IN SITU PERMEABILITY OF HOT DRY ROCK

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Abstract. The purpose of the study was to estimate the effect of fluid properties, external stress, and temperature on macroscopic parameters of low-porosity crystalline rock containing parallel fluid-filled inclusions. Inclusions were modeled as ellipsoids of revolution, and the effective-medium concept based on the Eshelby algorithm was used for numerical modelling. Granite saturated with brines of different composition (salinity) at temperatures in the range 100-300 ^{o}C was considered. The results are presented for effective permeability and velocity of slow shear-wave for different values of pore pressure and external uniaxial compression applied to a rock and with account for P-T dependence of physical properties of brines.

Key words: cracked rock, pore fluids, permeability, stress field, pore pressure, temperature, anisotropy

1. Introduction

Macroscopic *in situ* permeability of low-porosity crystalline rocks is of a great interest for the investigation of suitable site for the disposal of radioactive wastes and for a study of geothermal systems which are often embedded in fractured crystalline formations. Under external stress, variations of internal crack geometry can occur due to a closure of microcracks, leading to changes of macroscopic rock permeability. Data on stress-induced variations of effective permeability may be useful as well for earthquake prediction, because macroscopic seismic and transport properties of rocks are sensitive to temporal variations of rock parameters due to changes of stress field.

Macroscopic properties of fluid-saturated cracked rock depend greatly on physical parameters of pore fluids. Under pressure and temperature pore fluids can change greatly their physical characteristics (density, thermal conductivity, viscosity, bulk modulus) which may result in a drastic change of the overall physical parameters of a rock. The purpose of the study is to estimate the influence of pore fluid composition under different P-T conditions on macroscopic elastic (shear velocities) and transport parameters (permeability) of crustal rocks.

In the upper crust, at 5-10 km depth, where fluid-filled cracks and pores are likely to exist, pore-fluids are expected to be at pressures up to 100-300 MPa and temperatures 100-300^{o}C in platform areas and up to 500^{o}C in tectonically active regions. Numerical estimates show that fluid-filled elliptical cracks are not likely to exist deeper than 3 km, because confining pressure required to close elliptical cracks is proportional to the aspect ratio of cracks and Young's modulus of the saturating fluid (e.g. Doyen, 1987). However, for crack geometries more realistic than elliptical, significant *in situ* porosity may be found at confining pressures up to 300 MPa (Zang, 1993). Moreover, field observations show that in nature cracks can exist at depths of about 10 km due to high pore pressures (Christensen, 1989) which can be produced by tectonic stress, chemical reactions or phase changes in a saturating fluid.

In the present study we will consider only stress-induced changes of pore pressure and will limit ourselves by low fluid pressures when no hydraulic fracturing can occur (Zoback and Haimson, 1983). Modeling will be presented for cracked granites with very low aspect ratio of cracks, saturated with brines of different salinity and at temperature in the range 50-300^{o}C, where the process of thermal microcracking is not essential (e.g., Le Ravalec and Gueguen, 1994). The goal of the study is to estimate the possible range of permeability and seismic velocity changes for different fluid composition and pore pressure under stress and temperature conditions typical for the upper 5-10 km of the crust.

2. THE MODEL

Physical properties of *in situ* rock mass depend on a large number of parameters such as rock lithology, porosity, and P-T conditions which affect the physical characteristics of mineral components. The situation becomes even more complicated when an attempt is made to predict transport properties of fluid saturated rocks, which depend on physical state of both the confining rock and the high-pressure fluid, as well as on a fracture pattern (e.g., fracture geometry and connectivity, roughness of crack walls). If a chemical interaction between a rock and a fluid occurs, it will result in mineral dissolution or crack healing leading to a change of a fracture pattern; moreover, a rate of chemical reactions in a rock depends to a great extent on T-P conditions.

A complicated structure of a real rock makes it practically impossible to describe the behavior of such a complex dynamical system by a mathematical model, which could account for all physical and chemical phenomena that can occur at *in situ* conditions. However, under certain assumptions and simplifications, it is possible to understand the general behavior of the most essential characteristics of such a medium. That is why, for a calculation of macroscopic physical properties of heterogeneous materials such as rocks, which appear to behave as statistically homogeneous above the scale of their inhomogeneity, effective medium theories (EMT) are widely applied (e.g. Walsh, 1965; Salganik, 1973; O'Connell & Budiansky, 1974, 1976; Koplik, 1981; Sen et al., 1981; David et al., 1990). In the present study, when estimating elastic moduli of a medium under external stress, we follow the method of Eshelby (Eshelby, 1957; Hudson, 1980; Cheng, 1993). For simplicity we consider the case of parallel identical cracks oriented normal to the applied uniaxial compression. However, the model can be used for a rock of arbitrary type of symmetry.

The model rock was assumed to be formed by a low-porosity matrix (granite) containing non-interacting, non-intersecting identical inclusions (cracks), which were modeled by ellipsoids of revolution with small aspect ratio $\alpha \ll 1$. Crack roughness was not accounted for in the model (its effect was considered by Gavrilenko and Gueguen, 1989). Cracks are saturated with brines of different salinity at different pore pressures and temperatures.

The model was applied to consider rock under the undrained regime, when there is no evacuation of fluid from crack volume and heating occurs at constant fluid mass. These conditions are valid either for a very low permeable rocks where no connected network of fractures and pores is formed, or for a relatively weak external stress acting during such short periods of time that almost no fluid is evacuated from the rock mass. In this case, the main contribution to changes of macroscopic physical properties of rocks is made by the elastic closure of cracks resulting from the action of applied stress and differential fluid pressure.

We assume that host rock and fluids are chemically inert and, hence, do not consider effects of dissolution or crack healing. As we limit our study by the case of a very low-porosity, low-permeable unfragmented rock, percolation in a crack system was not considered. Even at high values of pore pressure, external stress applied to a rock will not allow cracks to join together and thus to form through-going fractures and percolating network.

