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In situ permeability and elastic parameters of reservoir and hot dry rocks

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ABSTRACT

The goal of the study is to estimate theoretically the possible range of permeability and seismic velocity changes in low-porous fluid-saturated cracked rocks for different fluid composition and pore pressure under stress and temperature conditions typical for the upper 5-10 km of the crust. Clayey limestones saturated with fluid of different composition and low-porosity granites saturated with brines were treated as models of reservoir and hot dry rocks.

Macroscopic cracks are described as non-interacting parallel fluid-filled inclusions of an increased permeability compared with the background permeability of a host rock, and percolation effects are not considered in the study. As physical characteristics of pore fluids are *P-T* dependent, variations of external stress and temperature can result in a drastic change of the macroscopic physical parameters of a rock. The model is applied to consider rock under the undrained regime, when there is no evacuation of fluid from crack volume. The effective-medium concept is used to model numerically variations of crack geometry (rock porosity), effective permeability and V_S for different values of pore pressure (10-100 MPa) and external uniaxial compression applied to a rock mass at T ~ 50-300°C.

The purpose of the study was to estimate the effect of both fluid properties and external stress and temperature conditions on macroscopic parameters of low-porous 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 modeling. A low-porous granite saturated with brines of different composition (salinity) (density) at temperatures in the range 100-300°C was considered as a hot dry rock; transport and elastic parameters of carbonate reservoirs are illustrated by an example of clayey limestone saturated with oils of different composition.

The effective-medium concept based on the Eshelby algorithm is used to estimate theoretically the effect of both fluid properties and external stress and temperature conditions on macroscopic parameters of a rock containing parallel fluid-filled inclusions. Inclusions are assumed to be non-interacting and non-intersecting, and thus percolation effects are not considered in the study. The model is 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. Under pressure and temperature pore fluids can change greatly their physical characteristics which may result in a drastic change of the overall physical parameters of a rock. That is why, the pressure-temperature dependence of physical properties of brines and oils is taken into account.

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The results of numerical modeling are presented for variations of crack geometry (rock porosity), effective permeability and velocity of slow shear-wave for different values of pore pressure (10-100 MPa), and external uniaxial compression applied to a rock mass at temperatures in the range 50-300°C with account for *P-T* dependence of physical properties of brines. They show that stress-induced changes of macroscopic properties of cracked rocks are very sensitive to variations of composition and temperature of a saturating fluid.

The results of the study show that variations of crack geometry and crack concentration due to the action of external stress are more sensitive to a composition of a saturating fluid than to initial pore pressure and/or temperature. Macroscopic properties of a rock depend almost linearly on fluid density and are less sensitive to temperature variations. Under externaluniaxial stress, the behavior of both permeability and shear velocities is strongly anisotropic until stress does not exceed the critical value when all pre-existing cracks are closed. At the crustal depth of 5-10 km and high values of compression, only cracks saturated with high-density fluids can remain open. Permeability of fluid-saturated low-porosity rocks decreases with an increase of fluid temperature; shear velocities change simultaneously, but in the opposite direction.

INTRODUCTION

Macroscopic in situ permeability of low-porous crystalline and sedimentary rocks is of a great interest for a disposal of radioactive wastes and for a study of geothermal systems which are often embedded in fractured crystalline formations. Oil deposits are often found in cracked carbonate sediments; productivity of such reservoirs depends on effective permeability of a host rock.

Under external stress, variations of internal crack geometry of a rock 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.

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

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. Laboratory data on attenuation and ultrasonic velocities in sandstones prove that elastic properties of a rock are affected by a presence of microcracks when subjected to hydrostatic confining pressures up to at least 200 MPa (Wulff and Burkhardt, 1996). Numerical estimates (Zang, 1993) show that for crack geometries more realistic than elliptical, significant in situ porosity may be found at confining pressures up to 300 MPa. 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°C (and can be as high as 500°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.

The goal of the study is to estimate the possible range of permeability and seismic velocity variations for low-porous crystalline and reservoir rocks under stress and temperature conditions typical for the upper 5-10 km of the crust. 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 crack aspect ratio of cracks, saturated with brines of different salinity and for low-porous cracked clayey limestones saturated with oils of different composition and at temperature in the range 50-300°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.

THE MODEL

Model assumptions

The complicated structure of a real rock makes it practically impossible to develop a mathematical model which could account for all physical and chemical processes that can occur in rocks at in situ conditions. Physical properties of in situ rock mass depend on a large number of parameters such as rock lithology, porosity, *P-T* conditions which affect physical characteristics of mineral components. The situation becomes even more complicated when an attempt is made to predict in situ transport and elastic properties of fluid saturated rocks, which depend on physical state of both the confining rock the host rock and the high-pressure fluidpore 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, which will leading to a change of a fracture pattern; moreover, and a rate of chemical reactions in a rock depends to a great extent on *T-P* conditions.

However, under certain assumptions and simplifications, it is possible to understand the general behavior of the most essential most essential characteristics of such a medium. That is why, for a calculation of macroscopic physical properties of heterogeneous materials, such as rocks, which are assumed 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 and 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). The model assumptions are the following.

1) Macroscopic cracks are described as non-interacting parallel identical fluid-filled inclusions (modeled by ellipsoids of revolution with small aspect ratio $\alpha <<1$) of an increased permeability compared with the background permeability of a host rock, which is formed on a scale of crystal grains and is estimated to be in the range 10^{-14} to 10^{-20} m^2 for different crystalline and sedimentary rocks (e.g., Turcotte and Schubert, 1982).
2) The flow in the rock mass is assumed to exist along grain boundaries ("matrix permeability" of the host rock) and in cracks ("permeability of inclusions"). Fluid flow in a crack volume is modeled by a flow in a plane channel. The limitations which this assumption posses on estimates of effective permeability were considered in detail in Artemieva and Zatsepin (1992).

3) The model rock was assumed to contain non-interacting, non-intersecting identical inclusions (cracks), which were modeled by ellipsoids of revolution with small aspect ratio $\alpha <<1$. The roughness of crack walls was not accounted for in the model. 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 roughness of crack walls was not accounted for in the model (this effect was studied in detail by Thompson and Brown (1991).
4) The model rock was assumed to be formed by a low-porous matrix (granite) containing non-interacting, non-intersecting identical inclusions (cracks), which were modeled by ellipsoids of revolution with small aspect ratio $\alpha <<1$. Crack roughness was not accounted for in the model (its effect was considered by Gavrilenko and Gueguen, 1989). We limit our study to the case of a low porosity, low permeability unfragmented rock. Even at high values of pore pressure, external stress applied to a rock does not allow cracks to join together and form through-going fractures and percolating network. Thus, percolation in a crack system is not considered in the frames of the model.
5) Cracks are saturated with brines of different salinity at different pore pressures and temperatures. The modeling was applied to 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 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. Fluid flow in a crack volume was modeled by a flow in a plane channel. The limitations which this assumption posses on estimates of effective permeability were considered in detail in Artemieva and Zatsepin (1992).
6) We assume that host rock and fluids are chemically inert and, hence, do not consider effects of dissolution or crack healing.
7) As we limit our study by the case of a very low-porous, 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 crack to join together and thus to form throughgoing fractures and percolating network. In the present study we limit ourselves by a consideration of such low pore pressures that no hydraulic fracturing can occur (Zoback and Haimson, 1983). The results are presented for the temperature range 50-300°C, where the process of thermal microcracking is not essential for the assumed crack geometry (e.g., Le Ravalec and Gueguen, 1994). 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.

