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Hydraulic testing of low-permeability formations
A case study in the granite of Cadalso de los Vidrios, Spain

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ABSTRACT

In recent years, the study of low-permeability geological formations has undergone considerable development. This is mainly due to the use of natural geological barriers to confine waste disposals, preventing leaking water from bringing contaminants into contact with the biosphere and the groundwater resources.

In that context, the Spanish Geological Survey (IGME, Spanish acronym), supported by the National Radioactive Waste Management Agency (ENRESA, Spanish acronym) and with the technical advice of the Swedish Nuclear Fuel and Waste Management Company (SKB) designed and built a Mobile Hydrogeological Unit (UMH, Spanish acronym) for low-permeability formations characterization, which has been operational since 1997 and has been used for different purposes. Among other possibilities, the UMH allows conducting: constant transient-state flow-rate injection tests, constant-head transient-state injection tests, pseudo-stationary state injection tests, pressure fall-off tests, slug tests and pulse tests.

The main objectives of this article are to describe the hydraulic characterization methodology used by IGME to carry out hydraulic tests in low permeability environment, to compare different testing methods and to summarize the results that have been obtained when characterizing the leucogranites of Cadalso de los Vidrios in Spain.

The study area presents an increasing interest for granite production inside the Community of Madrid. The petrological and structural characteristics of the granite rocks and the core-samples extracted from a 200 m deep borehole investigation are described. The packer tests are conducted with the Mobile Hydrogeological Unit.

The tests are interpreted with the help of analytical solutions. The main software used is Hytool, an open source matlab toolbox that provides a library of analytical solutions and a set of routines to facilitate hydraulic tests interpretation.

The results allow the elaboration of a comparative analysis of the applied hydraulic tests and to define the hydraulic conductivity optimum application interval most suited for each of the used methods.

Hydraulic conductivity values obtained varies from $3.20 \cdot 10^{-7}$ m/s, for the upper weathered layer, to $2.80 \cdot 10^{-12}$ m/s, for the test section from 97.36 to 116.15 m depth.

Finally, the hydraulic conductivity values obtained in this area are compared with other case studies of granite formations around the world.

1. Introduction

In hydrogeology, low permeability geological formations are still often considered of limited interest because of their poor capacity to supply groundwater. However, they can act as natural geological barriers to prevent the migration of contaminated water, and this is why an increasing interest in low-permeability formations has raised since the 1980s (Bredehoeft and Papadopulos, 1980; Witherspoon et al., 1981; Moench and Hsieh, 1985a; Neuzil, 1986; Mejías, 2005). Indeed there are numerous practical situations in which low-permeability environments have been investigated and their hydraulic properties characterized with hydraulic testing. Typical projects include underground nuclear waste disposals (Löw, 2004), landfills (Dorhofer and Siebert, 1998), deep CO2 sequestration (Croise et al., 2006), or underground constructions such as tunneling (Zhou and Li, 2001).

From a geological point of view, low-permeability formations are encountered in various lithologic groups: 1) igneous, metamorphic and consolidated sedimentary rocks, with little fractures and weathering; 2) unconsolidated sedimentary rocks such as clay and marl; 3) evaporitic rocks, and 4) volcanic rocks. Considering the relative

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abundance of these rocks on Earth, the three most important lithologies are granites (Clauser, 1992; Stober, 1996), evaporites (Beauheim and Roberts, 2002), and clays (Neuzil, 1994).

To estimate the hydraulic properties of these formations, standard pumping tests (Renard, 2005a,b) are not appropriate because they produce an excessively rapid exhaustion of the well. To avoid these issues, one has to use very low pumping rates, but their regulation (frequently at large depth) is technically difficult. In addition, well-bore storage effect masks the aquifer response during the early time of the test and imposes long lasting experiments. For these reasons, specific techniques and instrumentation have been developed during the last thirty years to obtain the physical characteristics of low and medium-permeability formations (see e.g. Almen et al., 1986 for an overview of testing methods).

In that context, the Spanish Geological Survey (IGME), supported by the National Radioactive Waste Management Agency (ENRESA), designed and built a Mobile Hydrogeological Unit (UMH) for low-permeability formation characterization (Mejías et al., 2002). The Swedish Nuclear Fuel and Waste Management Company (SKB) provided technical advice during the design and construction phases of this Unit, which has been operational since 1997 and has been used for different purposes. Among other possibilities, the UMH allows conducting: constant flow-rate injection tests, constant-head transient injection tests, pseudo-stationary state injection tests, pressure fall-off tests, slug tests and pulse tests.

The main aims of this report are: to describe the hydraulic characterization methodology used by IGME to conduct hydraulic tests in low permeability environment, to compare different testing methods and to summarize the results that have been obtained when characterizing the leucogranites of Cadalso de los Vidrios in Spain. The study was conducted in this quarry because it provides an ideal test site easily accessible from Madrid and located in very compact granite. About 40 hydraulic tests have been conducted on a 200 m deep borehole. 16 sections were tested individually. Even if the site is not considered for any particular application, the data collected is of potential interest for analog sites in which specific issues such as safety of waste repositories may need to be evaluated. This is why the report ends by a comparison with previous results published for other sites with similar lithology.

2. Description of the study area

2.1. Location and geology

The study area is located on a granite quarry at 3.5 km on the East of Cadalso de los Vidrios (Fig. 1), in the eastern sector of the Spanish Central System (65 km west of Madrid). The average annual precipitation is about 720 mm and the average temperature is 13–14 °C. The surface casing of the borehole is 840 masl. Over the four years of well monitoring, the piezometric head oscillated between 830.88 m and 831.55 m. From the hydrogeological point of view the area is considered as a low-permeability fracture zone; there are no significant springs or water supply boreholes; only some shallow wells, drilled in the weathered zone, are present. The Alberche River is the main fluvial stream. The research borehole was drilled in a low-fractured and low-weathered granitic area. The distance between two fractures is generally larger than 6 m and often even larger than 15 m, allowing the extraction of very large blocks during the quarry exploitation processes; the weathered zone affects only the eight first meters.

The granite outcrops over an approximate area of 8.5×7 km^2 (Fig. 1). It contains two main facies corresponding to biotitic monzogranites with megacristals and biotitic leucogranites (Díaz de Neira et al., 2007). The monzogranites have an equigranular texture with medium to large grains and some local porfiric tendency. The leucogranites have less biotite content, the grain size is smaller and they present quartzitic globular fenocristals of larger size than the rest (Mejías et al., 2005).

All the above mentioned facies are very homogeneous and are being exploited for ornamental rock (Gómez-Moreno et al., 1995). It is extracted under the commercial name “Blanco Cristal”. In some areas, a different facies can be found under the commercial name “Blanco Fino” with a finer and more homogeneous grain size. The borehole is located on the “Blanco Cristal”: the medium grain size biotitic leucogranite.