The calculation scheme is based on the results of Chesnokov and Zatsepin (1991), where the general case of ellipsoidal inclusions initially distributed over the length L and aspect ratio α was considered. It provides the algorithm for the calculation of effective elastic moduli of a crack ensemble as a function of applied stress and fluid pressure. This algorithm together with the algorithm for numerical calculations of effective thermal conductivity of a medium with ellipsoidal inclusions (Artemieva and Chesnokov, 1991) was applied to permeable cracked solids (see Appendix).

As earlier (Artemieva, 1996), stress-induced changes of crack geometry (crack volume) and, hence, pore pressure were considered at the first step of calculations. Physical parameters of a saturating fluid (density, bulk modulus, acoustic velocity) were recalculated for a new value of pore pressure and for given temperature. Then, effective-medium theory was applied to calculate macroscopic transport and elastic properties of the rock for different composition (salinity) of a saturating fluid and under different stress conditions (with account for P-T dependence of physical characteristics of brine).

3. RESULTS

3.1 Model parameters

The model is specified by densities and seismic velocities of the host rock (granite) and the saturating fluid (brines), crack geometry (α) and crack density (ε), fluid temperature, initial pore pressure, and values of external uniaxial compression. We studied the behavior of macroscopic parameters of brine-saturated granite under the action of uniaxial compressional stress of about 150 MPa. Such stress values can be expected, for example, for thrust faulting (Gretener, 1977).

All results are presented for aspect ratio $\alpha=10^{-3}$. Experimental investigations (Hadley, 1976) revealed that microcracks of such geometry are typical for Westerly granite. According to our estimates of EMT validity for permeability calculations (see Appendix), the results refer to cracks with length L>1 mm. Granite with density $\rho=2.7$ g/cm^3, $V_p=6.3$ km/s and $V_s=3.64$ km/s was considered as the host rock. To make the effect of fluid-saturated cracks on macroscopic properties of a rock more pronounced, we present the results of numerical modeling for the case of initial crack density $\varepsilon=0.1$. (Eshelby algorithm is valid for ε not higher than 0.1). Even for such relatively high values of crack density, porosity Φ of a rock is very low ($\Phi=4/3\pi\alpha\varepsilon$). The difference between numerical estimates of slow shear velocity and effective permeability calculated for $\varepsilon=0.05$ and $\varepsilon=0.1$ was found to be about 5-10%. At higher values of ε ($\varepsilon>0.1$) a medium cannot be considered as intact and unfractured, the effective medium concepts cannot be applied any longer and crack-to-crack interaction must be taken into account.

3.2 Physical properties of brines

Brines are the most common pore fluids and can vary widely in composition from almost pure water to highly saturated saline solutions. In field studies, brine salinity can be easily obtained from its resistivity, which is usually calculated during well log analysis.

That is why in our modelling, we considered brines of different salinity S (different concentration of NaCl dissolved in pure water) as saturating fluids. Fig. 1 shows the

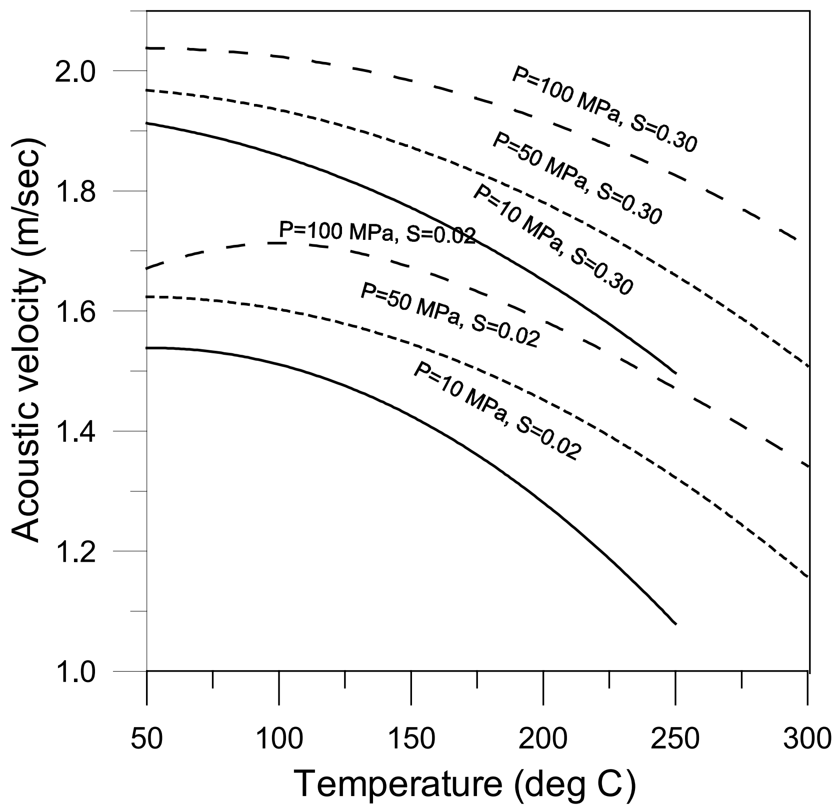

Fig. 1. Acoustic velocity in brines as a function of their salinity S (NaCl concentration), pressure and temperature. (The values calculated from the data of Batzle & Wang, 1992).

dependence of acoustic velocity in brines on P-T conditions and brine composition (salinity). The curves were calculated from the data of Batzle and Wang (1992). The results show a significant, almost linear, decrease of all physical properties of brines (density, bulk modulus, acoustic velocity) with temperature at $T>100^oC$; at lower temperatures ($T<50^oC$) the inverse type of dependence was found for bulk modulus and acoustic velocity, the maximal values of these parameters being observed at $T \cong 50\text{-}100^oC$.

As opposed to temperature, increasing salinity or/and pressure increases density and acoustic velocity in brines; however, the effect of salinity variations is more pronounced. Brine viscosity depends mainly on salinity, its pressure dependence is small (Batzle and Wang, 1992). Temperature effect on brine viscosity is essential only for $T<100^oC$. That is why in the present study we did not account for possible viscosity variations of a saturating fluid due to its heating.

These data on P-T-S dependence of physical properties of brines were used for numerical modelling.