The calculation scheme and model parameters

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 and aspect ratio 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 (Chesnokov and Zatsepin, 1991). This algorithm together with the algorithm for numerical calculations of effective permeability of cracked solids are based on an analogy between the D'Arcy's law for permeability and the Fourier's law for thermal conductivity of a medium with ellipsoidal inclusions. The algorithm for the numerical solution of the later problem is described in (Artemieva and Chesnokov, (1991); was applied to permeable cracked solids (see Appendix). The possibility of its application to permeable cracked solids was analyzed in Artemieva and Zatsepin (1992).

As earlier (Artemieva, 1996) variations of crack aspect ratio (and hence, volume) due to the action of external stress are estimated at the first step of calculations. Under the conditions of undrained regime, when there is no evacuation of fluid from crack volume and all processes in cracks occur at constant fluid mass, crack deformation results in stress-induced variations of pore pressure. This results in alteration of physical parameters of a saturating fluid (density, bulk modulus, acoustic velocity), 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, at the last step, effective-medium theory was applied to calculate macroscopic transport and elastic properties of the rock (permeability and shear velocities) as a function of stress, temperature, for different composition (salinity) of a saturating fluid, and under different stress conditions (with account for *P-T* dependence of physical characteristics of brine).

RESULTS

Model parameters

The model is specified by densities and seismic velocities of the host rock (granite) and the saturating fluid (brines), crack geometry (stipulated by crack aspect ratio α) and crack density ε (dimensionless parameter proportional to the number of cracks in a unit volume), fluid temperature T, initial pore pressure $P(0)$, and values of external uniaxial compression.

As a model of hot dry rock, 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). To model a carbonate reservoir rock, cracked clayey limestone saturated with oils of different composition is considered. For numerical calculations, density and seismic velocities of matrix (i.e., host rock at zero porosity) are taken as $\rho = 2.7$ g/cm^3, $V_P = 6.3$ km/s, $V_S = 3.64$ km/s for granite and $\rho = 2.7$ g/cm^3, $V_P = 6.4$ km/s, $V_S = 3.2$ km/s for limestone (Brodov et al., 1991).

All results are presented for aspect ratio $\alpha = 10^{-3}$;. Experimental investigations (Hadley, 1976) revealed that microcracks of such a geometry are typical for Westerly granite (Hadley, 1976). Eshelby algorithm is valid for crack density $\varepsilon \leq 0.1$; at higher values of ε a medium cannot be considered as intact and unfractured (e.g., Crampin and Leary, 1993), crack-to-crack interaction must be taken into account, and the effective medium concepts cannot be applied (e.g., Cheng, 1993; Le Ravalec and Gueguen, 1996). The results of numerical modeling are presented for the case of initial crack density $\varepsilon = 0.1$. 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 (= 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 (not higher than 0.1). However, even for such relatively high values of crack density, rock porosity Φ ($\Phi = 4/3\ \pi\ \alpha\ \varepsilon$) is very low (less than 3%), which is typical both for granites and clayey limestones. 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%. (for the treated model of a rock with parallel cracks subject to uniaxial compression, fast shear velocity remains almost unchanged). At higher values of (≤ 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.

Physical properties of brines

In situ macroscopic transport and elastic parameters of rocks, which are considered in the present study for brine-saturated granites and clayey limestones saturated with oils, depend to a great extent on physical properties of a fluid. Parameters of the host rocks were described in the previous section. The properties of pore fluids, important for the present study, are as follows. The detailed review of physical characteristics of different pore fluids can be found in the paper of Batzle and Wang (1992).

Brines, which 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 *S* (concentration of NaCl dissolved in pure water) can be easily obtained from its resistivity, which is usually calculated during well log analysis.

That is why in our modeling, we considered brines of different salinity *S* (different concentration of NaCl dissolved in pure water) as saturating fluids. Figure 1a shows the dependence of acoustic velocity in brines on *P-T* conditions, and brine composition (salinity (density). 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 $T > 100°C$; at lower temperatures ($T < 50°C$) this decrease is much less pronounced and even the inverse type of dependence is observed at high pressures for bulk modulus and acoustic velocity, the maximal values of these parameters being observed at *T* (50-100°C).

Opposite to temperature, increasing the brine density (salinity) and/or pressure increases density and acoustic velocity in brines; however, the effect of salinity variations is more pronounced.

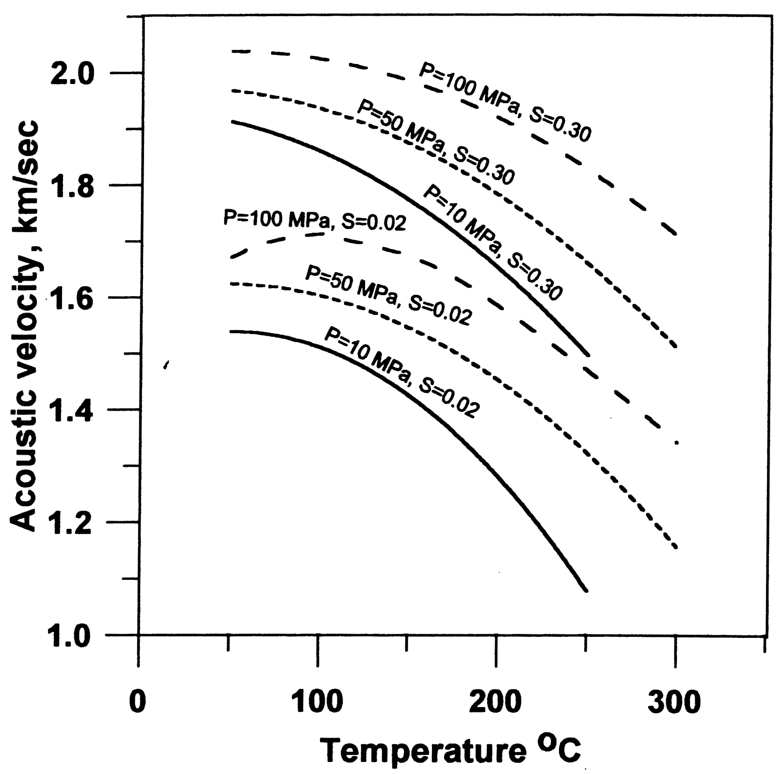

FIG. 1a. Acoustic velocity in brines as a function of their salinity *S* (NaCl concentration), pressure, and temperature. (The values calculated from the data of Batzle and Wang, 1992).

An effect of brine temperature increase by 60°C results in the same decrease of acoustic velocity (~4%), as a pressure decrease from 50 to 10 MPa. However, the effect of salinity variations is more pronounced; a decrease of brine salinity by a factor of 2 (from 0.30 to 0.15) results in approximately a 10% decrease of density and acoustic velocity.

To characterize oil density, the API (American Petroleum Institute) oil gravity numbers are usually used. They are inversely proportional to oil density: API = $141.5/\rho_o$-131.5 (where ρ_o is the density of a reference oil in g/cm^3 at T = 15.6°C and P = 1 atm), and can vary from about 10 for "heavy" oils to near 100 for "light" oils. Under crustal conditions, a large amount of gas can be dissolved in oils. The difference in physical properties of gas-saturated (live) oils and gas-free (dead) oils is studied in detail in Batzle and Wang (1992).

