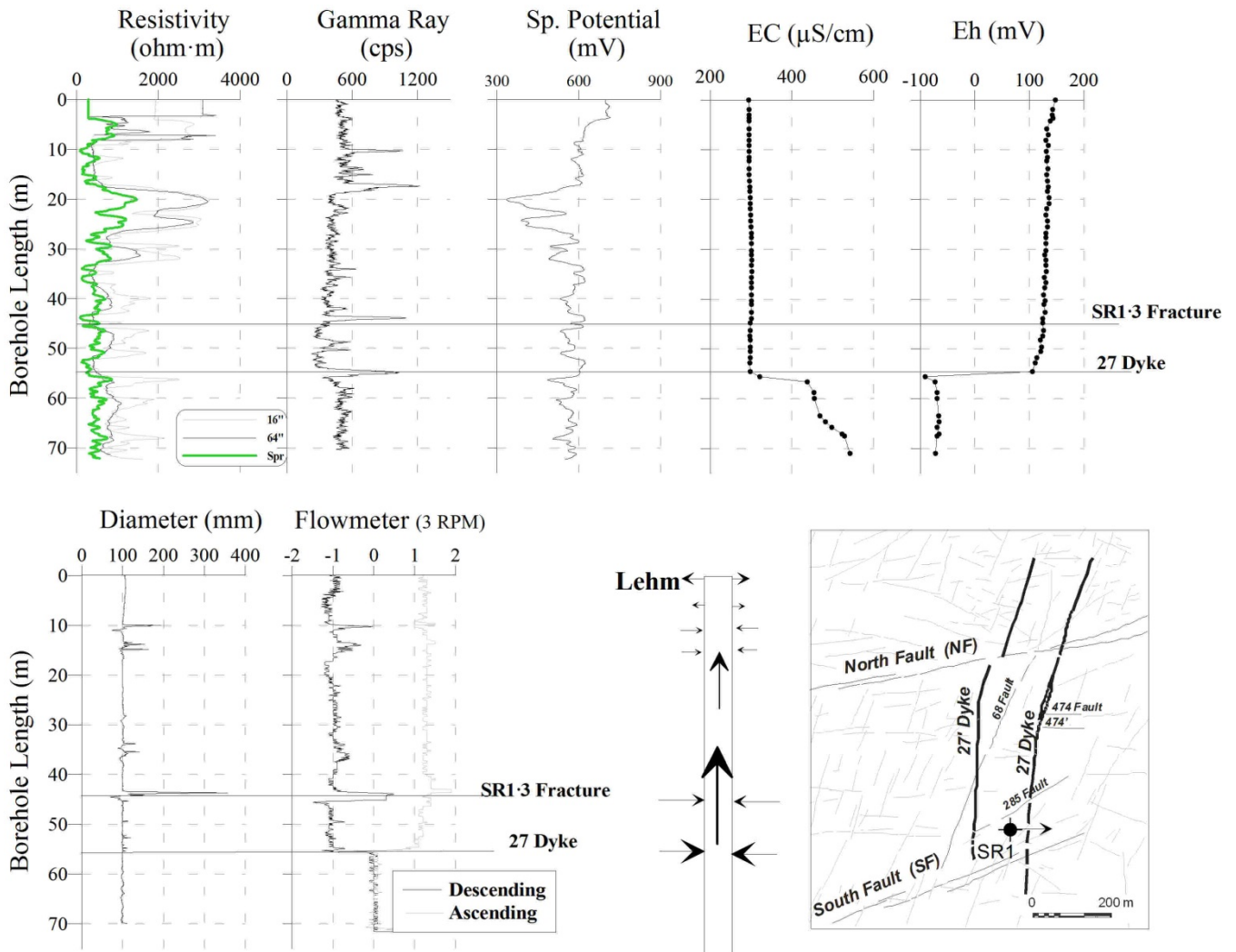



Figure 4: Chemical and geophysical logs recorded at borehole SR1, which helped identifying: dyke 27 and fracture SR1-3. The chemical logs only display the effect of dyke 27, because all upper water (including SR1-3) is mine water. The effect of both structures can be noticed in other logs, especially in the gamma log, due to the fractures fillings. Flowmeter measurements at the borehole vertical, with an upwards flow of 3 rpm (pumping) indicate that, below 56 m depth, there is little water flow up to the intersection with dyke 27. This provokes a water inflow with upwards circulation. The same applies to a lesser extent to fracture SR1-3.