3.3 Changes of crack geometry under uniaxial compression

External uniaxial stress applied to a cracked (porous) rock results in a gradual closure of microcracks oriented normal to stress. In our study we consider an influence of stress acting during a short enough period of time. In this case, the main contribution to changes of macroscopic physical properties of rocks is made by the elastic closure (opening) of cracks resulting from the action of applied stress and differential fluid pressure. In terms of inclusions characteristics the process of cracks closure (opening) results in changes of crack geometry (aspect ratio α) and concentration (crack density ε). Variation of external stress promotes deformation in an ellipsoidal inclusion (crack) and, hence, changes of pore pressure p^f. Under

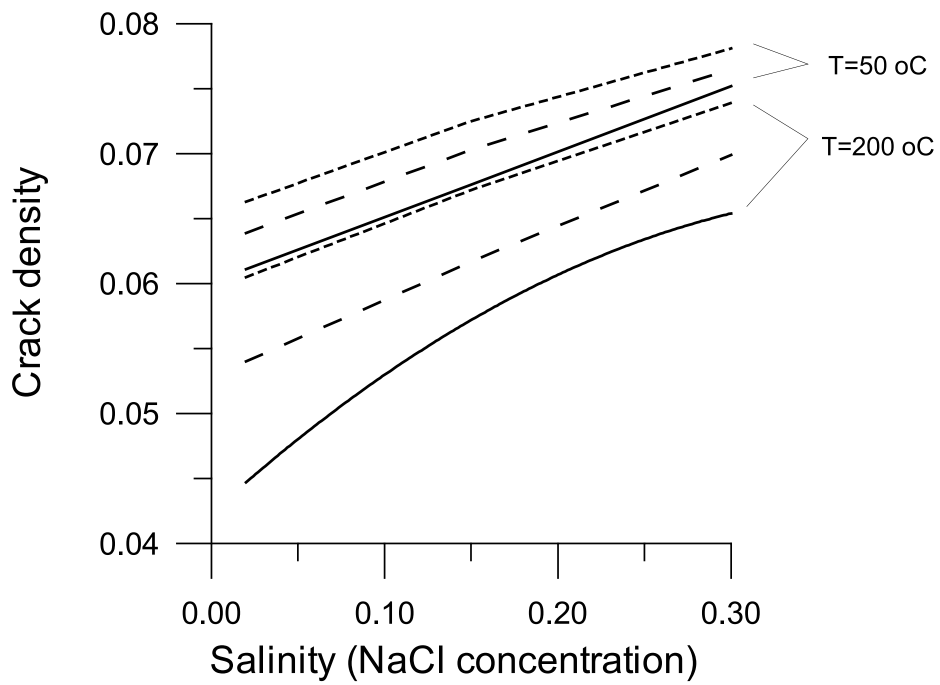

Fig. 2. Crack density Ncr as a function of brine salinity S and temperature T for granite with parallel brine-saturated cracks. Initial model parameters: pore pressure P(0)=10 MPa (solid lines), 50 MPa (long dashes), 100 MPa (short dashes). Uniaxial compression 150 MPa. Initial crack density Ncr(0)=0.1; aspect ratio of cracks AR=0.001.

the assumption of a uniform strain (in the volume of an inclusion), it is possible to determine the crack aperture for an ellipsoidal inclusion (i.e., a length of the short axis) as a function of stress (and, in general case, of orientation angles of an inclusion). As a crack aperture decreases when a crack is closed, its aspect ratio increases; the effect is more pronounced for initially small (low α) and dry cracks.

Fig. 2 and 3 illustrate variations of crack geometry and concentration as a function of temperature and salinity of brines, for different values of initial pore pressure. The results of modelling show that under uniaxial stress applied to a rock mass, cracks are closed faster if they are saturated with low-density (small values of salinity) or high-temperature brines at low

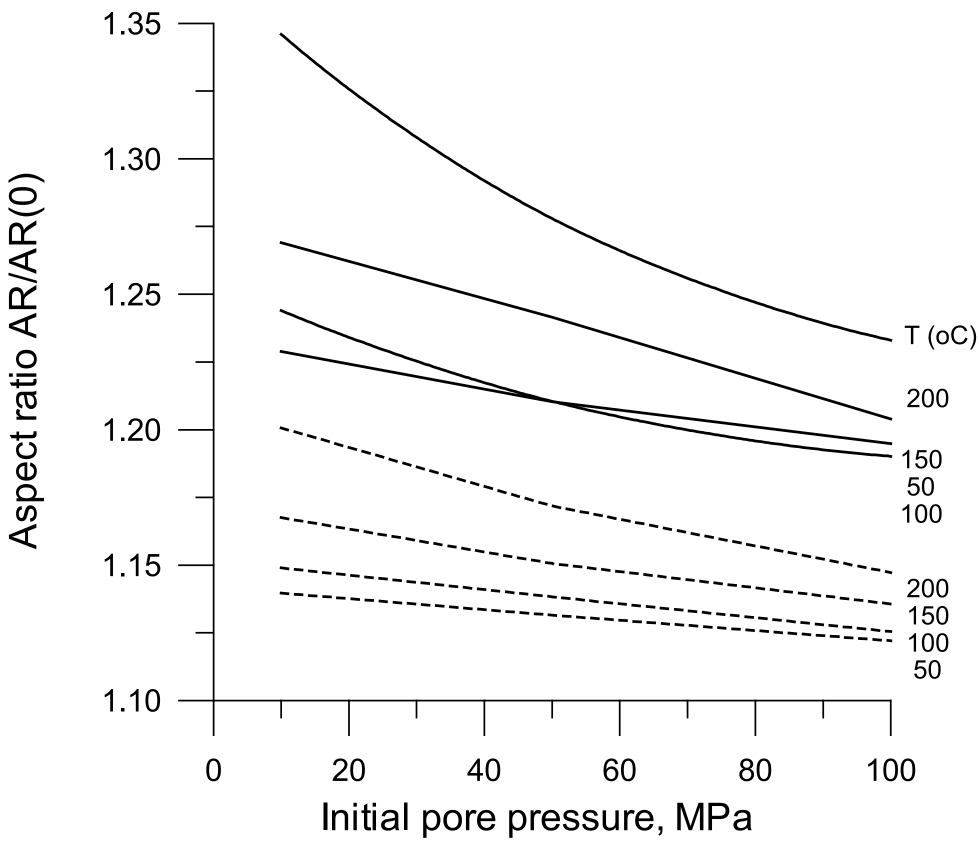

Fig. 3. Aspect ratio of brine-saturated cracks under uniaxial compression of 150 MPa as a function of initial pore pressure, brine temperature (numbers near curves) and salinity (solid lines for S=0.02, dashed - for S=0.30). Model of granite with parallel cracks; initial Ncr=0.1; AR=0.001.