Figure 1b illustrates the dependence of acoustic velocity in both dead and live oils on temperature and oil density (inverse proportional to API). Like brines, a temperature increase results in a decrease of acoustic velocity; however, at low temperatures acoustic velocities of oils can vary in a wider range (1.3 to 1.7 km/s depending on oil density) than at high temperatures (0.7-0.8 km/s at T = 300°C). Pressure dependence of acoustic velocity of oils is linear; increasing of pressure from 10 to 50 MPa results in velocity increase by 0.20-0.45 m/s depending on oil temperature and composition.

Temperature effect on brine and oil viscosity is essential only for T < 100°C; pressure dependence of viscosity is small (Batzle and Wang, 1992). That is why in the present study we did not account for possible viscosity variations of a saturating fluid due to its heating. The data on *P-T-S* dependence of physical properties of brines and oils were used for numerical modeling.

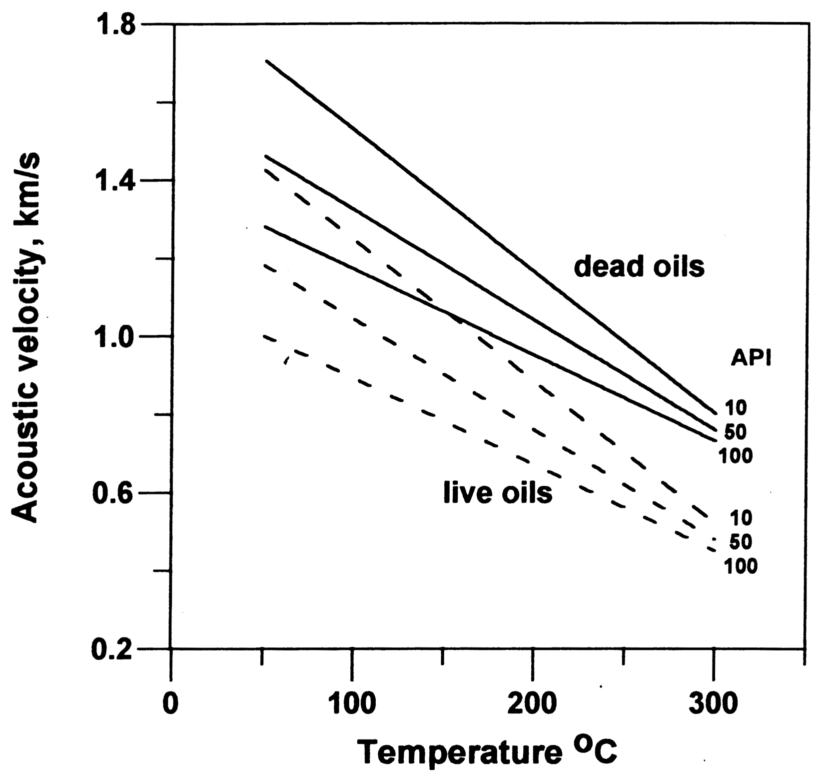

FIG. 1b. Acoustic velocity in oils as a function of inverse density (numbers on the curves - API number). Solid lines - dead oils, dashed - live (gas saturated) oils. (The values calculated from the data of Batzle and Wang, 1992).

Changes of crack geometry under uniaxial compression

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) and thus lead to variations of α and ε and porosity Φ changes ($\Phi = 4/3\ \pi\ \alpha\ \varepsilon$). Stress-induced changes of aspect ratio of cracks were calculated from the tensor of deformation (see Landau and Lifshitz, 1984), and the new value of rock porosity was estimated. Data on α and Φ were used to calculate new value of crack density.

Figures 2a and 2b show the dependence of dimensionless crack density (i.e. crack concentration in a unit volume) and porosity as a function of pore fluid density, pressure, and temperature. The results are presented for the values of uniaxial compression 150 MPa for brine-saturated granite and 100 MPa for oil-saturated clayey limestone (stress is normal to crack orientation). As one can expect, the higher pore pressure is, the less pronounced is crack closure; cracks saturated with low-density fluids are more "compliant" and are easier closed than cracks of the same geometry saturated with high-density fluids (Figure 2a).

The effect of temperature variations on a rock porosity is illustrated in Figure 2b; at high temperatures cracks are closed easier. Under the action of external compression, oriented normal to

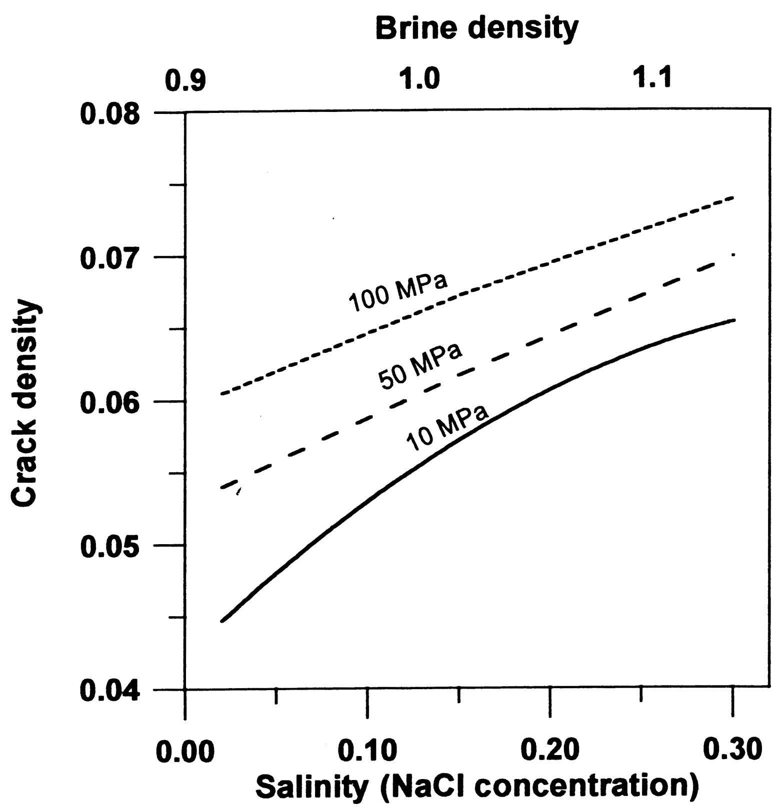

FIG. 2a. Crack density as a function of brine salinity (density) and temperature for granite with parallel cracks saturated with brines at different initial pore pressures (numbers on the curves). Uniaxial stress normal to crack orientation 150 MPa. Initial crack density Ncr(0)=0.1; aspect ratio of cracks 0.001.

a crack, cracks saturated with low-density oils (dead oils with high API number or live oils) start to close even at relatively low temperature. An increase of temperature by 100°C leads to approximately 50% porosity decrease, and at high temperature can result even in entire closure of all microcracks (the lines for gas-free oil at 300°C and for live oil at 150°C in Figure 2b). Under uniaxial compression, the effect of gas saturation of oil-filled cracks on porosity is rather essential. ariation of external stress promotes deformation in an ellipsoidal inclusion (crack) and, hence, changes of pore pressure pf. Under the assumption of a uniform strain (in the volume of an inclusion), it is possible to determine stress-induced variations of the crack aperture (i.e., a length of the short axis) and, hence, changes of aspect ratio 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 () and dry cracks.