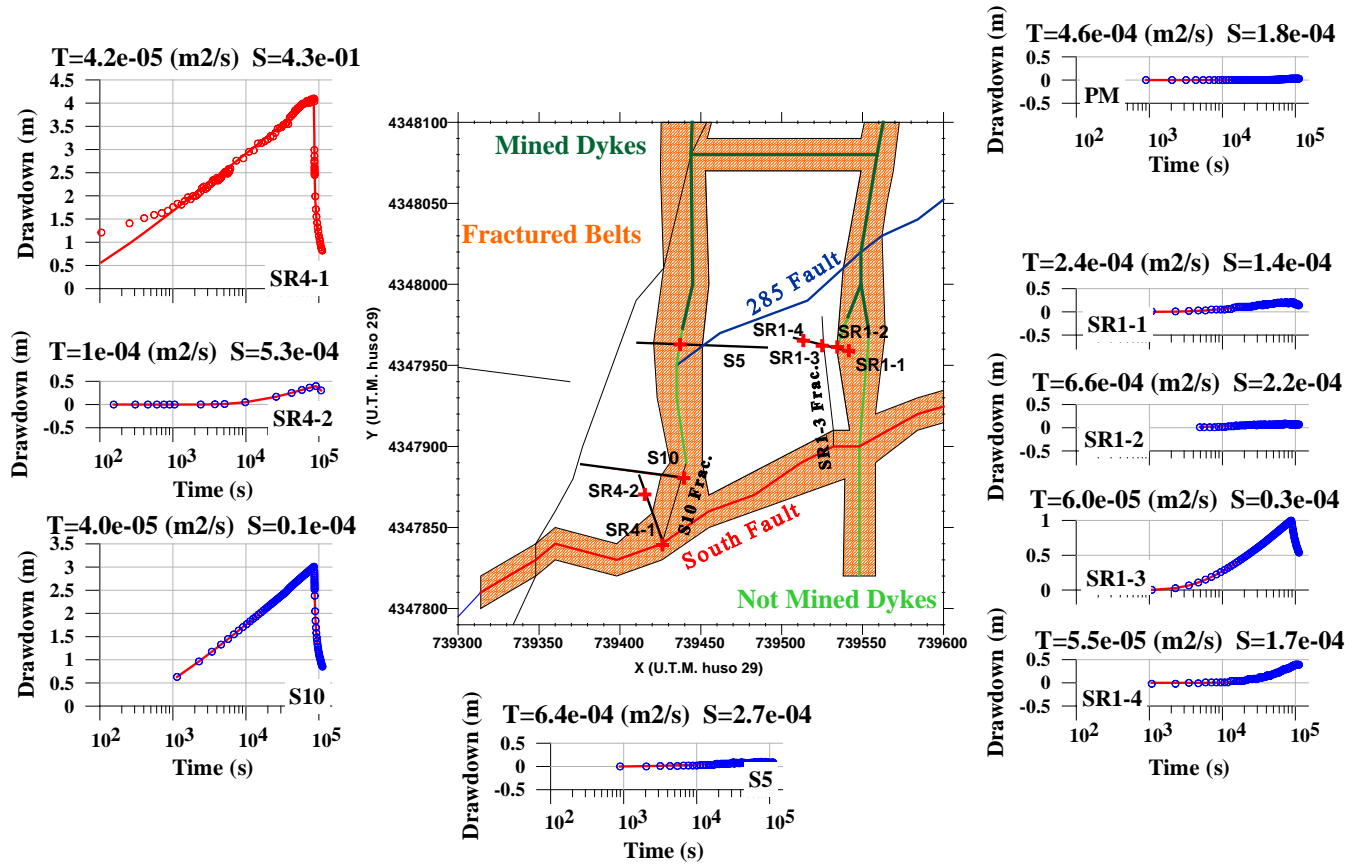



Figure 5: Results from preliminary interpretation of the South cross-hole test (pumping at SR4-1). Transmissivity and storativity are derived by fitting each borehole drawdowns, one-at-a-time, using Theis' model. Degree of connectivity is derived from the estimates of storage coefficients. T varies from 4 to 64·10-5 m2·s-1, while S ranges from 1 to 53·10-3. We take S estimates to reflect connectivity. A small S (fast response) implies good hydraulic connection between pumping and observation wells. This suggest that best connections take place between the pumping interval and points S10 and SR1-3, whilst points S5 and SR1-2, and, especially point PM, were damped by the mine influence (which behaves as a constant head boundary).