values of pore pressure. However, the effect of salinity on closure of microcracks is the most essential: under the same values of uniaxial compression, crack density of a rock saturated with brines at the same temperature and pore pressure but of different salinity (S=0.02 and 0.30) can differ by about 50%.

3.4 Variations of pore pressure under uniaxial compression

External compressional stress applied to a porous rock promotes variations of crack aperture which, in their turn, result in changes of pore volume. If a crack volume is decreased during the deformation process and a rock is at undrained regime (i.e. no evacuation of fluid from pore and/or crack space occurs), an increase of fluid pressure should occur.

Fig. 4 illustrates the behavior of pore pressure as a function of brine temperature, salinity and initial pore pressure. When a pore fluid is relatively cold (T<150 ^{o}C; such temperatures are typical for the upper 3 km of the crust), brine-filled cracks in a rock behave as "stiff" inclusions,

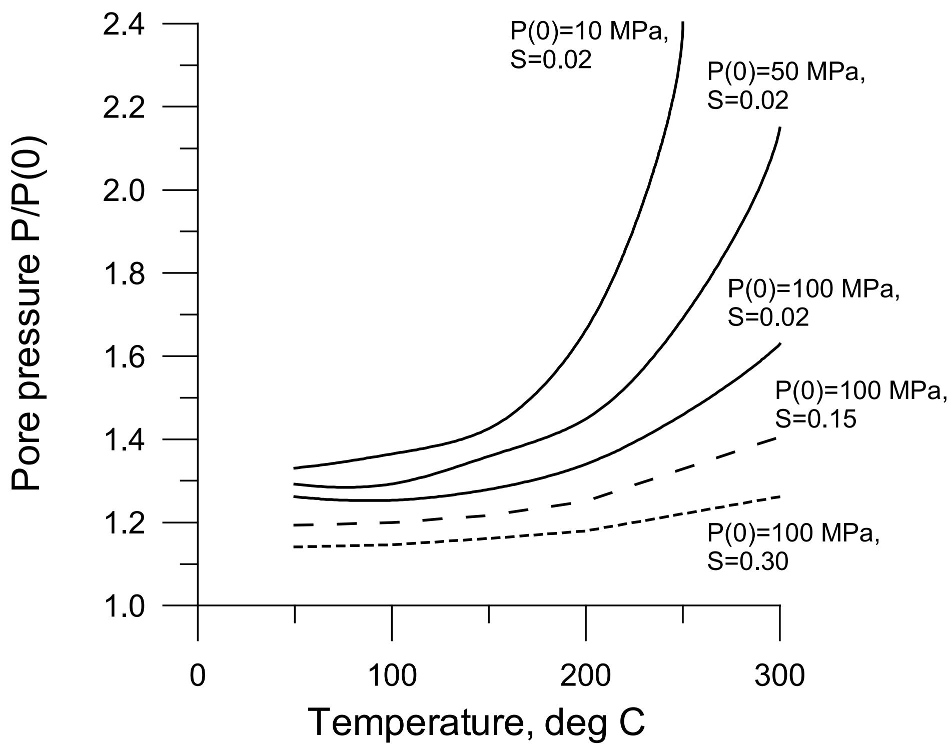

Fig. 4. Pore pressure as a function of temperature, brine salinity S and initial pore pressure P(0) for granite with parallel cracks saturated with brines. Uniaxial compression 150 MPa, Ncr=0.1; AR=0.001.

and external stress does not lead to essential variations of a crack volume and pore pressure. In this temperature interval crack behavior is almost independent of brine salinity. However, if cracks are filled with hydrocarbon gases or gas-saturated oils, which elastic properties can vary dramatically at T≅~50-100 ^{o}C, a composition of a saturating fluid is an important parameter which affects greatly variations of pore pressure even at relatively low temperatures (Artemieva, 1996).

The effect of brine salinity on variations of pore pressure becomes dramatic at temperatures 200-300 ^{o}C, As one can expect, under external compression cracks saturated with almost pure water (S=0.02) are closed the first, while those filled with high-density fluids change little their volume even at high temperatures. On the whole, the higher temperature is, more pronounced is a change in pore pressure. As pore pressure prevents cracks of being closed by the action of tectonic stress, it is evident that cracks saturated with fluids at low values of initial pore pressure are closed the first and at relatively low values of compressional stress. If initial pore pressure is of the same order of magnitude as tectonic stress, small changes of pore volume and fluid pressure can be expected only for low-density brines at T>250-300 ^{o}C. However, if cracks are filled by gas-saturated low-density fluids, they can be almost entirely closed at such temperatures (Artemieva, 1996).

3.5 In situ effective permeability and shear-velocities

Fig. 5 a, b depict graphically the form and behavior of specific permeability of brine-saturated granite as a function of brine temperature and composition. The results are presented for the direction along applied stress (remind that we considered the model with parallel identical cracks subject to uniaxial compression normal to crack orientation). Permeability in the orthogonal direction will be almost equal to that typical for the matrix, which means that an essential anisotropy of macroscopic permeability exists under these conditions.

Numerical results indicate that at T>100^{o}C permeability of a fluid-saturated rock decreases almost linearly with temperature increase. A notable reduction of granite permeability at elevated temperatures was found in laboratory experiments (Moore et al., 1994); however, it is likely that in this study a large part of effect was due to mineral dissolution and precipitation.