Figures 2 and 3 illustrate the variations of crack geometry and concentration as a function of initial pore pressure and salinity of brines, for different values of temperature and density (salinity) of brines initial pore pressure. The results of numerical modeling 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 values of pore pressure. However, the effect of salinfluid density on closure of microcracks (due to variations of fluid compressibility with changes in fluid density) is the most essential: under the same values of uniaxial compression, crack density of a

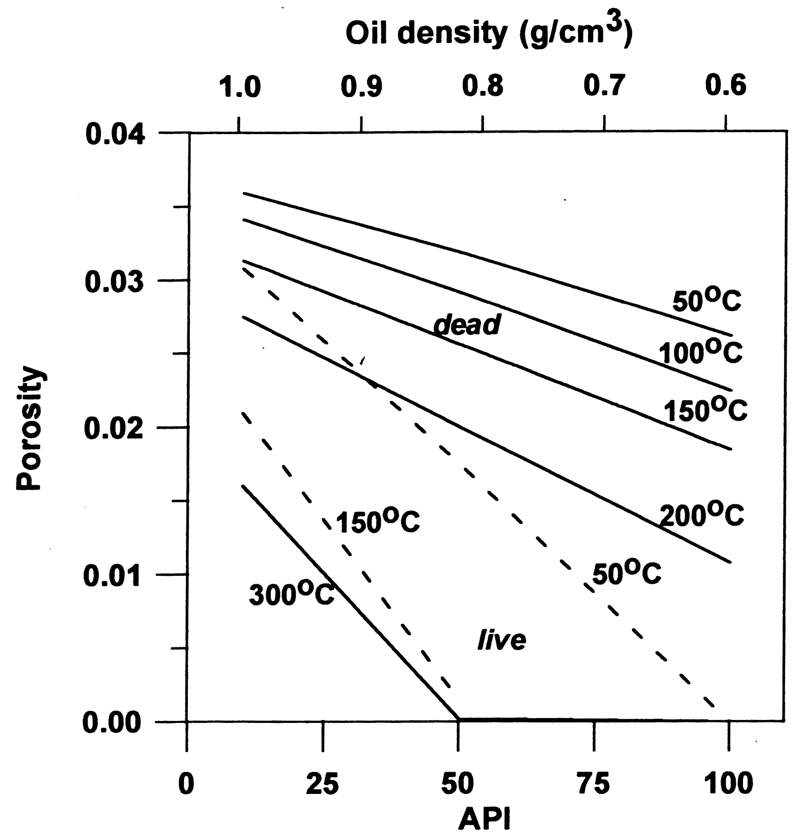

Fig. 2b. Porosity of clayey limestone with parallel cracks saturated with oil at different temparature. Solid lines - dead oil, dashed lines - gas saturated (live) oil. Initial pore pressure 50 MPa, uniaxial stress normal to crack orientation 100 MPa, aspect ratio of cracks 0.001.

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%. The effect of temperature on variations of crack geometry is more pronounced at low values of pore pressure.

Variations of pore pressure under uniaxial compression

Under the conditions of undrained regime (which were assumed in all calculations of the present study), when no fluid is extracted from a crack volume and all processes in cracks occur at constant fluid mass, deformation of a crack results in stress-induced variations of pore pressure.

Figures 4a and 4b illustrate variations of pore pressure with respect to initial pore pressure $P(0)$, which existed in cracks prior to the action of external stress, as a function of fluid temperature, composition and initial pore pressure. Complex dependence of elastic moduli of pore fluids on pressure and temperature leads to P-T dependence of pore-fluid pressure variations under the action of external stress. The dependence of pore pressure on composition of oils and brines was considered earlier (see Figure 3 in Artemieva (1996)). When a rock is subject to external compression, variations of pore-fluid pressure are more pronounced for gas-saturated oils than for gas-free oils or high-salinity brines.

At relatively low temperatures (T < 150°C) typical for the upper 3 km of the crust, crack behavior is almost independent of brine salinity (Figure 4a). In this temperature range, cracks 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.

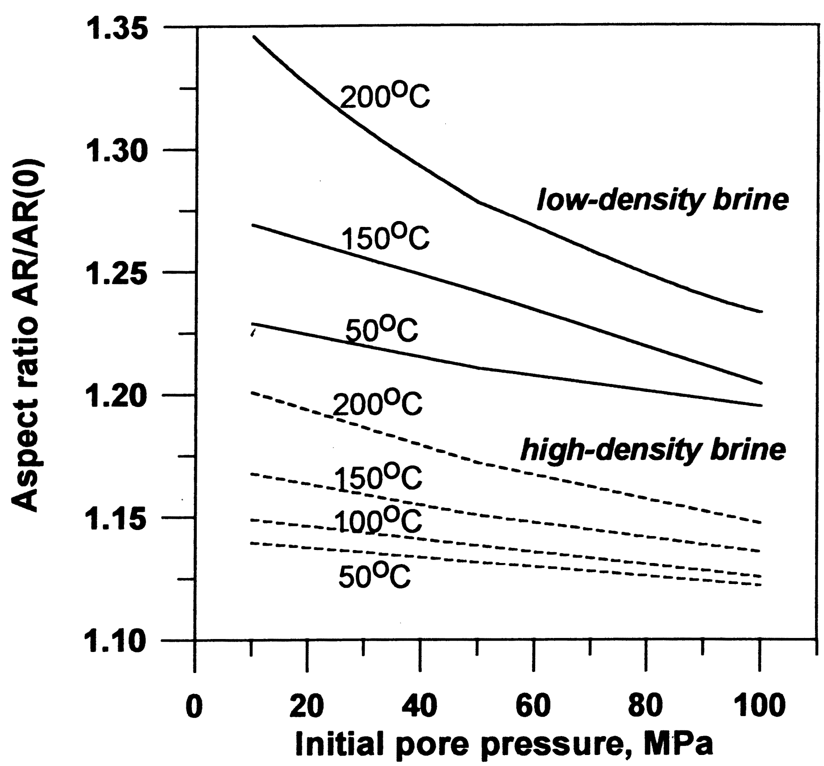

FIG. 3. Variations of aspect ratio of brine-saturated cracks under uniaxial compression of 150 MPa as a function of initial pore pressure, brine temperature (numbers near the curves) and salinity (solid lines - for S = 0.02, dashed - for S = 0.30). Model of granite with parallel cracks, initial aspect ratio of cracks AR(0) = 0.001.

Figure 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°C; such temperatures are typical for the upper 3 km of the crust), brine-filled cracks at relatively low temperatures (*T* < 150°C) typical for the upper 3 km of the crust, crack behavior is almost independent of brine salinity (Figure 4a). In this temperature range, cracks saturated with brines in a rock behave as "stiff" inclusions, and external stress does not lead to essential variations of a crack volume and pore pressure. However, at higher temperatures and low values of initial pore-fluid pressure, small temperature alterations in a low-density fluid can lead to a drastic increase of pore pressure and, thus, result in hydraulic fracturing; such *P-T* conditions are not considered in this study for low-density fluids. In this temperature interval crack behavior is almost independent of brine salinity. However, if cracks are filled with hydrocarbon gases or gas-saturated oils, the elastic properties of which can vary dramatically at T ~ 50-100°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). (Figure 4b). On the whole, the higher the temperature is, the more pronounced the change in pore pressure. For gas-saturated oils the expansion of gas plays a large role and variations of pore pressure are more dramatic (dashed line).

The effect of brine salinity on fluid composition on variations of pore pressure becomes dramatic at temperatures 200-300 is shown in Figure 4b. As one can expect, under external compression cracks saturated with almost pure water (*S* = 0.02) gas-saturated or low-density (large API numbers) oils are closed the first, while the volume of those filled with high-density fluids changes little their volume even at high temperatures.