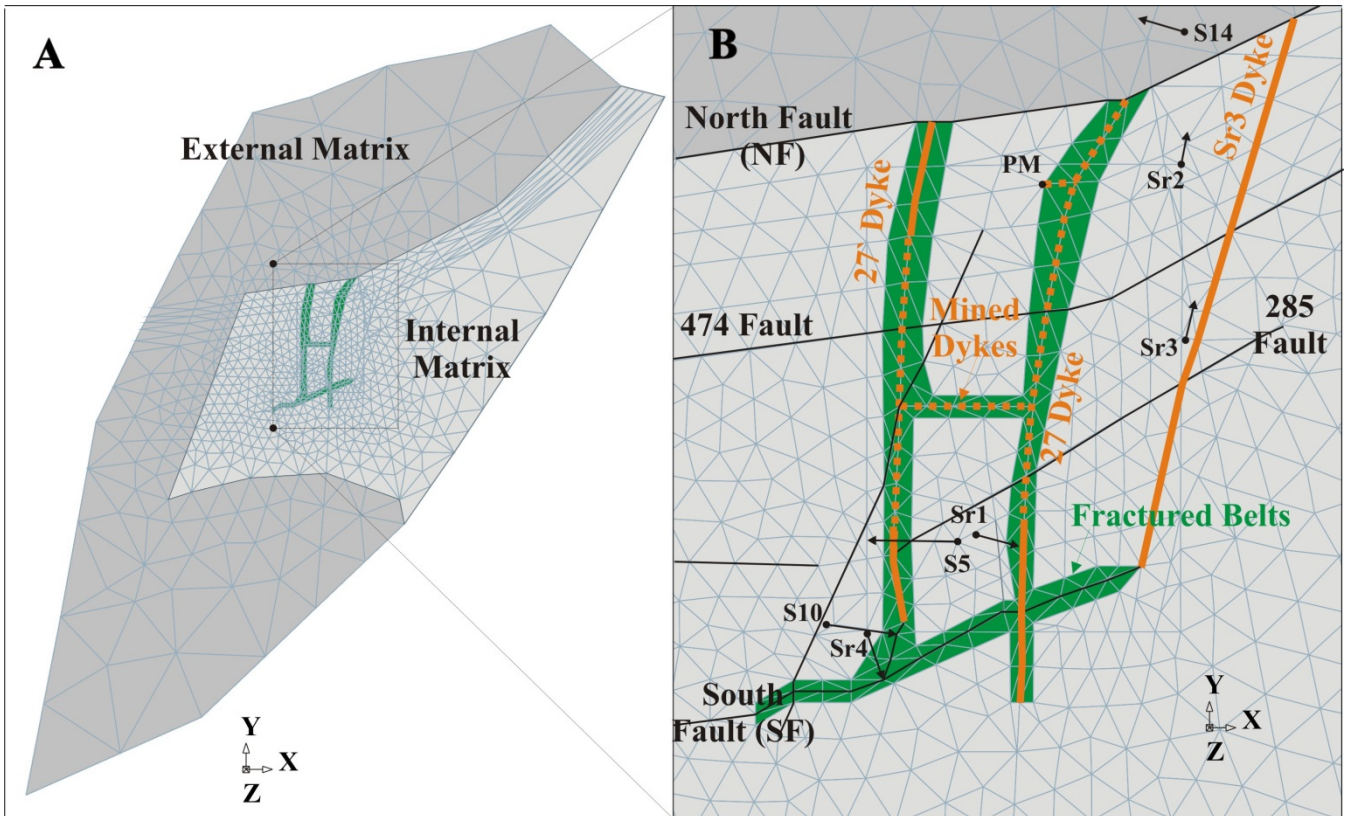



Figure 6: Model geometry. The model consists of two areas. The "external matrix" area is treated as an equivalent porous media without explicit fractures, because the main structures have not been identified. At the local level (right picture), the main structures are explicitly taken into account, including the fractures, dykes 27, 27' and SR3, and the mine itself, which is excavated in both dykes. The structures are represented by means of two-dimensional elements. The Maderos creek is embedded in the SF. Projections of the boreholes that are closer to the mine are represented by a black dot on surface and by an arrow pointed to the borehole end.