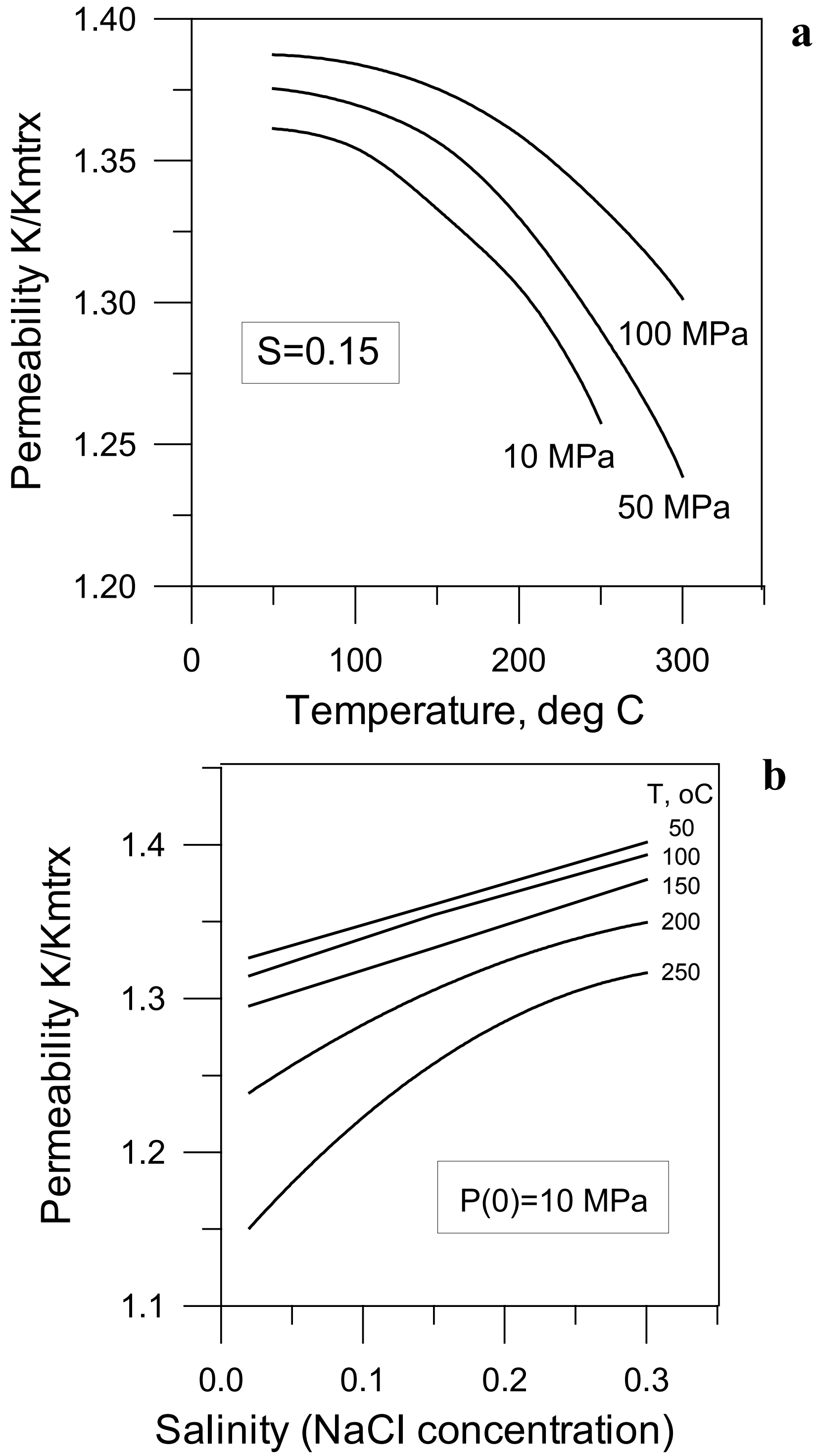

Fig. 5 a, b. Permeability of granite with brine-saturated parallel cracks (in direction parallel to crack orientation) as a function of brine salinity S, temperature and initial pore pressure P(0). Uniaxial compression 150 MPa. Model parameters:Ncr=0.1, AR=0.001.

The effect of fluid composition on macroscopic permeability of a rock is the most dramatic: dissolution of a large amount of mineral components in water (S=0.3 or 300 000 PPM) can increase rock permeability by 10-15%.

It is important that even at high values of compression, a large part of brine-saturated cracks remains open and, thus, rock permeability differs from matrix permeability of a host rock. Experimental studies (Pratt et al., 1977) show that even under high values of uniaxial compression normal to crack orientation, permeability of granite is greater than its matrix permeability. According to the data from the Kola super-deep borehole, even near the borehole base, where hydrostatic pressure is extremely high and, hence, all open cracks should be tightly closed, a strong circulation of highly mineralized water was observed (Kozlovsky, 1982). At a depth of about 3.5 km and 7.8 km a sudden decrease of acoustic velocity in the Kola borehole was recorded, which can be interpreted by as an increase in porosity and, as a consequence, an increased rock permeability at these depths (Kozlovsky, 1984).

Fig. 6 a, b show the dependence of the slow shear wave velocity in brine-saturated granite on fluid temperature, salinity and pore pressure. As it follows from the comparison of results in Fig. 5-7, changes of shear velocity and permeability caused by varying external conditions are coupled. As for macroscopic permeability, a behavior of shear waves under uniaxial compression is strongly anisotropic resulting in shear-wave splitting which is widely observed in nature. Oppose to permeability, higher temperatures of a saturating fluid result in higher values of seismic velocities, while an increase of brine salinity (density) is marked by a decrease of shear velocity associated with a high rock porosity.

The dependence of effective permeability and shear velocity on the value of uniaxial compression is shown in Fig. 7. At low values of stress, a large fraction of cracks remains open due to high pore pressures. An increase of external stress results in gradual closure of microcracks; for the same values of pore pressure, cracks with small aspect ratio, or saturated either by low-density or by hot fluids are closed the first (Fig. 2-3). When stress is high enough to close essentially a large group of cracks, a decrease of effective permeability accompanied by an increase of seismic velocities occurs; for extremely high stress values when almost all cracks are tightly closed permeability and seismic velocities behave asymptotically and tend to the matrix values (Fig. 7).