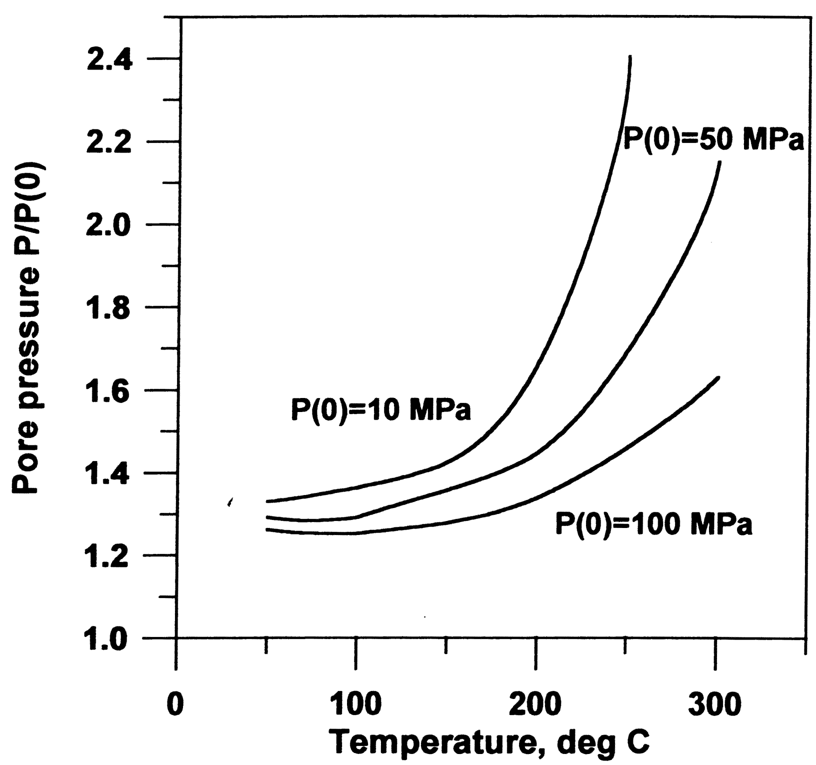

FIG. 4a. Pore pressure as a function of temperature and initial pore pressure P(0) for granite with parallel cracks saturated with brines (brine salinity S=0.02). Uniaxial compression 150 MPa, Ncr=0.1, AR=0.001.

As pore pressure prevents cracks from closing by the action of tectonic stress, it is evident that cracks saturated with fluids at low values of initial pore pressures are closed first and at relatively low values of compressional stresses (Figure 4a). 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 and at $T > 250$-300°C. However, if cracks are filled by gas-saturated -or saturated low-density fluids, they can be almost entirely closed at such temperatures (Artemieva, 1996, Figure 2b).

In situ effective permeability and shear-velocities

Variations of pore-fluid pressure due to the action of uniaxial compression result in changes of all fluid properties (density, elastic properties), all of which are pressure dependent, and thus, together with variations of crack geometry and concentration, affect all macroscopic properties of a rock mass.

Figures 5a and 5b depict graphically the form and behavior of the macroscopic permeability of brine-saturated granite as a function of brine temperature and composition. The results are presented for the direction along applied stress for fluid flow along cracks (note 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 under these conditions an essential anisotropy of macroscopic permeability of a rock is essentially anisotropic exists under these conditions.

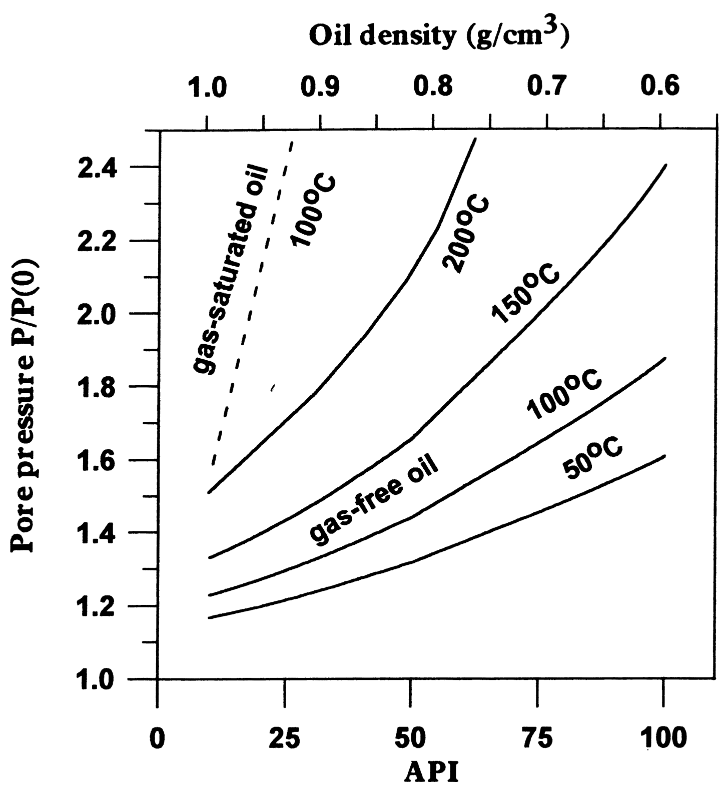

Fig. 4b. Pore pressure as a function of oil density and temperature for clayey limestone with parallel cracks saturated with dead oils. Initial pore pressure P(0) = 50 MPa, uniaxial compression normal to crack orientation 100 MPa. Dashed line - for gas saturated oil.

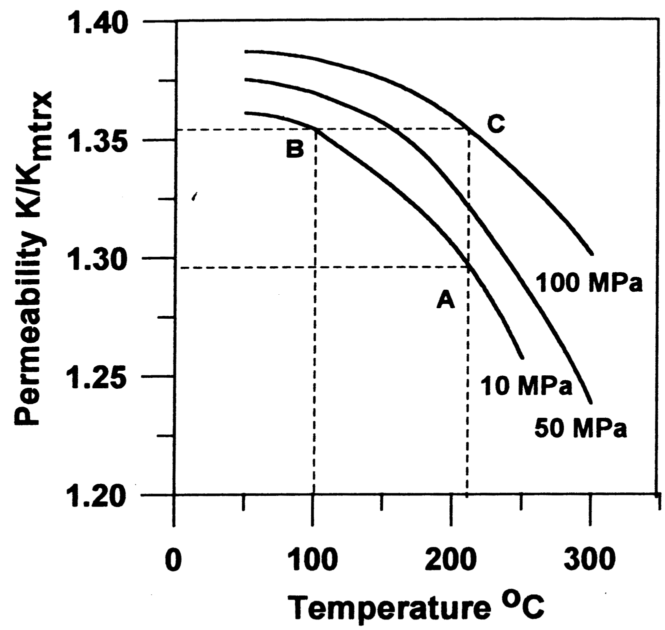

FIG. 5a. Permeability of granite with parallel brine-saturated cracks (direction parallel to crack orientation) as a function of brine temperature and initial pore pressure. Uniaxial compression 150 MPa, AR = 0.001. An increase of brine temperature by 110°C (points B and A) results in almost the same decrease of effective permeability as a drop of pore pressure from 100 MPa to 10 MPa (points C and A).