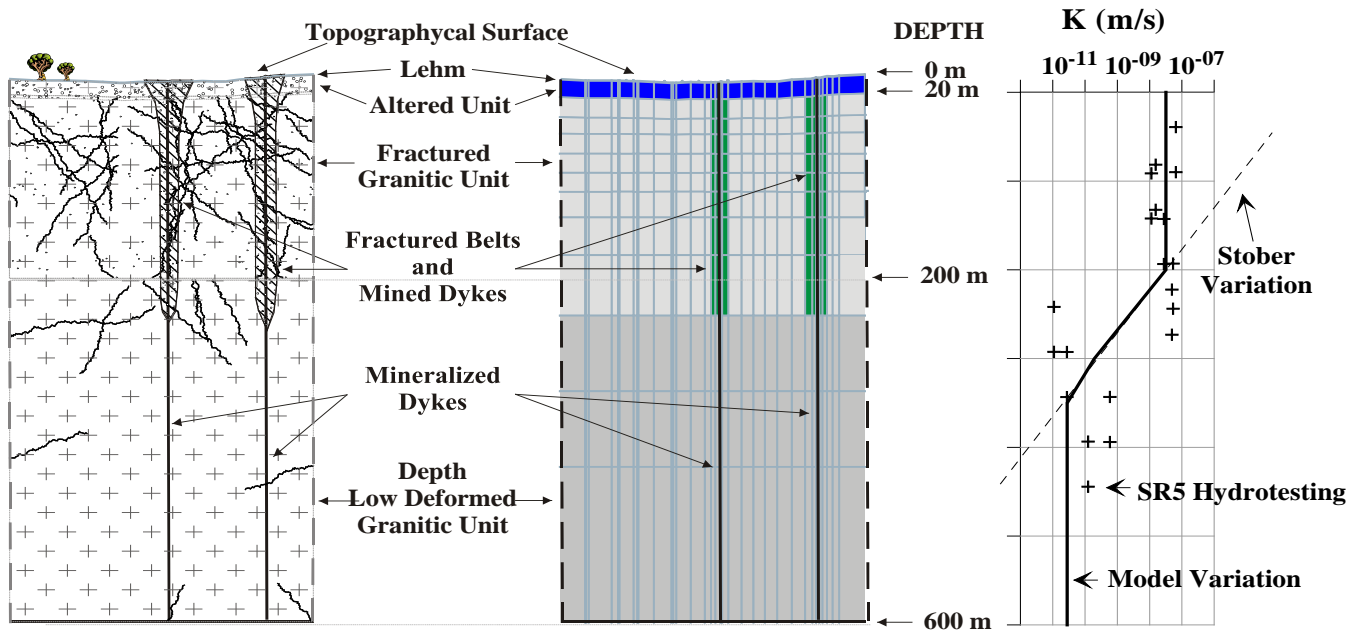



Figure 7: Schematic vertical section representing variations in data derived from the hydraulic characterization of borehole SR5 (500-m deep) indicate that hydraulic conductivity changes with depth. This fact was studied by Stober (1997). The model uses a modification of Stober's equation: hydraulic conductivity is kept constant up to the base of the fractured granitic unit (200 m), then changes with depth down to 350 m. From there, it remains constant down to the model bottom.