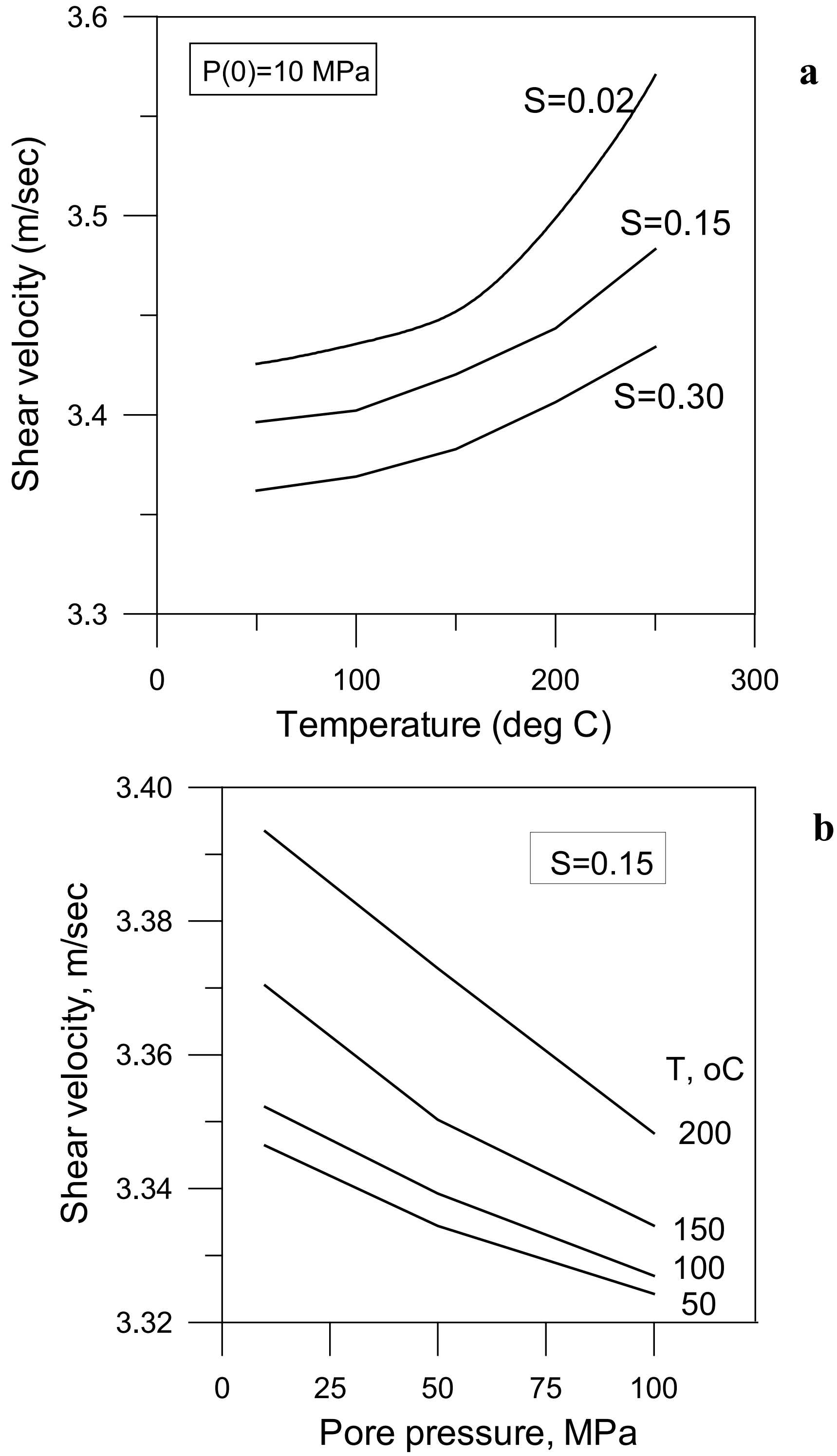

Fig. 6 a, b. Shear velocities in granite with parallel cracks (in direction normal to crack orientation) as a function of brine salinity, temperature and initial pore pressure. Uniaxial compression 150 MPa; Ncr=0.1, AR=0.001.

4. Discussion

A distribution of fluid-filled cracks, microcracks and pore-spaces exist in most rocks and are often preferentially aligned by the stress-field acting on the rock mass. In our study we considered granite saturated with brines at P-T conditions typical for the upper crust (down to 5-10 km). At these depths, fractures and pores can be held open only if a pore-fluid pressure is comparable to the lithostatic pressure, i.e. is about 50-100 MPa. At these depths temperature can vary in the range from about 0^oC at the surface to $300\text{-}500^oC$ at 10 km depth depending on the tectonic and thermal regime of an area.

Gold and Soter (1984) mention indirect evidence obtained by electrical measurements for the existence of open fluid-saturated layers in the crystalline rocks at near lithostatic pressure; seismic studies in the Canadian Shield showed a low velocity layer at depths below 5 km which can be also associated with a zone of high fluid pressure, overlapped by a low