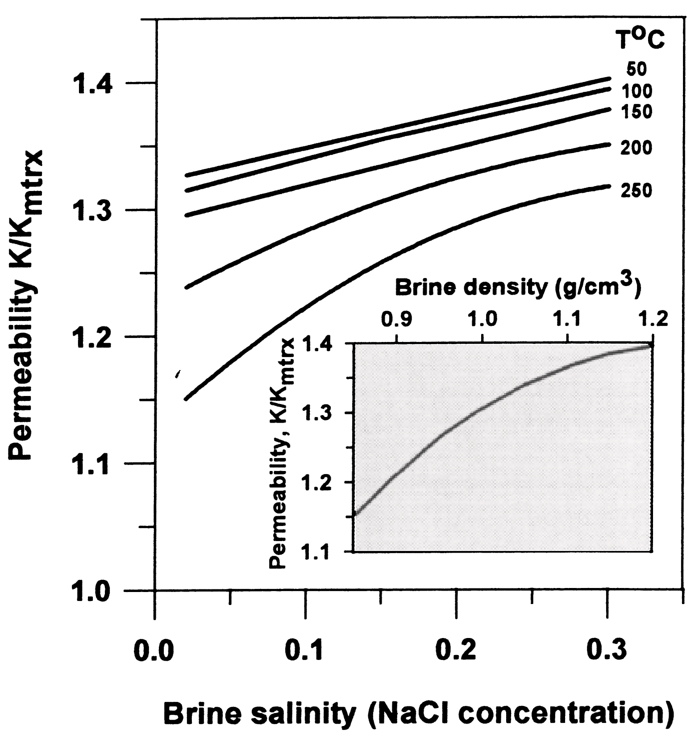

FIG. 5b. Permeability of granite with parallel cracks (in direction parallel to crack orientation) saturated with brines as a function of brine salinity and temperature. Initial pore pressure 10 MPa, uniaxial stress normal to crack orientation 150 MPa.

Numerical results indicate that at $T > 100°C$ 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.

An increase of brine temperature from 100°C to 300°C results in 10-15% decrease of rock permeability, while a change of brine temperature by 110°C (points B and A in Figure 5a) results in almost the same decrease of effective permeability as a drop of pore pressure from 100 MPa to 10 MPa (points C and A in Figure 5a). However, the effect of fluid composition on macroscopic permeability of a rock is the most dramatic: dissolution of a large amount of mineral components in pure water (and thus changing water salinity S from 0 up to $S = 0.3$ or 300 000 PPM) can increase rock permeability by 10-15% (Figure 5b). Density of a saturating fluid was calculated for the presented range of brine salinity, temperature and pressure; the dependence of macroscopic permeability of a cracked granite on a density of a saturating fluid is shown in the lower part of Figure 5b.

Permeability of clayey limestones with oil-saturated parallel cracks for fluid flow along cracks is shown in Figure 5c for different composition of oils (gas-free and gas-saturated oils of different density, which is inverse proportional to API number). From the results of numerical modeling it follows that macroscopic permeability is very sensitive to variations of fluid temperature: a decrease of oil density from 1.00 g/cm^3 (API = 10) to 0.78 g/cm^3 (API = 50) results in the same decrease of effective permeability (approximately by 10%) as a temperature increase by about 80°C.

At $T > 150°C$ (Figure 5c), uniaxial compression of 100 MPa is high enough to close tightly all cracks saturated with live oils of intermediate composition. However, gas-free cracks, independent of oil density, remain open even at very high fluid temperatures, and thus effective permeability of such a rock essentially differs from matrix value.

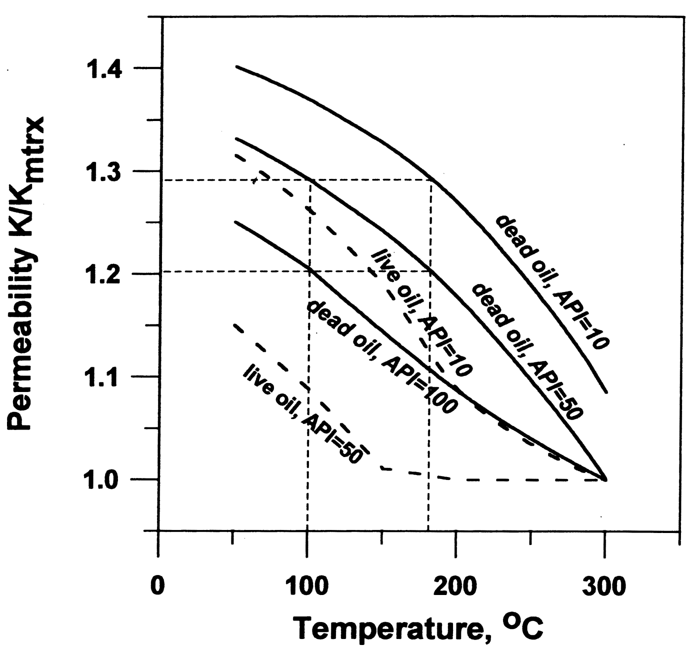

FIG. 5c. Permeability of clayey limestones with oil-saturated parallel cracks in direction along the cracks. Initial pore pressure 50 MPa, uniaxial compressio normal to crack orientation 100 MPa, initial aspect ratio of cracks AR(0)=0.001. Solid lines - for dead oils, dashed lines - for gas saturated oils. Numbers on the curves - API number (proportional to inverse oil density). A decrease of oil density from 1.00 g/cm3 (API=10) to 0.78 g/cm3 (API=50) results in the same 10% decrease of effective premeability as a temperature increase by about 80oC.

It is important that even at high values of uniaxial compression acting normal to crack orientation, a large part of brine-saturated cracks remains open and, thus, macroscopic rock permeability differs from matrix permeability of a host rock granite (Figure 5a). The same effect phenomenon was observed calculated for clayey limestones saturated with heavy oils (Figure 5c). 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. One should expect that at crustal depths of 10 km and more, hydrostatic pressure is extremely high to close all pre-existing cracks. 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 in field observations even at the base of the Kola super-deep borehole (Kozlovsky, 1982). At depths of about 3.5 km and 7.8 km a sudden decrease of acoustic velocity in Kola borehole was recorded, which can be interpreted by an increased porosity and, as a consequence, an increased rock permeability at these depths (Kozlovsky, 1984).

Stress-induced variations of shear velocity and macroscopic permeability are coupled. Figures 6a and 6b show the dependence of slow shear velocity in brine-saturated granite and oil-saturated clayey limestone on fluid temperature, composition, salinity, and pore pressure. As it follows from the comparison of results in Figures 5 through 7, changes of shear velocity and permeability caused by varying external conditions are coupled. As for macroscopic permeability, the behavior of shear waves under uniaxial compression is strongly anisotropic, resulting in shear-wave splitting which is widely observed in nature. Opposed to permeability, under uniaxial stress acting normal to crack orientation, higher temperatures of a saturating fluid result in higher values of seismic velocities

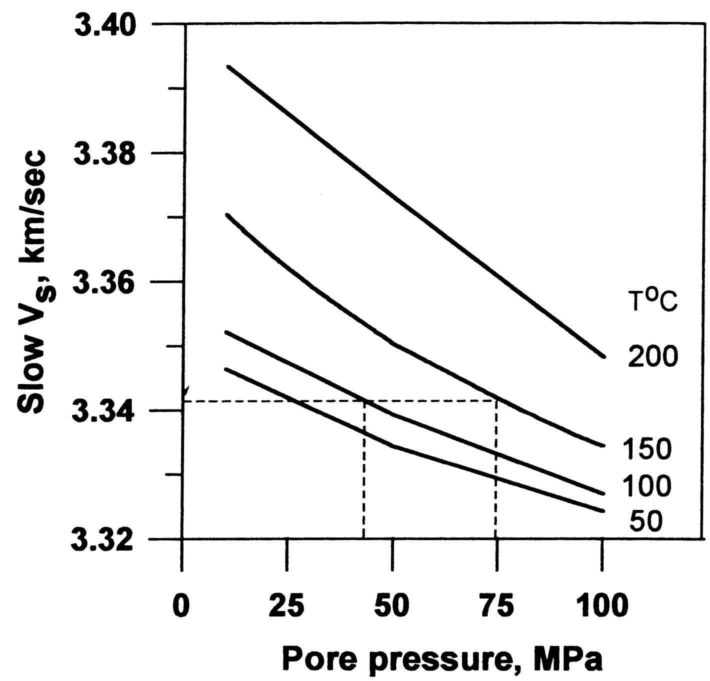

Fig. 6a. Slow shear velocities in low-porosity granite with parallel cracks saturated with brines at different temperature (numbers near the curves) as a function of initial pore pressure. Direction normal to crack orientation. Uniaxial compression 150 MPa, brine salinity S=0.15. The effect of brine temperature increase from 100oC to 150oC is compensated by an increase of initial pore pressure from 40 to 75 MPa.