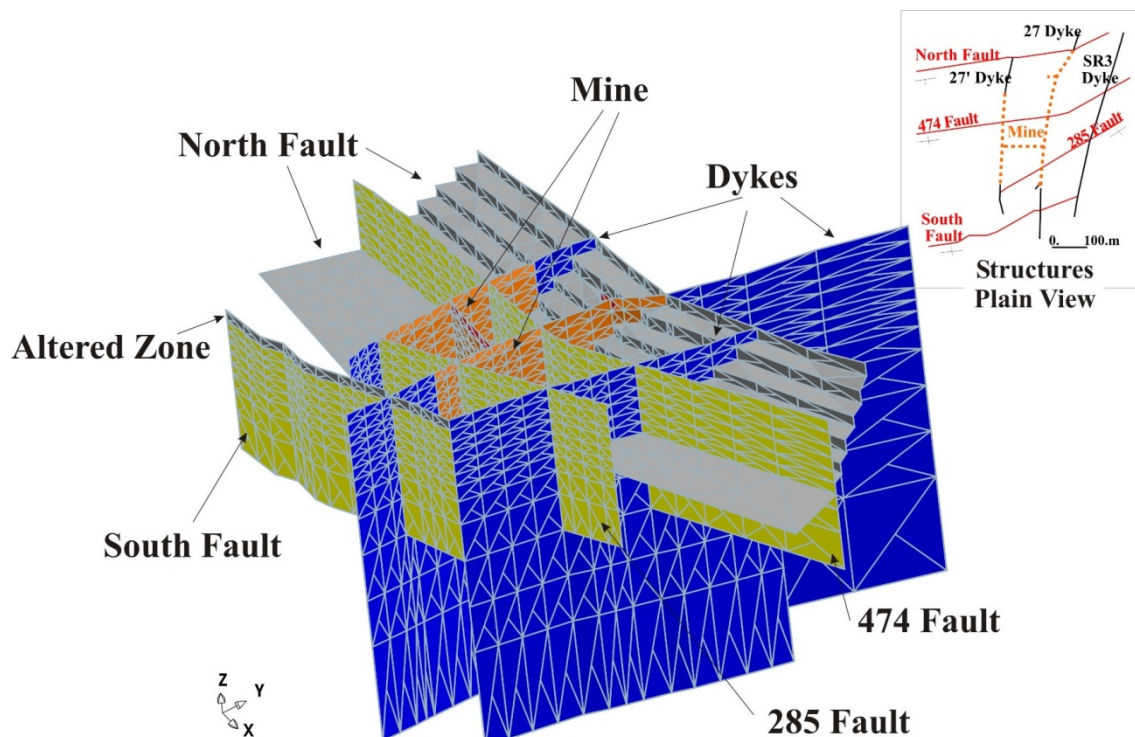



Figure 8: Main structures implemented in the model as planar structures. They are defined by two-dimensional elements. The model honors surface traces and dips. Downwards extension of these structures is performed with the aid of geophysics, structural geology and intersections at boreholes. The NF is the more vertical one at its upper section, and it is cut and disconnected by faults 474 and 285 towards the South. The mine is also represented by means of two-dimensional elements, because it results from the exploitation of the dykes. The SF is zonated at the surface, in order to reproduce the altered zone in which the stream is embedded, where most of the water flows.