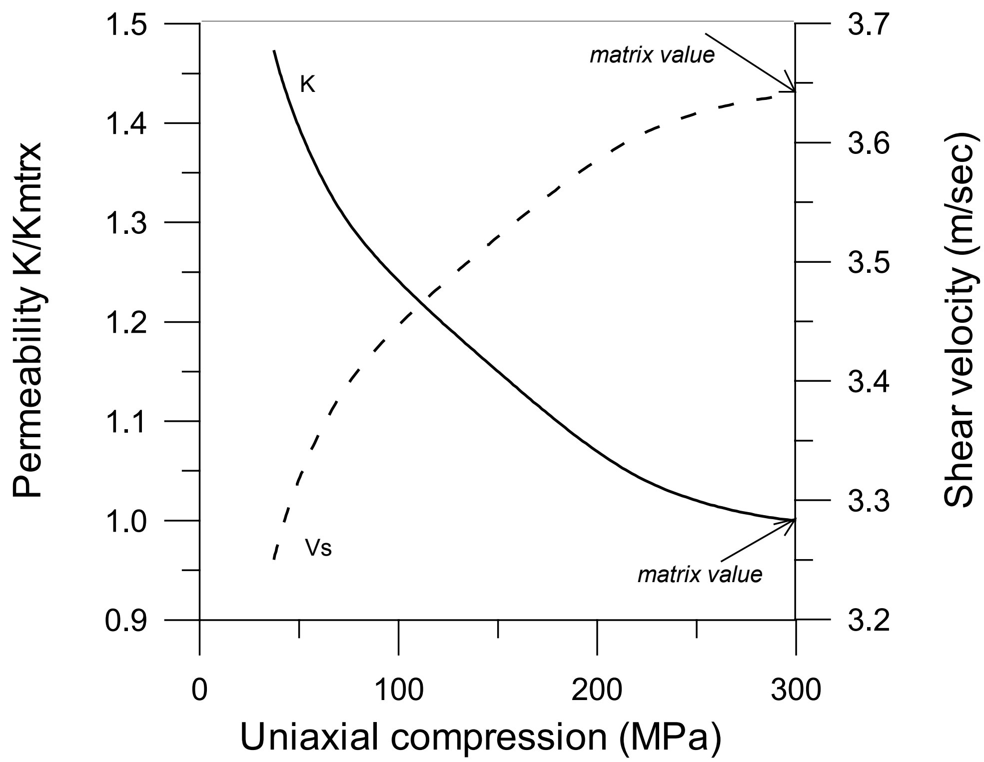

Fig. 7. Permeability and shear-velocity in brine-saturated granite with parallel cracks (in directions correspondingly parallel and normal to crack orientation) as a function of applied uniaxial compression.
S=0.02; P(0)= 10 MPa, T=250 oC; Ncr=0.1; AR=0.001.

permeability 'cap'. However, as it follows from the present results, deep layers should have lower permeability not only due to high lithostatic pressure, but also due to a temperature increase with depth. A possible explanation of the observed phenomenon can be based on a strong dependence of macroscopic rock permeability on a fluid composition (Fig. 5b). It is likely that an increase of permeability with depth can be observed only in deep-seated layers, where a large amount of heavy minerals is dissolved in water (the rate of chemical interactions between a host rock and a fluid strongly depends on pressure and temperature); pores saturated with such high-dense fluids can remain open even under high stress.

At depths where heat exchange reservoirs of hot-dry-rock geothermal heat extraction are usually located (below 3 km), the minimum compressional stress is likely to be horizontal, and cracks tend to be vertical, parallel to the maximum horizontal stress (Crampin, 1990), the average direction of which is controlled by tectonic forces acting over large areas. Field data from the Cornwall hot-dry-rock geothermal experiments proved the presence of parallel or near-parallel vertical fractures at depths down to 3-4 km (e.g., Pine & Batchelor, 1983). This means that when a fluid is pumped to an exchange reservoir in geothermal experiments, its flux from the injection point to the production well is normal to the principal crack orientation, and thus macroscopic horizontal permeability will behave in the way depicted graphically in Fig. 5 and 7, and a strong dependence of reservoir permeability on fluid temperature and composition should be expected..

Field experiments in geothermal systems of Iceland revealed that, after pumping of cold water into a reservoir, reservoir permeability changed with time as water was heated at *in situ* conditions (Stefansson, 1996). Temperatures of reservoir rocks in geothermal systems of Iceland correspond to the values presented in this paper and are about 100^{o}C or 200-300^{o}C (Axelsson et al., 1996).

As was shown in the previous section (Fig. 7), changes of a stress regime promote variations of crack aperture and, hence, affect elastic properties and macroscopic permeability of a rock mass. As convective heat transfer caused by fluid migration in the crust influences greatly near-surface thermal regime, it is likely, that stress-induced temporal temperature variations in wells can be used as earthquake precursors. Such temperature variations in wells were observed in field studies in Georgia before earthquakes (Buntebarth, ...)

5. CONCLUSIONS

This paper examines the effect of both fluid properties and external stress and temperature conditions on macroscopic parameters of low-porosity crystalline rocks containing parallel fluid-saturated cracks. The following conclusions can be made from the results of the study.

1. The major factor which influences permeability of a rock mass is external stress. Its increase results in a notable reduction of macroscopic rock permeability and its anisotropy. However, this dependence is essential only when the stress value is large enough to start closure of cracks, but does not exceed some critical value when all cracks are closed. An increase of pore-pressure shifts both of these points to higher stress values.

2. Permeability of fluid-saturated crystalline rock decreases with an increase of brine temperature. At a crustal depth of 5-10 km and high values of compressional stress (>250 MPa), only cracks saturated with high-dense brines can remain open. An increase of brine temperature from 100^{o}C to 300^{o}C results in 10-15% decrease of rock permeability.

3. Permeability depends almost linearly on brine density (salinity) and is less sensitive to stress or temperature variations. For P-T conditions of the upper crust, difference in permeability of a rock saturated with brines of different salinity may be as large as 15-20%.

4. Shear velocities in a rock mass, as well as its macroscopic thermal conductivity change simultaneously with permeability, but in the opposite direction. The effect for shear velocities is of the same magnitude as for permeability, while it is much less pronounced for thermal conductivity.