(Figure 6a), while an increase of brine salinity density (inverse proportional to oil API number) is marked by a decrease of shear velocity associated with a high rock porosity (Figure 6b). Variations of fluid temperature and pore pressure change shear velocity of a rock in opposite directions. For example, the effect of initial pore pressure increase from 40 to 75 MPa can be entirely compensated by a simultaneous increase of brine temperature from 100°C to 150°C (Figure 6a).

For low-density oils (API > 50) at high temperatures (T ~ 300°C), all cracks can be tightly closed under the action of uniaxial compression of 100 MPa subject to a cracked rock with initial pore pressure 50 MPa (the upper line in Figure 6b). For gas-saturated oils the effect of oil density on stress-induced variations of shear velocities and, thus, on shear wave splitting is more pronounced. For the model considered in this study, the behavior of shear waves is strongly anisotropic; the velocity of the slower shear wave can range from 2.92 km/s to 3.2 km/s depending on the physical properties of a saturating fluid (Figure 6b), while the velocity of the faster shear wave is almost equal to shear velocity in the matrix. Thus, the anisotropy coefficient can vary from 0 to ~9%.

External uniaxial compression applied to cracked rock with parallel cracks oriented normal to stress results in a gradual closure of pre-existing cracks. The rate of crack closure depends on a large number of inherent rock characteristics (e.g., crack geometry, elastic moduli of a saturating fluid) and external parameters (stress, temperature). Gradual closure of cracks under the action of external stress results in variations of macroscopic properties of a rock. The dependence of effective permeability and shear velocity on the value of uniaxial compression is shown in Figure 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 a gradual closure of microcracks; for the same values of pore pressure, cracks with

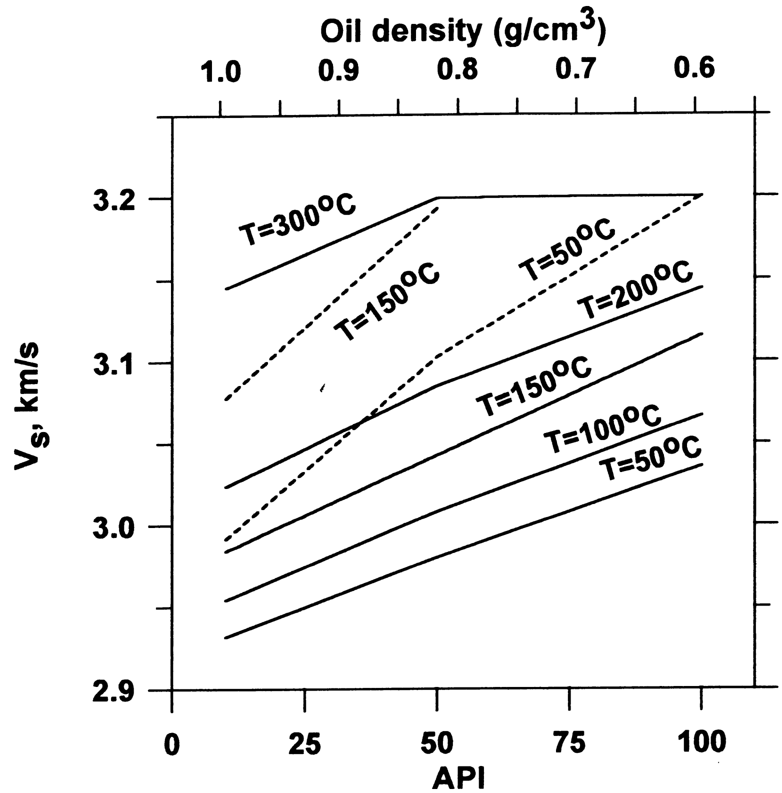

Fig. 6b. Slow shear velocity (direction normal to crack orientation) in clayey limestone with parallel cracks saturated with oils at different temperature. Solid lines - dead oils, dashed lines - gas saturated oils. Initial pore pressure 50 MPa, uniaxial compression (normal to crack orientation) 100 MPa, aspect ratio of cracks (= 0.001.

small aspect ratio, or saturated either by low-density or by hot fluids are closed first (Figures 2 and 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 of compression, when almost all cracks are tightly closed, permeability and seismic velocities behave asymptotically and tend to the matrix values (Figure 7).

DISCUSSION

Macroscopic transport and elastic parameters of fluid-saturated rocks depend in a complex way on a large number of rock characteristics, material properties (among which the most important are rock porosity, crack size and orientation, density and elastic moduli of matrix and fluid) and external parameters, (fluid viscosity, and pore pressure, pressure, temperature and effective stress), density and elastic moduli of matrix and fluid. In field and laboratory measurements only a limited set of these characteristics is often determined, while the proper choice of other model parameters usually allows to fit experimental data. Moreover, laboratory measurements on rocks from large depths may not reflect real in situ effective macroscopic properties of a cracked rock due to the effects of stress relief and many uncertainties in in situ rock characteristics (e.g., pore pressure, properties of a saturating fluid, etc.). Nevertheless, a qualitative comparison of model predictions with experimental data is of a particular interest.