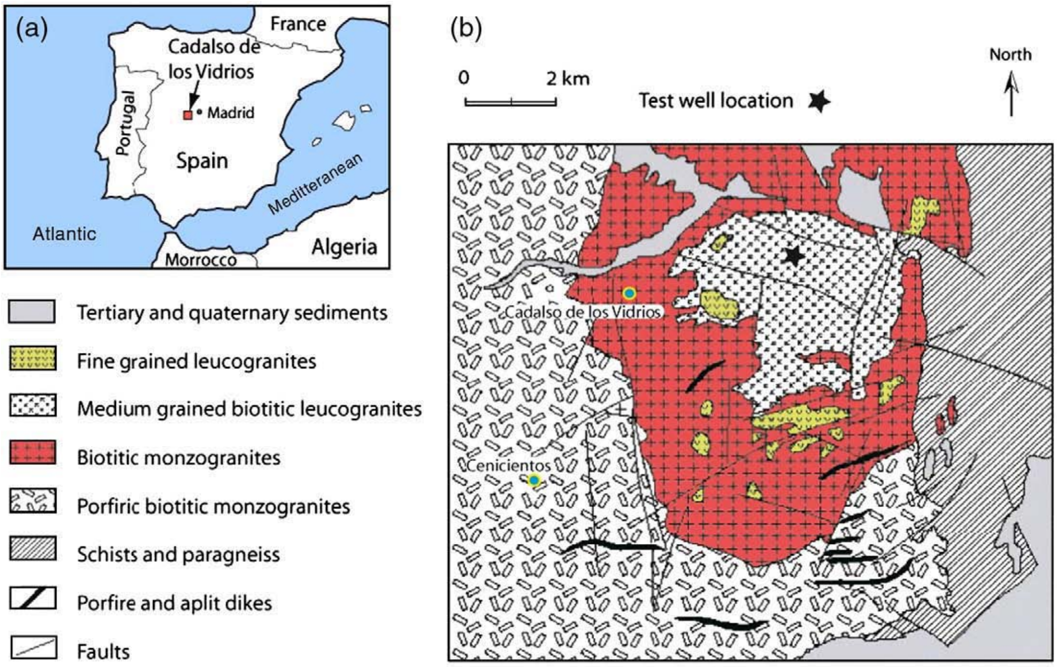

Fig. 1. (a) Situation map of the study area and (b) test well location superimposed on a simplified geological map based on the MAGNA series (1:50′000) of the geological maps of Spain (adapted from Mejías et al., 2005).

The granite is composed of 27% quartz, 38% potassium feldspar, 27% plagioclase and 8% biotite (Rodriguez-Suárez and Muñoz de la Nava, 1988). The most common accessory minerals are apatite, zircon, monacite and fluorite. The secondary minerals are chlorite, muscovite, yellowish micas, sericite, clinozoisite, prehnite, epidote, potassium feldspar, albite, calcite and oxides. The structure is mainly medium-grained, hipidiomorphic and somehow inequigranular due to the presence of disperse quartz fenocristals.

2.2. Deformation and heterogeneity

There is no observable orientation related to hercinic deformations (Devonian–Carboniferous systems). There are nevertheless fragile structures associated with posthercinic fracturation processes (Permian–Triassic systems). The most important ones are a series of fractures filled with low-temperature hydrothermal fluids (quartz, chlorite, epidote, calcium carbonate, and sulphurs). Other structures are associated with the episienitization of the affected granites, observable by the pinkish tones of the rock.

There are occasional pegmatitic mass of no more than some centimetres of quartz, albite, potassium feldspar, biotite and tourmaline. In some cases, the pegmatitic mass can be hollow inside, allowing quartz and chlorite crystals to develop.

There are very few filonian manifestations, like small aplite dikes with occasional quartz and feldspar crystals or thin biotite and tourmaline layers. The general dipping is lower than 30°.

Other heterogeneities identified in the drilling cores correspond to granitoid masses or bands very similar to the “Blanco Cristal” granite but containing less biotite. In some places, the granite is slightly pink due to changes in the color of potassium feldspar. Stronger pink