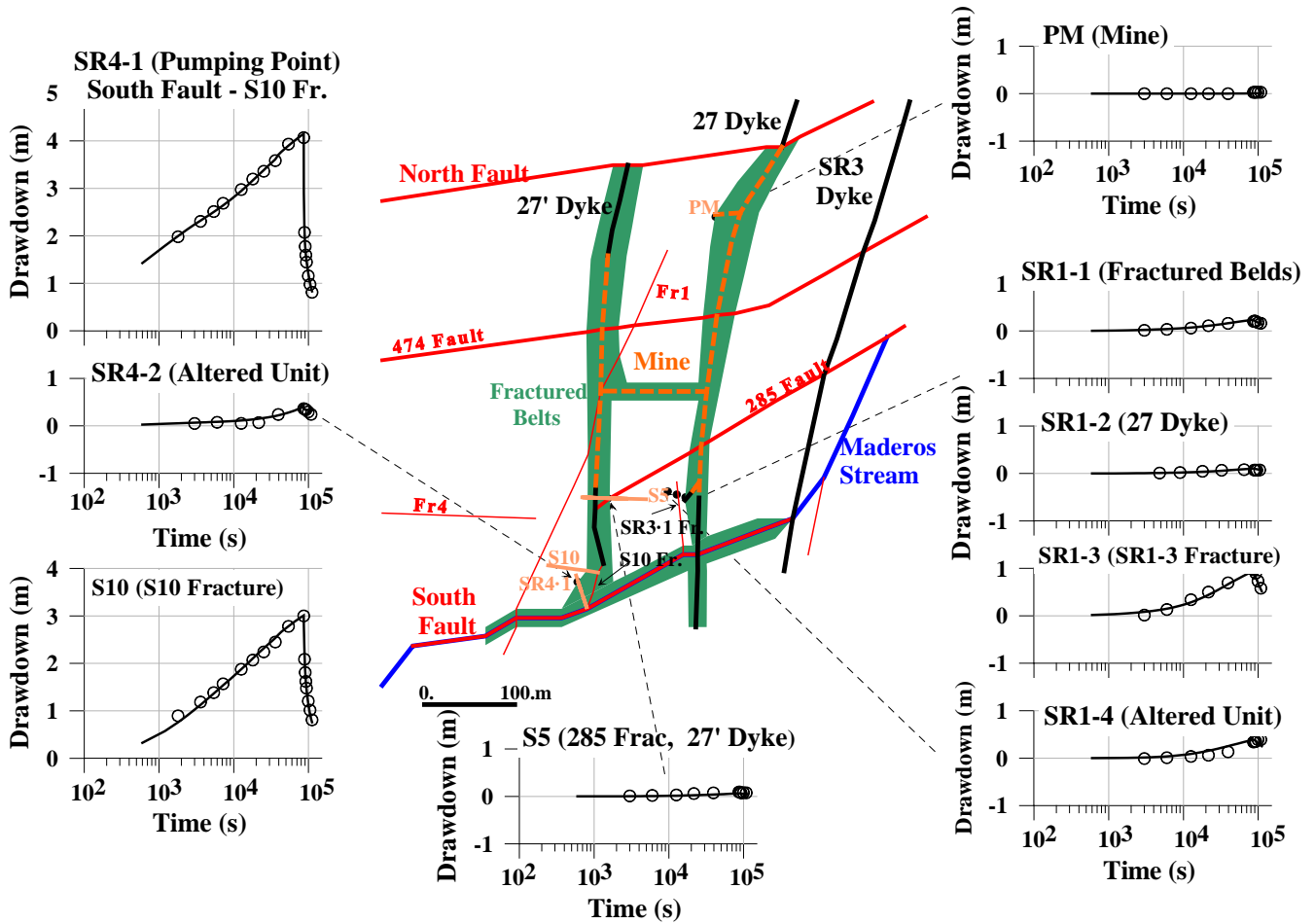



Figure 9: Results (line) obtained after calibrating the SR4-1 cross-hole test data (dots) with the three-dimensional model. All graphs maintain the vertical scale to ease a comparison among the responses.