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APPENDIX. APPLICATION OF EMT FOR A CALCULATION OF EFFECTIVE PERMEABILITY

For a permeable matrix, D'Arcy's law for an incompressible fluid is formally analogous to Fourier's law for thermal conductivity:

$$\text{div } v = 0 \tag{A1}$$

$$v = -k^m/\mu \text{ grad } p^f,$$

where v is pore-fluid velocity; k^m - specific matrix permeability; μ - pore-fluid viscosity; p^f is pore pressure. Consider the fluid flux in an ellipsoidal inclusion parallel to the strike of a crack with $\alpha \ll 1$. To a first order approximation, the boundary effects may be neglected, and fluid flux in a plane-parallel channel may be considered. Then, an average velocity v over the cross-section of a channel depends on fluid viscosity μ and channel width h:

$$v = -12\, h^2/\mu \text{ grad } p^f \tag{A2}$$

Equations (A1) and (A2) are analogous to the equation for a heat transfer, and thus some 'effective' medium permeability may be introduced with

$$k^i = Ba^2 \cong 12\, h^2 \tag{A3}$$

as specific 'permeability' for the inclusions. Here B is a numerical coefficient, taking into account the difference between an ellipsoid and a plane channel, where a is the crack aperture. This is true only for a flux in the direction parallel to a crack. For arbitrary orientations of fluid flux with respect to a crack, the concept of a channel width is less valid and the averaged flux velocity in an inclusion will be specified by (A2) with some effective constant k^i depending on an inclusion shape and flux direction. A direct analogy between EMT formulations for thermal conductivity and permeability still is possible in some region of the aperture values $a \gg a^*(k^m)$. It depends on the asymptotic behavior of the general equation for the effective parameters, when $k^i/k^m \gg 1$ and the effective parameters do not depend upon k^i . This condition may be presented as:

$$k^i/k^m = B\, a^2/k^m = B\, AR^2\, L^2 / k^m \gg 1. \tag{A4}$$

If we introduce some 'critical' crack aperture a^* and crack length $L^* = a^* /\alpha$, where

$$a^* = (k^m /B)^{1/2} \tag{A5}$$

then (A4) can be written in the equivalent form:

$$(a/ a^*)^2 = (L/L^*)^2 \gg 1. \tag{A6}$$

$L^* \cong 10^{-4}$ mm for granite with matrix permeability $k^m \cong 5 \bullet 10^{-19}$ m^2 and $\alpha = 10^{-3}$.

As an illustration, we consider the behavior of effective specific permeability for aligned parallel cracks when fluid flux is along cracks. The computational algorithm for effective thermal conductivity (Artemieva and Chesnokov, 1991) was used by replacing thermal conductivities χ^m and χ^i with k^m and $k^i = 12\, a^2 = 12\alpha^2 L^2$, correspondingly.

In Fig.A, the normalized effective specific permeability $k(L)/k^m$ for a flux parallel to the striking of aligned cracks is shown (matrix permeability was taken equal to $5 \bullet 10^{-19}$ m^2 for granite and $5 \bullet 10^{-14}$ m^2 for sandstone). Cracks with length $L \leq 10L^*$ (where $L^* = L^*(k^m, \alpha)$ in the form of equation (A5)) contribute very little to the effective permeability (due to a high viscous friction of a fluid in a crack). At the same time, for cracks of the length $L \geq 10L^*$ the effective permeability is asymptotic. The numerical coefficient B=10 was taken from the comparison of Fig.A with the calculated value L^*. For all other directions of flux with respect to a crack

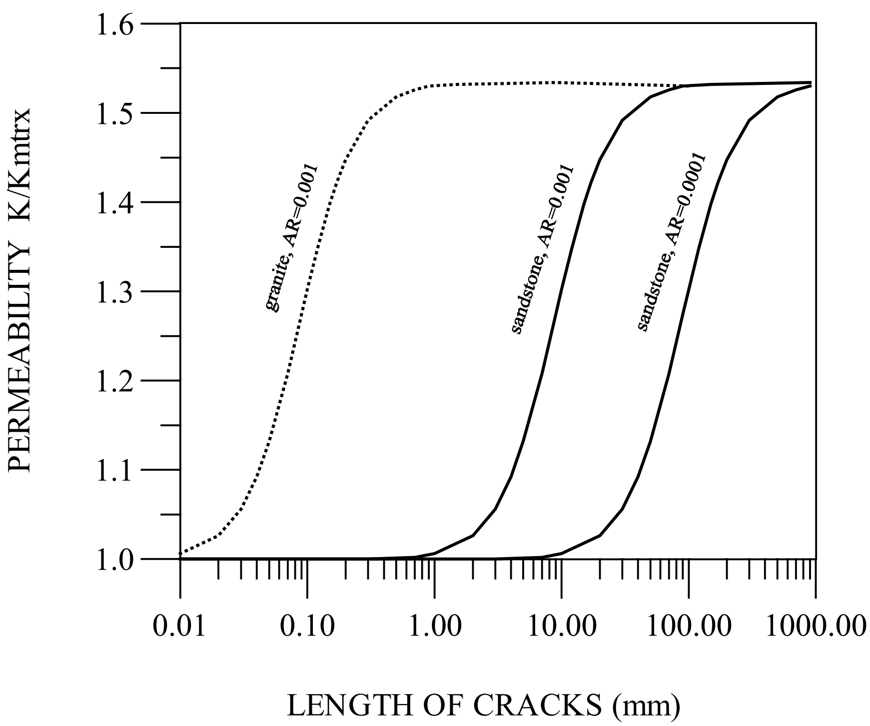

Fig. A. Normalized effective permeability for granite and sandstone as a function of crack length and aspect ratio of cracks calculated for matrix permeability 5.E-7 Darcy for granite and 5.E-3 Darcy for sandstone.

orientation, the 'effective' permeability of inclusion k^i is much greater (for a flux in the direction of the crack normal $k \sim BL^2 = Ba^2/\alpha^2 \gg k = Ba^2$). Consequently, the general equation for effective parameters has asymptotic behavior, and it is possible to speak about effective permeability tensor k^*_{ij} for a crack length $L \geq 10L^*$. These results show that the EMT approach, in its simplest form, is valid for relatively long isolated cracks with dimensions exceeding some characteristic length L^* (critical crack length); equations (A5)-(A6) allow to estimate the range of crack parameters L^* and α where the EMT approach is valid for a calculation of effective permeability.

When calculating Fig.A for different crack lengths, aspect ratio α was assumed to be constant, corresponding to a varying crack aperture $a=\alpha L$. This is the reason for the apparent independence of k^* on crack length in the asymptote of $F(\alpha, k^i/k^m \gg 1)$ in Fig.A. At the same time, it seems physically realistic that long cracks should contribute more to permeability than short cracks with the same aperture a.

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