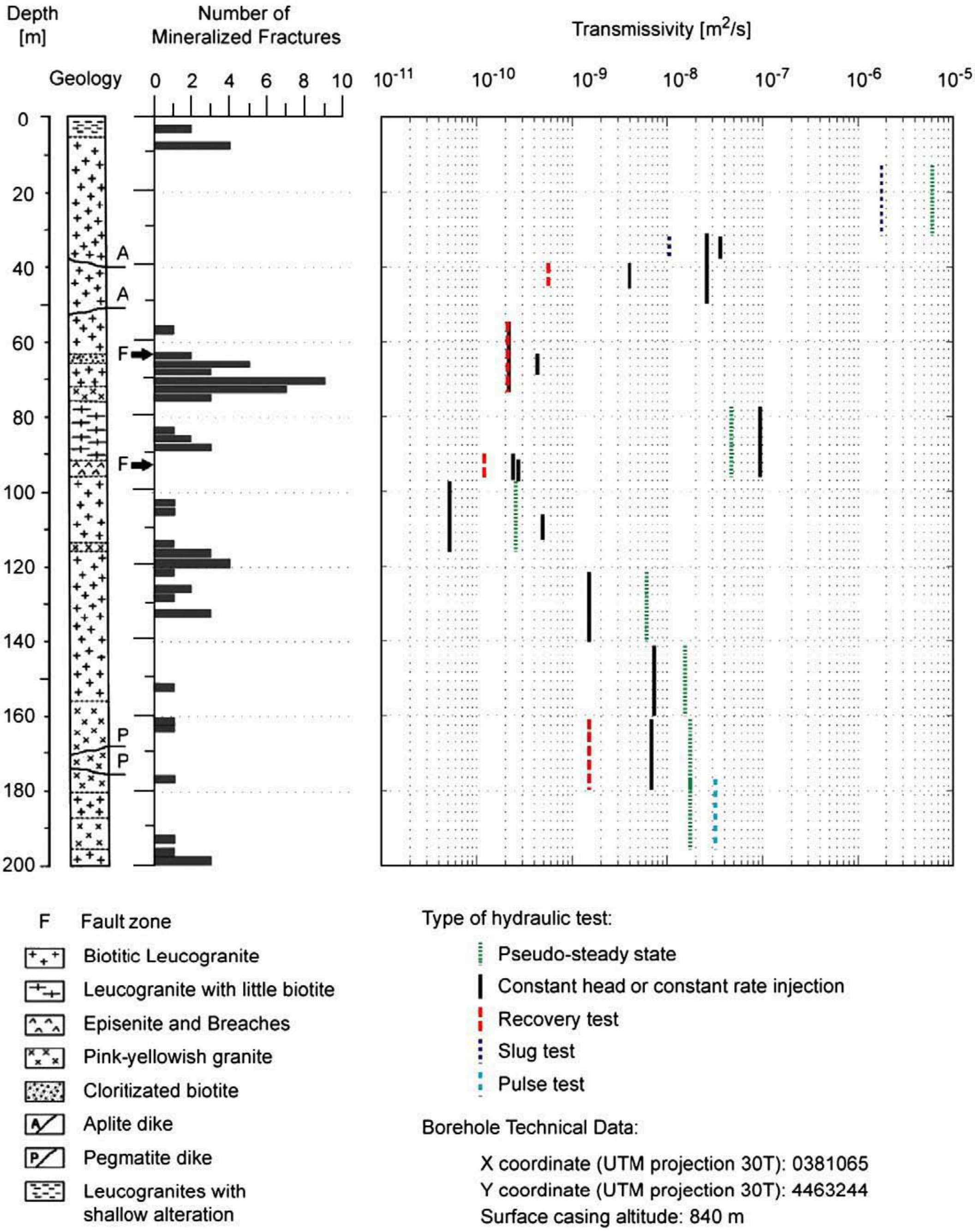

Fig. 2. Lithological log of the Cadalso de los Vidrios borehole, fractures distribution and estimated transmissivities (geological log adapted from Mejías et al., 2005).

colours appear when fractured areas affected by episietization from hydrothermal fluids are present. These fractures usually have a green colour and are filled with quartz, calcite, chlorite and epidote. In these fractured areas microbreachifications with fine-grained micas, albitizations, and carbonatations can be found. These textural and structural coloration and compositional modifications are schematically shown in the lithological log (Fig. 2).

2.3. Fracturation

The surface fracturation of the rock massif is not dense. Aerial photographs show a main fracture direction of N 100° E. Systematic orientation measurements in different areas of the quarry close to the borehole show two main fracture sets.

The dominant one is oriented N 95° E and has a subvertical dipping. These fractures are usually several meters long (decametres), with a pinkish alteration of the rock 4 to 10 cm wide, with the presence of chlorite, carbonates and iron oxides. The most important ones show feldspar kaolinization and rock crushing. The distance between fractures can vary between 6.25 m and 5.62 m, even wider, allowing the extraction of very large blocks during the quarry exploitation processes.

The second fracture set (much less common than the previous one) is oriented N 30° E. It is composed by fractures of medium to high continuity (meters to decameters), with no rock alteration association.

In addition, some other fractures have a dipping lower than 15° which are essential for the quarry exploitation, because they define the length or height of the exploitation fronts.

The research borehole has been entirely cored. This allowed analyzing the fracturation as a function of depth. Different types of fractures were encountered:

- Planar fractures and joints: they are subhorizontal structures conditioned by the joint system developed during the cooling down of the plutonic body and during the decompression due to the erosion of the overlying materials or to the extraction of the granite.
- Sub-vertical fractures and joints: they are associated to fault areas from tardihercinic or alpine brittle deformation. They usually present high dipping and low angles (<30°) with respect to the borehole axis. These structures are associated to the main fracture system observed on surface, with a direction or strike of fractures N 95° E.
- Mineralized fractures and joints: these fissures are filled with minerals from ascending fluids (related to post-magmatic evolution or to hydrothermal activity) or from descending fluids (related to meteoric water circulation). The minerals found in these fractures are calcite, quartz, mica and clay. Most of these fillings are less than 1 mm wide.

The granites from the two areas associated to tardihercinic or alpine faults are affected by hydrothermal alterations due to the circulation of mineralized thermal fluids. These areas are located at depths of 66.6 m and 93 m respectively (Fig. 2). The last one is associated to an intense granite episienitization responsible for its pink coloration. In this area an important biotite chloritization and epidotization, as well as carbonatation and quartz mobilization can be observed. There is also granite argilization with low temperature alterations associated to surface water circulation. The cores obtained from this area correspond to very fractured and altered granites, broken into small pieces. The dipping of the fracture surface is about 70°–75°. Both the interferences between the different fracture surfaces and the different granite alterations indicate a superposition of two fracturation phases. In the rest of the borehole, the dominant fractures have a dipping of 45° and are associated to the erosive discharge and to the decompression due to the granite extraction.

Concerning the general distribution of the fracturation, we distinguish two areas: an upper one, between 0 and 55 m, where the fracturation is very low. Under this area, the fracture density increases considerably, with a series of maximum and minimum values presenting an average pick spacing of 20 m. This configuration could be due to the sudden relaxation of the stresses in the rock with the core extraction at certain depths. That could be the reason for the smaller fracturation near the surface, where there is less relaxation due to the smaller stress in the granite. Clearly, neither these fractures, produced by stress relief due to the extraction of the granite blocks, nor the extraction of the cores from the borehole can develop any fluid transmissivity. Only the fractures associated with faults, alterations and mineral fillings present fluid circulation.

3. Hydraulic testing

3.1. Instrumentation

Fig. 3 shows the Mobile Hydrogeological Unit (UMH). It comprises two 4-wheel drive trucks. The *base vehicle* allows controlling all the experimental equipment and monitoring system. It includes a personal computer that controls the data acquisition of pressure, temperature and flow rate. It contains also the pressure vessels and the system for inflating or deflating the packers with nitrogen or water. A pressurized line allows opening or closing the shut-in test valve. Finally, the vehicle also contains the flow control board allowing to perform injection tests with flow rates ranging between 0.5 ml/min and 40.3 l/min (Mejías et al., 1995).

The *descent vehicle* is used to transport the pipes and for lowering the in-depth equipment by means of a modified drilling rig.

To isolate the test section from the rest of the borehole, one or two packers are used (Fig. 4). The packers are inflated with pressures ranging between 10 and 50 bars, depending on the radius of the well, the piezometric level of the test section and the test injection pressure. The test section can be closed by a shut-in valve operated from the surface. This allows reducing well bore storage effects during recovery tests or shut-in slug test (pulse test).

The system is equipped with pressure and temperature sensors located within the test section, as well as above, and beneath it, in order to check the proper sealing of the packers. The sensors are connected to the surface data acquisition system by an electrical cable.

Fig. 3. Photograph of the Mobile Hydrogeological Unit operating in the field. On the left, one can see the descent vehicle and on the right the base vehicle.