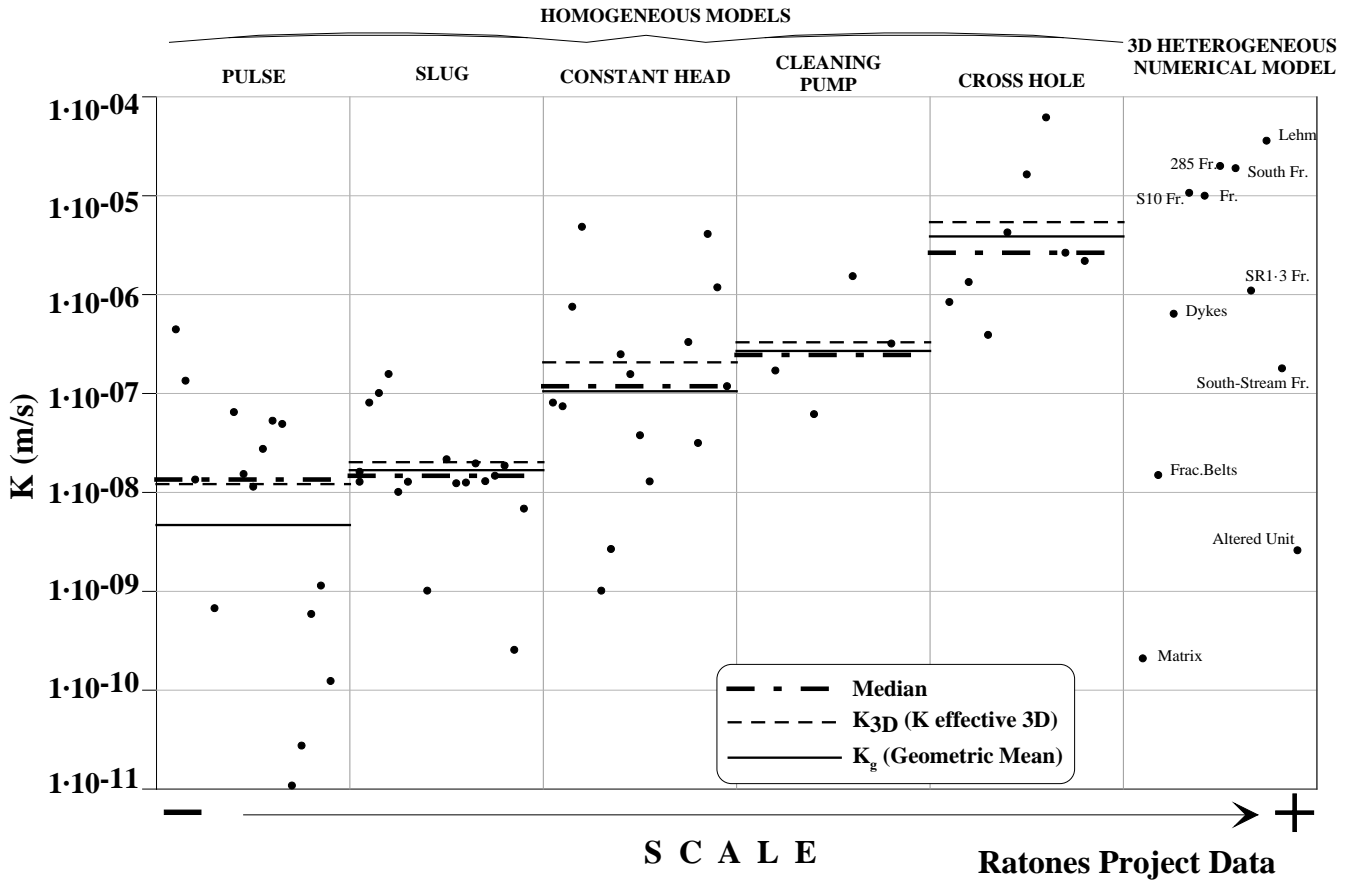



Figure 10: Transmissivity values obtained from interpretation of hydraulic tests performed at varying scales in different holes and intervals. In general, transmissivity grows with the scale, except for the cross-hole test, which was performed in the highly transmissive portion of the site.