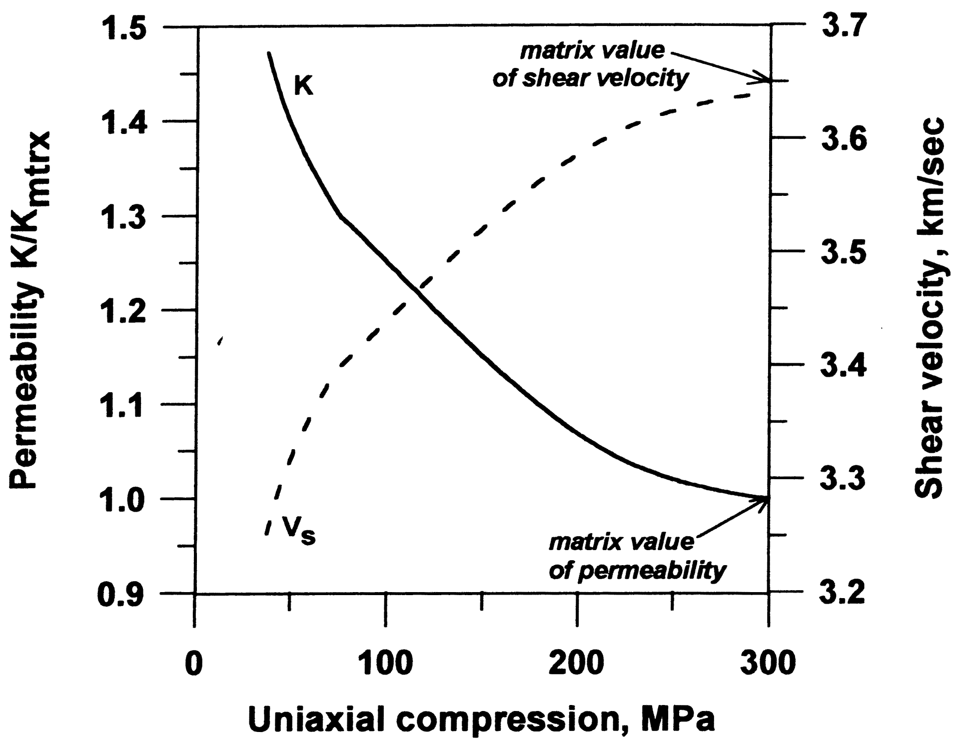

FIG. 7. Permeability and shear velocity in brine-saturated granite with parallel cracks (in directions correspondingly parallel and normal to crack orientation) as a function of applied uniaxial compression. P(0) = 10 MPa; *T* = 250°C; *S* = 0.02. = 0.001.

The distributions 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 the present study we considered reservoir and hot dry rock granite saturated with brines at *P-T* conditions typical for the upper crust (down to 5-10 km). Temperature in the upper crust of tectonically stable areas, where oil reservoirs are usually found, can vary in the range from about 0°C at the surface up to 200-300°C at 10 km depth; in hydrothermal areas such high temperatures can exist at shallower depths (~ 5 km). At these depths, fractures and pores, which can be preferentially aligned by the stress-field acting on the rock mass, can be held open only if pore-fluid pressure is comparable to the lithostatic pressure, (i.e., is about 50-100 MPa). That is why, to model in situ conditions in the upper crust, macroscopic properties of fluid-saturated low-porosity rocks were studied for temperatures in the range 100-300°C and pore pressure up to 100 MPa; a rock was assumed to be subject to tectonic stress specified by the value of uniaxial compression (up to 150 MPa). At these depths temperature can vary in the range from about 0°C at the surface to 300-500°C 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 Schield 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 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 (Figure 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 in this case, cracks will 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. This is proved by field data from the Cornwall hot-dry-rock geothermal experiments, where the presence of parallel or near-parallel vertical fractures was found at depths down to 3-4 km (e.g., Pine and Batchelor, 1983).

It means that when a fluid is pumped to exchange reservoirs with such crack orientation in geothermal experiments, fluid from the injection point to the production well is normal to the principal crack orientation, and thus macroscopic horizontal permeability of reservoir will behave in the way depicted graphically in Figures 5 and 7, a strong dependence of reservoir permeability on fluid temperature and composition should be expected.

This notion is proved by the results of field experiments in geothermal systems of Iceland, which revealed that, after pumping of cold water into a reservoir, reservoir permeability changed with time as water was heated at in situ conditions (V. Stefansson, personal communication, 1996). Temperature of reservoir rocks in geothermal systems of Iceland corresponds to the values presented in this paper and is about 100°C or 200-300°C (Axelsson et al., 1996).

Experimental studies of seismic velocities in Boise sandstone saturated with different fluids (Wang and Nur, 1990) at low values of effective stress and temperatures in the range 0-130°C show, opposed to the results of the present study, a decrease of shear and compressional velocities with increasing temperature. However, as mentioned above, in this temperature range fluid viscosity is strongly temperature dependent and cannot be neglected in modeling of a fluid flow through fractures and cracks. Moreover, at low temperatures (T < 50-100°C) the dependence of bulk modulus and acoustic velocity in brines and water is opposite to that at higher temperatures: these parameters increase with increasing temperature and reach their maximal values at $T > 100°C$. That is why the effect of temperature on seismic velocities can be essentially different at temperatures above and below 100°C.

According to the results of numerical modeling, at $T > 100°C$ permeability of granite saturated with brine decreases almost linearly with a temperature increase (Figure 5a). Such a behavior of permeability is proved by laboratory experiments (Moore et al., 1994), in which a notable reduction of granite permeability was observed at elevated temperatures. However, as the rate of chemical interaction between a host rock and a fluid is temperature dependent, it is likely that a large part of the effect observed in these experiments was due to mineral dissolution and precipitation.

As it was shown in the previous section (Figure 7), changes of a stress regime promote variations of a 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 (G. Buntebarth, personal communication, 1996).

CONCLUSIONS

This paper examines the effect of uniaxial compression on both fluid properties and external stress and temperature conditions on macroscopic transport and elastic parameters of low-porous crystalline and sedimentary rocks containing parallel, non-interacting fluid-saturated cracks. The influence of fluid composition, temperature, and pore pressure on macroscopic properties of rocks and variations of crack geometry under external stress was considered. Clayey limestones saturated with oils of different composition and low-porosity granites saturated with brines were treated as models of reservoir and hot dry rocks.

The following conclusions can be made from the results of the study.

1) Under the action of external stress variations of crack geometry and concentration due to the action of external stress depend greatly on the composition of a saturating fluid; an effect of compositional variations is more pronounced than changes in initial pore-fluid though pressure and/or temperature dependence of a crack pattern is essential as well, it is less pronounced that an effect of compositional variations.
2) The major factor which influences macroscopic permeability and shear velocities of a rock mass is controlled by external stress. Its increase of stress results in a gradual closure of cracks and, hence, in a notable reduction of macroscopic rock permeability and an increase of shear velocities to the matrix value. The behavior of both permeability and shear velocities is strongly anisotropic. However, this dependence is essential only when stress value is large enough to start closure of cracks, but does not exceed some the critical value when all pre-existing cracks are closed. An increase of pore-pressure shifts both of these points to higher stress values.
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:

div v = 0 (A1)
v = -km/(grad pf,

where v is pore-fluid velocity; km - specific matrix permeability; (- pore-fluid viscosity; pf is pore pressure. Consider the fluid flux in an ellipsoidal inclusion parallel to the strike of a crack with (´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 (and channel width h:

v = -12 h2/(grad pf (A2)

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

ki = Ba2 (12 h2 (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 ki 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 aªa*(km). It depends on the asymptotic behavior of the general equation for the effective parameters, when ki/km ª1 and the effective parameters do not depend upon ki . This condition may be presented as:

ki/km = B a 2/km = B AR2 L2 / km ª 1. (A4)

If we introduce some 'critical' crack aperture a* and crack length L* = a* /(, where

a* = (km /B)1/2 (A5)

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

(a/ a*)2 = (L/L*)2 ª 1. (A6)

L* (10-4 mm for granite with matrix permeability km (5(10-19 m2 and (= 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 (m and (i with km and ki=12 a2=12(2 L2, correspondingly.

In Fig.A, the normalized effective specific permeability k(L)/km for a flux parallel to the striking of aligned cracks is shown (matrix permeability was taken equal to 5(10-19 m^2 for granite and 5(10-14 m^2 for sandstone). Cracks with length L(10L* (where L*=L*(km, () 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(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 orientation, the 'effective' permeability of inclusion ki is much greater (for a flux in the direction of the crack normal k ~ BL^2 = Ba^2/(2^a 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 (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 (where the EMT approach is valid for a calculation of effective permeability.

When calculating Fig.A for different crack lengths, aspect ratio (was assumed to be constant, corresponding to a varying crack aperture a = (L. This is the reason for the apparent independence of k* on crack length in the asymptote of F((, ki/km ^{a}1) in Figure 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.