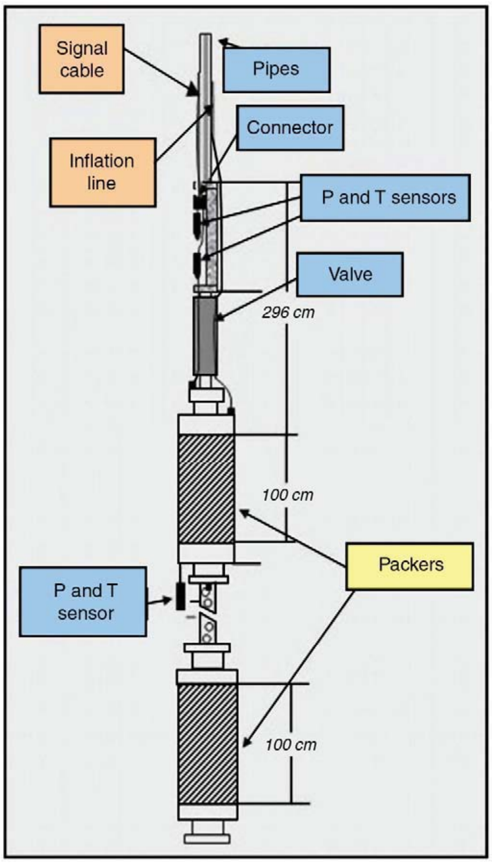

Fig. 4. The double-packer device (Mejías and López-Geta, 2003).

3.2. Testing procedure

The testing procedure comprises an overview and a detailed reconnaissance phases (Mejías and López-Geta, 2003).

The overview phase consists in a series of pseudo-stationary injection tests in sections measuring around 10% of the total length of the borehole and isolated by the double packer system. These tests are conducted over the whole length of the borehole. They can be applied for permeabilities equal or greater than 10^{-10} m/s (Fig. 5). To achieve the pseudo-stationary state during a short period of time (30–40 min), water is injected into the test section while the flow-rate and the pressure are controlled until they both stabilize (Almen et al., 1986). This is then followed by a pressure recovery of similar duration. The hydraulic conductivity values are obtained from Dupuit's formula assuming that the radius of influence is equal to half of the length of the test section (Moye, 1967). These estimations are fast but not very precise. They serve only to provide an estimate of the relative distribution of the hydraulic conductivities along the borehole. In this first phase, it is also interesting to carry out a transient-state injection test in the whole column, with a single packer device. This gives a global estimate of the transmissivity of the tested formation. After having obtained an initial distribution of the hydraulic conductivities, together with the information provided by the core analysis and geophysical testing, the intervals to be tested in the second phase can be determined. These sections are usually selected in order to characterize the most permeable fractures, where the main groundwater flow is conducted.

Therefore, during the detailed reconnaissance phase, the length of the test section is much shorter (1 to 6 m). This length is chosen to test precisely some specific intervals while ensuring a correct sealing of the packers (the packers must be located in areas with no fractures). When possible, the same section length is used for a series of tests at different depths to avoid as much as possible phases of instrumentation and de-instrumentation when the section length is modified.

Because it is essential to have a stabilized pressure before the beginning of the test, the section is isolated by inflating the packers and closing the shut-in valve days before the test begins. The pressure in the interval is then monitored during a period that can last up to several days to obtain the stabilization of the head.

The general test sequence for a section begins with an evaluation of the type of test that can be realized depending on the estimated hydraulic conductivity (Fig. 5).

When possible, constant head injection tests are preferred because they allow avoiding wellbore storage effects and are then able to provide most reliable values of the permeability than constant rate injection test. They are applicable for hydraulic conductivities ranging between 10^{-6} and 10^{-11} m/s with the UMH (Fig. 5). The increase of pressure imposed during such tests is about 20 to 40 m. It is obtained by injecting water at a very slow rate. After imposing the initial increase of pressure, the flow-rate decreases slowly, depending on the transmissivity, and the pressure is maintained constant. During the procedure the over pressure is maintained far below the values that could produce fracturing.

The minimum duration of the injection period is 3 h. However, it is always a compromise between practical constraints on a site and the needs to obtain a representative value of the hydraulic parameters. Long-term tests may be performed to analyze the connectivity of the fractures and to identify boundary effects. Once the injection phase is finished, it is followed by a pressure recovery period of approximately the same duration as the injection phase.

In addition to the previous tests, pulse tests and slug tests are conducted to allow verifying the quality of the results. Furthermore, pulse tests are used to investigate very low permeability zones ($K < 10^{-11}$ m/s) in which the flow-rate for the injection tests cannot be regulated properly (Fig. 5). When the hydraulic conductivity is large ($K > 10^{-7}$ m/s), slug tests are conducted, because the UMH is not designed and equipped to sustain and measure large injection rates. The optimum range of application for this type of test is between 10^{-6} and 10^{-9} m/s. For lower values of hydraulic conductivity, the pressure recovery times are too long.

4. Interpretation methods

The tests are interpreted with the help of analytical solutions. Two softwares are used: Aquifer test pro (Waterloo, 2002) and Hytool (Renard, 2003). Hytool is an open source matlab toolbox that provides a library of analytical solutions and a set of routines to facilitate hydraulic tests interpretation. These include for example pre and postprocessing facilities and diagnostic plots (Renard et al., 2009). Hytool uses all the power of matlab and especially the least squares algorithms available either in the Statistics toolbox or Optimization

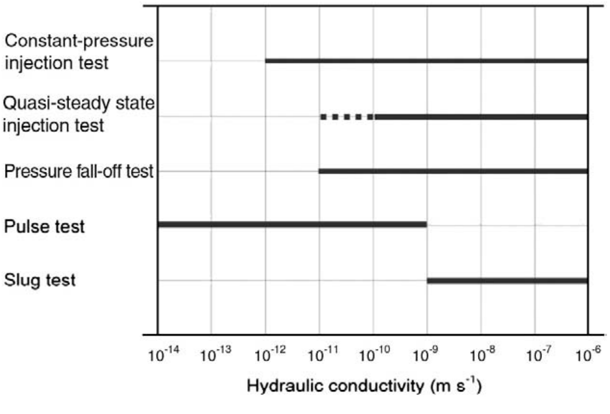

Fig. 5. Range of applications of the different tests (Mejías, 2005).

toolbox. This allows for example to provide an estimate of the uncertainty on the parameters when fitting the models in a manner similar to Bardsley et al. (1985). In addition, after the fit, Hytool provides basic statistics related to the quality of the fit (mean and standard deviation of the residuals). Most of the analytical solutions used for interpretation are programmed in the Laplace domain and inverted numerically with the Stefhest (1970) or the de Hoog et al. (1982) algorithms. Specific import functions can be developed for any type of input file, and in this way Hytool can directly load the data recorded by the acquisition system.

As described in the previous section, the main tests that are conducted in low-permeability environment are constant head test, constant rate injection test, recovery test, pulse test and slug tests. Each of these tests is interpreted with a different set of analytical solutions.

Constant head injection tests are most often interpreted with the Jacob and Lohman (1952) solution (Fig. 6a). Constant rate injection tests require solutions that account for well-bore storage effects (Fig. 7a). They are generally interpreted with the Papadopulos and Cooper (1967) solution, knowing that it allows to describe not only wellbore storage effect but skin effect as well even if both effects cannot be distinguished from the shape of the solution (Agarwal, 1980). Other more advanced solution such as the one of Hamm and Bideaux (1996) are available in the Hytool code, but they were not used in this test campaign as the diagnostic plots (logarithmic derivative) of the data have not shown evidence of double porosity or non integer flow dimension effects.