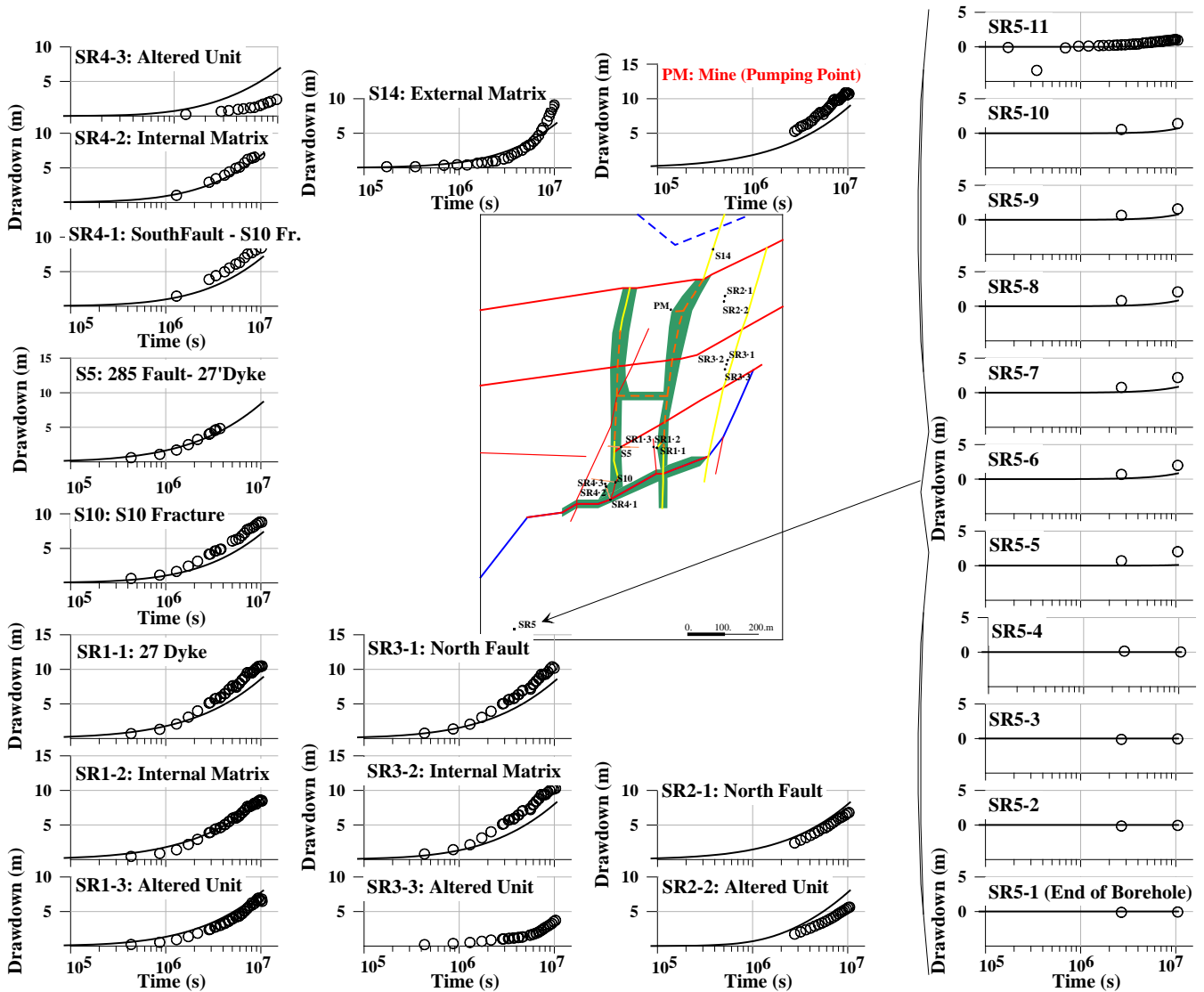



Figure 11: Blind prediction of the long term pumping of the mine (point PM), using calibrated with the SR4-1 cross-hole test. This pumping lasted for four months, and its influence reached all the observation points.