Recovery tests (fall-off tests after injection period) are interpreted using the technique of Agarwal (1980). These consist in computing an equivalent time for the recovery period that accounts for the pumping or injection rate history. These allow interpreting the recovery as if it were a constant rate injection test (Fig. 6b).

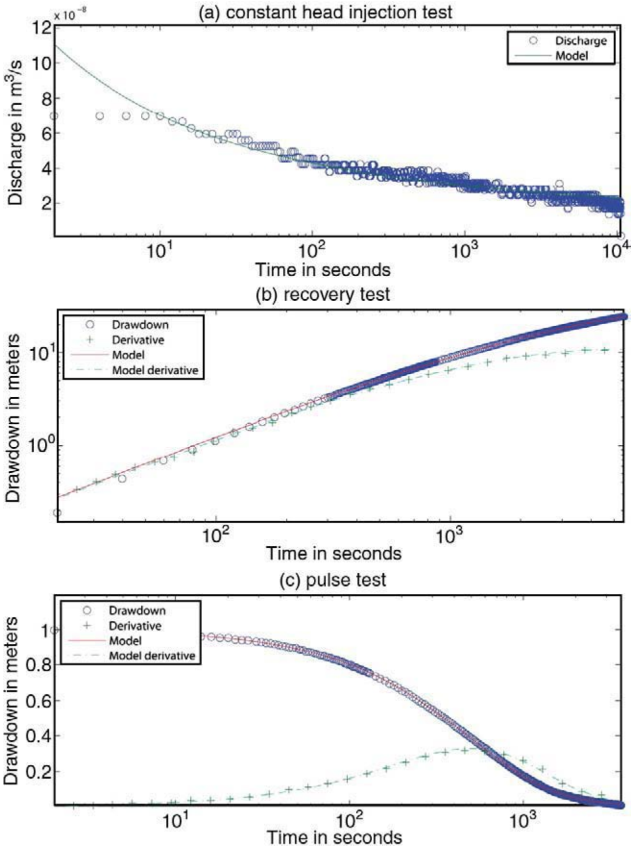

Fig. 6. Typical graphs resulting from the interpretation with Hytool of (a) constant head injection test, (b) recovery test and (c) pulse test. The data shown in these three graphs correspond to the tests conducted in the interval 39 m–46 m, of the borehole of Cadalso de los Vidrios.

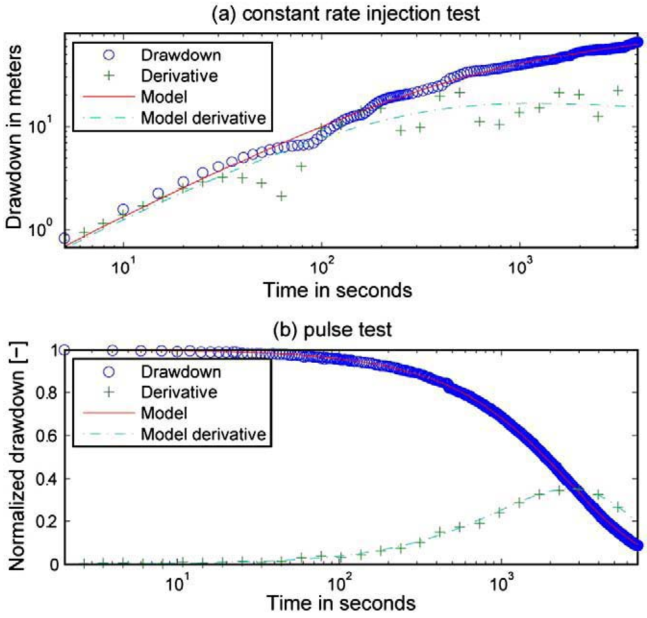

Fig. 7. Typical graphs resulting from the interpretation with Hytool of (a) constant rate injection test, and (b) pulse test. The data shown in these two graphs correspond to the tests conducted in the interval of 106 m–113 m, of the borehole of Cadalso de los Vidrios.

Pulse tests (Fig. 6c) are interpreted with the Cooper et al. (1967) solution accounting for system compressibility as described by Bredehoeft and Papadopulos (1980) and Neuzil (1982). Because equipment compressibility is usually higher than the water compressibility, it dominates well-bore storage effect and must be known for the interpretation. Therefore, the equipment compressibility was measured in the laboratory, following the procedure described by Almen et al. (1986) it was found to be $2.78\cdot10^{-8}$ Pa^{-1} (Martínez-Navarrete et al., 1995). For the slug test, the solution of Cooper et al. (1967) provides in general very good fit with the data and is therefore intensively used.

5. Results

The hydraulic tests in Cadalso de Los Vidrios were conducted during three successive field campaigns. The first and second phases of tests were done from April to June 2004. The third phase was conducted in March 2007 and in October 2007. A total amount of 40 hydraulic tests have been interpreted including 10 pseudo-stationary tests, 13 constant-head injection tests, 1 constant flow-rate injection test, 5 recovery tests, 2 slug tests and 9 pulse tests. The results (see Table 2) are displayed in Fig. 2. Note that in total, about 100 tests were performed. Many of those tests were conducted for checking the instrumentation (functioning of the test valve to different pressures, different kind of pressure sensors, etc.), others had some implementation problems (i.e. packers sealing, bad functioning of the pressure sensors, etc.). A limited number of tests could not be interpreted (for example because the head did not stabilize before the test or because the data were not interpretable with usual models). In these cases, the tests were repeated in the same interval or moving slightly the packers if the problem was due to an imperfect sealing. Among all the tests, 40 could be used to estimate the hydraulic properties of the granite. The results of these tests show a reasonable fit between the model and the observations. The mean of the residuals is always very small (always less than 2/1000 of the total head variation), with a standard deviation of the residuals varying from 1/1000 to less than 5/100 of the total head variations. The posterior parameter uncertainty was also evaluated and is generally small. For example, for the constant rate injection test shown in Fig. 7a, the 95% confidence interval for the transmissivity is estimated to be between 4.3 10^{-10} m^2/s and 5.7 10^{-10} m^2/s. However, for the same interval, the interpretation of the pulse test data (Fig. 7b) provides a 95% confidence interval for the transmissivity ranging between 1.8 10^{-8} and 2.2 10^{-8} m^2/s. In both cases, the fit is rather good but there are still large differences between the estimations obtained by the two approaches. This shows clearly that even if each test can be interpreted with a small level of parametric uncertainty, there is still some high level of uncertainty due to the type of tests themselves or the interpretation technique. In the example shown above, the value obtained by the injection test is considered to be the more reliable of the two estimates because it corresponds to a much larger investigation volume. The pulse test on the opposite may be highly influenced by skin effect.

The constant-head test for the whole borehole provides a value of transmissivity of 4.5 10^{-7} m^2/s (average hydraulic conductivity of 2.4 10^{-9} m/s) which corresponds rather well to the mean of the values obtained for each separate section. More precisely, most of the tests show a transmissivity value comprised between 10^{-7} and 10^{-10} m^2/s (hydraulic conductivity between 10^{-9} and 10^{-11} m/s) corresponding to a low-permeability medium. In the rest of this report, only transmissivity values will be presented because the flow is focused in a limited number of fractures. These fracture transmissivities are not affected by the length of the test section. Dividing their values by the length of the section to obtain mean hydraulic conductivity would not be physically sound at that scale.

The values obtained during the different campaigns are in general very close for similar intervals in which the same tests have been repeated. For example, for the interval between 32 m and 37.83 m, the transmissivity obtained during the second campaign was 3.6 10^{-8} m^2/s while it was 2.6 10^{-8} m^2/s in the first campaign, for the test section 31.21 m–50 m.

The distribution of the transmissivities versus depth (Fig. 2) shows high transmissivity values (around $6 \cdot 10^{-6}$ m^2/s) close to the surface (13–31.79 m). This is attributed to superficial alteration caused by weathering and the nearby quarry works. At larger depth, the transmissivity decreases probably because of the progressive closing of the fractures and joints with depth. The range of values obtained in the same interval with different techniques, exception pulse tests, is very similar, in general less than one order of magnitude. Likewise, *T* values in equivalent sections (i.e. 90.00–97.00 m and 91.5–97.33 m) from constant head tests are 2.4 10^{-10} m^2/s and 2.7 10^{-10} m^2/s respectively, in spite of the difficulty in obtaining reliable values of transmissivities in very low permeability environment. The minimum estimated transmissivity (5.2 10^{-11} m^2/s) occurs at depth ranging between 97.36 m and 116.15 m. Slightly higher values are observed between 63 m and 97 m where two faults are intercepted by the borehole (at 66.6 m and 93 m). The increase of the transmissivity values in this interval is lower than expected probably because the hydrothermal activity associated with these fractures has partially sealed them by mineral deposition. At depth larger than 120 m, the transmissivity values slightly rise until they reach a maximum of 2 10^{-8} m^2/s (177–195.79 m). This increase is correlated to a slight development in the density of the fractures at a depth close to 190 m, with the evidence of mineralized thermal fluids circulation in the cores. It is possible that this effect is due to the presence of a fault at further depth that could have been encountered if the well had been drilled a little deeper.

6. Discussion and conclusion

A varying number of methods for determining the hydraulic parameters were used in each test section. The time available, the work planning in the quarry and the limited applicability of individual methods to certain ranges of hydraulic conductivity restricted the number of tests.

The differences between the transmissivities obtained from different tests in the same section show that some uncertainties remain and some systematic difference can be observed between the different methods.

First, the transmissivity values obtained from the pulse tests are almost always different from the others tests. Nine pulse tests were done (see Table 2) and only in three of them a transmissivity similar to the values acquired with the other tests was obtained (sections: 39.00 m–46.00 m; 91.50 m–97.33 m and 177.00 m–195.29 m). In the other pulse tests, significant differences were obtained and the values were usually larger than those calculated with the other tests. In the sections with higher transmissivity values: 13.00 m–31.79 m and 32.00 m–37.83 m, the transmissivities calculated by means of pulse tests are smaller (two orders of magnitude in the first section and one in the second) than the transmissivities acquired with the other methods. Whereas, in the intervals where transmissivity, from the other tests, is smaller, the transmissivity data obtained by means of pulse tests are higher, usually by two orders of magnitude. Significantly, from the nine transmissivity values obtained from the pulse tests, six have a transmissivity of 10^{-8} m^2/s, two about 6.10^{-9} m^2/s and the other is 1.6 10^{-9} m^2/s. These values may be affected by skin effect. In a pulse test only a very small amount of water is introduced in the test section and this amount of water could easily be taken up in a finite-thickness skin with storativity different from zero; consequently, a pulse test, due to its extremely small radius of investigation, may yield only the hydraulic properties of the skin (Moench and Hsieh, 1985b). Note however that to minimize that effect, the drilling and cleaning operations were conducted only with water. Another possible issue with pulse test is the brief duration of the pulse (Connell, 1994). While in theory, it should be instantaneous, it is not always the case because the operation of the test valve at depth can take up to 30 s. This delay causes uncertainty in the estimation of the transmissivity. In addition, another possible problem may be the stabilization of the head in the interval prior to the test. Even if this could not be completely avoided, (as one can see in Fig. 6c where the tangent of the late time data is not horizontal, indicating that the head did not equilibrate yet) a special attention was devoted to minimize this issue; more precisely, the tests data were acquired after waiting for stabilization during several hours and up to several days between the moment in which the valve was closed and the test executed. Overall, in spite of all the precautions taken to minimize these effects, the results of the interpretation show that some significant differences between the results of the pulse test and the other tests remain. Most probably, the transmissivity values obtained with the pulse tests correspond only to the value from the zone disturbed by the drilling operations in the borehole, due to the small radius of investigation of the pulse test. This transmissivity value may be about 10^{-8} m^2/s, and only the transmissivity obtained from pulse tests coincides with the others when the test sections have around this value.

For the constant head injection tests, the main difficulty was that of the regulation of the flow-rate. It was done by manually operated valves and not automatically. This is specially affecting the early time of the data, where the flowmeter and the corresponding data acquisition were used for flow rates around 3 ml/min, almost reaching the limits of accuracy of the system. This leads to a flow rate signal that was rather noisy for these small values and taking only discrete values.

In spite of that, transmissivity values obtained by transient constant-rate and constant-head injection tests provide the most reliable interpretation for the transmissivity interval from 10^{-7} m/s^2 to10^{-10} m/s^2. That is, for hydraulic conductivity values above 10^{-12} m/s, which may be regarded as the lower measurement limit of the equipment, the agreement is good between this method and the pseudo-steady, pressure fall-off and the slug tests.

Surprisingly the very simple approach with the pseudo-steady state assumption (green lines in Fig. 2) provides values that agree reasonably well with the values obtained from transient injection tests or recovery tests. In general, this kind of test is used for obtaining a first approximation of the transmissivity values, based on the Dupuit formula for steady-state. Doe and Ramer (1982) and Andersson and Persson (1985) presented a comparison of a large number of hydraulic conductivity estimated from pseudo-steady-state and transient tests in fractured rocks. They found that the hydraulic conductivity is generally overestimated by the pseudo-steady-state method. In average, the mean value of K from 423 tests was about 2.7 times greater than the value obtained by a transient analysis. Occasionally, the ratio of the two estimates reached a ratio of 20. They concluded that the error is generally less than one order of magnitude as compared to the transient methods.

In this case study, the pseudo-steady state estimates are also slightly larger than the values estimated with transient injection tests. The difference is lower than one order of magnitude; except in Section 31.21 — 50.00 m where it is slightly higher. It is therefore reasonable to think that the orders of magnitude of the transmissivities are estimated correctly by the test presented in this work.

The selection of a method for determining hydraulic parameters must be made on the basis of the range of transmissivity within which determination is to be carried out. In very low-permeability rocks the interest is centered in determining low hydraulic conductivity with accuracy over a relatively wide range of values, i.e. below 10^{-6} m/s. The measurement limits of the various methods depend on the equipment characteristics and the duration of the tests. The upper measurement limit is defined by the minimum test duration to achieve a good measurement accuracy. The ranges presented in Fig. 5 could be an indication taking into account the features of the equipment used. As final recommendation it could be said that transient constant-head injection tests, and subsequent fall-off phase, are regarded as the best methods. Their advantages include: possibility of measuring a large range of hydraulic conductivity; negligible borehole storage effects; larger radius of investigation than other methods; possibility of determining the skin factor, type of aquifer, and boundaries. The pressure fall-off test allows comparing the results with values obtained from the injection phase.

In this work, analytical solutions were used to interpret independently every single hydraulic test. Numerical interpretation could have been an alternative technique allowing to account for the well bore history and to interpret globally a series of tests (as shown for example by Johns, 1998). This is a topic of possible future development in the Hytool toolbox but could not be tested during this work.

Finally, the results obtained in this work compares well with values from other sites in the world. For comparison, keeping in mind the limitations due to the fractured nature of the medium, hydraulic conductivities were computed by dividing the transmissivities by the length of the test sections. Based on the 40 estimated hydraulic conductivities, basic statistical estimators (minimum values, median, and maximum) were computed and compared with the values that were obtained from the bibliography (Table 1). Note that some details about the different sites are provided in Appendix 1. Table 1 shows that hydraulic conductivities estimated in Cadalso (10^{-12} m/s – 10^{-7} m/s) fall within the range of values that were obtained in the other sites worldwide (10^{-13} m/s to 10^{-4} m/s). The median for Cadalso de los Vidrios ($K = 8.6\ 10^{-10}$ m/s) is lower than the values reported as most frequent for the other case studies. This is not surprising because the site is located in a quarry (exploited for ornamental rocks) that is known for the good quality of its granite, i.e for the small amount of fractures that are present in the granite body.

Table 1
Comparison of the hydraulic conductivity values estimated in this study and those published in other granitic formations worldwide (Appendix A).

	Hydraulic conductivity [m/s]		
Test site	Min	Most frequent	Max.
Cadalso de los Vidrios, Spain	$2.8.\ 10^{-12}$	10^{-10}	$3\ 10^{-7}$
Aspö hard rock laboratory, Sweden	$3.\ 10^{-10}$		10^{-8}
Oliluoto research site, Finland	10^{-9}		10^{-8}
Stripa research site, Sweden	10^{-11}	10^{-9}	10^{-8}
Grimsel test site, Switzerland	10^{-13}	10^{-9}	$4.\ 10^{-4}$
Black forest, Germany	$8.\ 10^{-7}$	$7.\ 10^{-6}$	$7.\ 10^{-5}$
Carnmenellis, United Kingdom	10^{-9}	10^{-8}	10^{-5}
Lac de Gras and Lac du Bonnet, Canada	10^{-13}	10^{-7}	10^{-4}
Graphton County, United States	10^{-8}		$4.\ 10^{-7}$

Table 2
Results obtained in the hydraulic characterization campaigns carried out in the granite of Cadalso de los Vidrios (Spain).

Top [m]	Base [m]	T [m^2/s]	K [m/s]	Test phase	Test type	File name
13.00	**31.79**	**6.1E-06**	**3.2E-07**	**1**	**Pseudo-steady**	**cvf12ip**
13.00	**31.79**	**1.8E-06**	**9.4E-08**	**1**	**Slug**	**cvf13s**
13.00	31.79	4.3E-08	2.3E-09	1	Pulse	cvf14p
31.21	50.00	5.2E-07	2.7E-08	1	Pseudo-steady	cvf16ip
31.21	**50.00**	**2.6E-08**	**1.4E-09**	**1**	**Constant head**	**cvf15nc**
32.00	**37.83**	**3.6E-08**	**6.2E-09**	**2**	**Constant head**	**cvf223nc**
32.00	**37.83**	**1.1E-08**	**1.8E-09**	**2**	**Slug**	**cvf221s**
32.00	37.83	1.6E-09	2.7E-10	2	Pulse	cvf224p
39.00	**46.00**	**4.0E-09**	**5.7E-10**	**3**	**Constant head**	**cv2s1nc2**
39.00	**46.00**	**5.6E-10**	**8.0E-11**	**3**	**Recovery**	**cv2s1nc2r**
39.00	46.00	6.5E-09	9.3E-10	3	Pulse	cv2s1p1
54.71	73.50	1.1E-09	5.8E-11	1	Pseudo-steady	cvf17ip
54.71	**73.50**	**2.2E-10**	**1.2E-11**	**1**	**Constant head**	**cvf18nc**
54.71	**73.50**	**2.1E-10**	**1.1E-11**	**1**	**Recovery**	**cvf18ncr**
63.15	**68.98**	**4.3E-10**	**7.4E-11**	**2**	**Constant head**	**cvf226nc**
63.15	68.98	2.5E-08	4.3E-09	2	Pulse	cvf225p
77.31	**96.10**	**4.7E-08**	**2.5E-09**	**1**	**Pseudo-steady**	**cvf19ip**
77.31	**96.10**	**9.4E-08**	**5.0E-09**	**1**	**Constant head**	**cvf110nc**
90.00	**97.00**	**2.4E-10**	**3.4E-11**	**3**	**Constant head**	**cv2s2nc1**
90.00	**97.00**	**1.2E-10**	**1.7E-11**	**3**	**Recovery**	**cv2s2nc1r**
90.00	97.00	2.0E-08	2.9E-09	3	Pulse	cv2s2p1
91.50	97.33	1.8E-09	3.1E-10	2	Pseudo-steady	cvf228ip
91.50	**97.33**	**2.7E-10**	**4.7E-11**	**2**	**Constant head**	**cvf229nc**
91.50	97.33	5.2E-09	8.9E-10	2	Pulse	cvf227p
97.36	**116.15**	**2.6E-10**	**1.4E-11**	**1**	**Pseudo-steady**	**cvf111ip**
97.36	**116.15**	**5.2E-11**	**2.8E-12**	**1**	**Constant head**	**cvf112nc**
97.36	116.15	4.3E-08	2.3E-09	1	Pulse	cvf114p
106.00	**113.00**	**4.9E-10**	**7.0E-11**	**3**	**Constant rate**	**cv2s3cc1**
106.00	113.00	2.0E-08	2.9E-09	3	Pulse	cv2s3p2
121.50	**140.29**	**6.1E-09**	**3.2E-10**	**1**	**Pseudo-steady**	**cvf121ip**
121.50	**140.29**	**1.5E-09**	**8.0E-11**	**1**	**Constant head**	**cvf122nc**
141.29	**160.08**	**1.5E-08**	**8.2E-10**	**1**	**Pseudo-steady**	**cvf120ip**
141.29	**160.08**	**7.3E-09**	**3.9E-10**	**1**	**Constant head**	**cvf119nc**
161.00	**179.79**	**1.8E-08**	**9.3E-10**	**1**	**Pseudo-steady**	**cvf118ip**
161.00	**179.79**	**6.9E-09**	**3.7E-10**	**1**	**Constant head**	**cvf117nc**
161.00	**179.79**	**1.5E-09**	**8.0E-11**	**1**	**Recovery**	**cvf117ncr**
177.00	**195.79**	**1.8E-08**	**9.3E-10**	**1**	**Pseudo-steady**	**cvf115ip**
177.00	**195.79**	**3.2E-08**	**1.7E-09**	**1**	**Pulse**	**cvf116p**
15.68	200.00	4.5E-07	2.4E-09	1	Constant head	cvf130nc
15.68	200.00	6.5E-07	3.5E-09	1	Recovery	cvf130ncr
Minimum		**5.2E-11**	**2.8E-12**			
Maximum		**6.1E-06**	**3.2E-07**			
Median		**7.1E-09**	**8.6E-10**			

The bold items correspond to the test values represented in Fig. 2.

Overall the results of the different tests presented in this work (Table 2) and the comparison with worldwide estimation lead us to conclude that the fractured leucogranites of Cadalso de los Vidrios have a low permeability due to the low degree of fracturation. The study shows as well that it is important to use a set of different tests in order to compare the results and evaluate the reliability of the estimates. This is very important especially for low permeability media in which the field experimentations are particularly difficult.

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Appendix A

This appendix provides a description of the main sites where hydraulic testing has been performed in granite up to 1 km below the surface. Much of these tests are related to studies related to the safety of nuclear waste repositories.

Carnmenellis granite in Cornwall, UK

The Carnmenellis granite is part of the Cornubian batholith of SW England. Multi-packer hydraulic tests carried out in boreholes have shown that the flow of water through the rock is largely confined to narrow zones separated by areas of very low permeability. Correlation of the hydraulic data with geological data from oriented cores has shown that most of the flow is associated to discrete geological features, including veins, dykes and joints, particularly in the upper 250 m of the granite. The hydraulic conductivity values of the granite ranged from 10^{-9} to 10^{-5} m s^{-1}, with 10^{-8} m s^{-1} being more typical (Watkins, 2003).

Äspö hard rock laboratory (ÄHRL) in Sweden

The Äspö Hard Rock Laboratory is the most important part of the work SKB (The Swedish Nuclear Fuel and Waste Management) has performed in the last 30 years on designing a deep repository for high-radioactive nuclear wastes, and is located near Oskarshamn, south of Stockholm, Sweden (Stanfors et al., 1999). The most conductive lithological unit is the fine-grained granite due to the existing numerous joints. Fracture zones with different hydraulic conductivity values characterize the geological formation in the area. Hydraulic conductivity values obtained mainly from injection tests with 3-m test sections, between packers, were between $3\cdot10^{-10}$ and $3\cdot10^{-8}$ m s^{-1}, with no clear decrease with depth (Walker et al., 1997).

Olkiluoto research site in Finland

Olkiluoto, in the municipality of Eurajoki, Finland, was chosen by Posiva Oy (the Finnish Expert Organization in Nuclear Waste Management) as the site of the final disposal facility for spent nuclear fuel. A study made by SKB and Posiva Oy showed that the hydraulic conductivity in this area composed by granite and mica gneiss varied from 10^{-9} to 10^{-8} m s^{-1} (Pitkänen et al., 1992).

Stripa research site in Sweden

The Stripa project, a cooperative project between seven countries directed by SKB, involved a series of in situ experiments with the objective of investigating the mechanical and hydrogeological behaviour of granitic rocks in the context of their potential to host a radioactive waste repository. Different types of hydraulic tests were made in an attempt to identify the hydraulic characteristics. The Stripa project, in the granite of the Baltic shield, showed hydraulic conductivities between 10^{-11} and 10^{-8}, being the most common value of 10^{-9} m s^{-1} (Gale et al., 1987, 1982), diminishing with depth.

Grimsel Test Site, Switzerland

The Grimsel Test Site is a first-generation underground rock laboratory used to investigate hard fractured rocks and is operated since 1984 by the Swiss National Cooperative for the Disposal of Radioactive Waste (NAGRA). The Grimsel Test Site is located in the crystalline rock of the Central Aar Massif (Nagra, 1989). A series of boreholes drilled into the granite from Northern Switzerland provided conductivity values between $4\cdot10^{-4}$ and 10^{-13} m s^{-1}. This enormous variation relates to local variations in fracture density, being the most abundant hydraulic conductivity value of 10^{-9} m s^{-1} (Leech et al., 1984).

Black Forest in Germany

The hydraulic properties of the crystalline basement of the Black Forest in Germany have been studied by means of a large number of hydraulic tests in wells. The mean hydraulic conductivity in this granitic area was of $7\cdot10^{-6}$ m s^{-1}, ranging between $8\cdot10^{-7}$ m s^{-1} and $7\cdot10^{-5}$ m s^{-1} (Stober and Bucher, 2005). The hydraulic conductivity values showed a very large variance near the surface, but they decreased with depth.

Lac de Gras in Canada

The Lac de Gras is situated in the Canadian Shield, in the Northwest Territories, and it consists mainly of a granite basement. A mean hydraulic conductivity value for this area was of $2\cdot10^{-7}$ m s^{-1}, decreasing with depth (Kuchling et al., 2000).

Lac du Bonnet in Canada

The Lac du Bonnet is located in Southeastern Manitoba, and it has been studied as part of the Canadian Nuclear Fuel Waste Management Program by the Atomic Energy of Canada Limited. The most fractured area of the granite from this area showed a hydraulic conductivity of 10^{-4} m s^{-1}, while in the unfractured area, values ranged from 10^{-13} to 10^{-9} m s^{-1} (Stevenson et al., 1996).

Mirror Lake, USA

Mirror Lake, located in Grafton County, New Hampshire, USA, has been studied using multiple-well pumping tests. The hydraulic conductivity obtained from pumping tests in this area was between $4\cdot10^{-7}$ and $1.8\cdot10^{-8}$ m s^{-1} (Hsieh et al., 1999).

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