THE DEPENDENCE OF TRANSPORT PROPERTIES OF *IN SITU* ROCKS ON PORE FLUID COMPOSITION AND TEMPERATURE

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ABSTRACT

Fluids saturating cracked rocks within the crust can vary widely in composition and physical properties, which depend greatly on pressure and temperature. External non-hydrostatic stress applied to a cracked medium may result in a significant change of crack volume (and hence, for the undrained regime, pore-fluid pressure) due to the processes of crack closure (opening), and thus lead to a drastic change of the overall physical parameters of a rock. The purpose of the study is to estimate theoretically, using the effective-medium theory technique, the macroscopic seismic and transport parameters (such as permeability) of cracked rocks (granites) saturated with hydrocarbon gases, oils, brines and water. Variations of crack geometry and fluid parameters in the closed system (at constant fluid mass) under uniaxial compression are considered as well. The results show that composition of a saturating fluid as well as fluid temperature influence greatly specific permeability and shear velocities of a rock mass, while thermal conductivity is not so sensitive to variations of fluid parameters.

Key words: effective parameters, pore fluids, cracked rock, permeability, stress, temperature

1. INTRODUCTION

The stress and pressure dependence of macroscopic seismic and transport properties of rocks (e.g. permeability, thermal conductivity) is of a great interest for oil recovery, geothermics, and the disposal of radioactive wastes. In the crust, the stress field and differential fluid pressure variations are necessarily dependent. The stress-induced variations of the internal crack geometry (due to opening, closure, subcritical and dynamic crack growth, and nucleations of cracks) promote a variation of fluid pressure and consequently changes in rock permeability. These data may be useful as well for the earthquake prediction, because macroscopic physical properties of rocks are sensitive to possible temporal variations of rock parameters.

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. Such aligned microcracks caused by regional stress-induced deformation are widely observed in nature, for example in metamorphic complexes (Etheridge, 1983). Laboratory and field studies revealed that most microfractures are extensional features oriented perpendicular to the direction of current minimum compressional stress (e.g. Tapponnier and Brace, 1976; Kranz, 1983; Crampin, 1990). However, in case of stress-relief thermal microcracking of isotropic material subjected to deviatoric *in situ* stress, a formation of randomly oriented crack pattern would be expected.

Geochemical studies show that a large amount of fluids exist in crustal rocks (e.g. Fyfe et al., 1978; Ethbridge et al., 1984) and greatly influence the macroscopic properties of rock masses. The purpose of the study is to estimate macroscopic seismic and transport parameters of crustal rocks saturated with typical pore fluids under different P-T conditions. Under pressure and temperature pore fluids can change greatly their physical characteristics (density, conductivity, viscosity, acoustic velocities) which may result in a drastic change of the overall physical parameters of rock. In this study all effects are considered within the limits of undrained regime.

In crystalline rocks fluids can exist in microinclusions (pores or partly healed microcracks). Seismic studies revealed that such fluid-filled microcracks are likely to exist in the uppermost 10 to 20 km of the crust (Crampin, 1987) where the pore-fluids are expected to be at temperatures up to 500^{o}C and pressures up to 400 MPa. However, the idea that fluid-filled cracks cannot exist deeper than 3 km is widely accepted and is based on the fact that 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). It means that for the realistic values of crack aspect ratio and fluid parameters, all cracks would be closed at pressures 30-100 MPa.

Nevertheless, numerical modeling of the closure of thermal microcracks (Zang, 1993) revealed that for crack geometries more realistic than elliptical, significant *in situ* porosity may be found at confining pressures up to 300 MPa, i.e. at the crustal depth of about 10 km, and the fraction of cracks which remain partially open under high pressures depends on the shape of initial cracks. N. Christensen (1989) suggested that open cracks can exist at these depths due to high pore pressures.

Usually it is assumed that pore pressure is higher than hydrostatic pressure and less than lithostatic pressure. High pore pressures in fluid saturated rocks can be produced by different mechanisms, e.g. tectonic stress (subhorizontal tectonic compression, rapid tectonic loading due to sedimentation), chemical reactions (crack sealing by mineral deposition, metamorphic reactions involving pore-pressure buildup during dehydration), phase changes in saturating fluid.

In the present study we will consider only the first of the above mentioned mechanisms of pore pressure increase. In this case, external non-hydrostatic stress applied to a cracked rock may result in a significant change of pore and crack volume due to processes of crack closure (or opening in case of tensile external stress) and thus lead to a pronounced change of pore-fluid pressure. However, as fluid pressure plays an important role in fracture initiation and propagation, in the present study we will not consider the case of a very high pore pressure which can lead to hydraulic fracturing (Zoback and Haimson, 1983).

In the upper crust, at 5-10 km depth, where fluid-filled cracks and pores are likely to exist, temperatures can vary from about 100-300^{O}C in platform areas to 200-600^{O}C in tectonically active regions (e.g. Lachenbruck and Sass, 1977). However, experimental studies (e.g. Wong and Brace, 1979) revealed that, above some critical temperature which depends on a grain size (Evans, 1978), a relatively small temperature change can result in a propagation of pre-existing cracks which were partially closed by confining pressure. That is why in the present study we will consider rocks containing saturated cracks with very low aspect ratios in the temperature range 0-300^{O}C, where the process of thermal microcracking is not essential (e.g. Le Ravalec and Gueguen, 1994).

2. PROPERTIES OF TYPICAL PORE FLUIDS

Fluids saturating cracked rocks within the crust can vary widely in composition and physical properties. However, sedimentary rocks are mostly saturated with hydrocarbon gases, oils, brines and water. A detailed overview of their seismic properties is presented by Batzle and Wang (1992).

Water is assumed to be one of the most important fluids in the crust. Studies of the Kola Superdeep Borehole (Kozlovsky, 1984) revealed the existence of porous, water-saturated fractured rocks in the depth range of 4.5-10.1 km. The origin of water in this depth interval may be associated with mineral dehydration during progressive metamorphism (Meissner, 1986; Christensen, 1989). In deeper crustal regions, where high-grade metamorphic pressures exist, fluids rich in CO_2 may be important at elevated pore-pressures (Christensen, 1989). In general, under real crustal conditions, one can hardly expect to find rocks saturated with pure water .

Thermodynamic properties of pure water over an extensive temperature and pressure range have been reported during the past two decades in a large number of papers (Burnham et al., 1969; Keenen et al., 1969; Helgeson and Kirkham, 1974; Raznjevic, 1976; Brodholt and Wood, 1993).

Brines, which are the most typical pore fluid, are formed as a result of water mineralization and can vary in composition from almost pure water to saline solutions with a rather high (up to 50%) salt concentration. Their properties were considered in details in a number of studies (Rowe and Chou, 1970; Chen et al., 1978; Batzle and Wang, 1992). The results of the above mentioned studies, important for the present work, are the following.

Density of pure water and brines depends greatly on temperature: an increase of T at constant pressure from 20^{o}C to 300^{o}C results in 30-40% density reduction. Water and brines are characterized by a velocity inversion with increasing temperature, the maximum values of acoustic velocity V_p being observed at T ~100^{o}C. Density, acoustic velocity and viscosity of brines increase with an increase of brine salinity and pressure. However, pressure dependence of density and acoustic velocity of pure water and brines is rather weak for P>50 MPa and almost linear, with velocity gradient being of about 0.002 km/sec MPa.

Salinity affects all physical properties of brines. Estimations of Batzle and Wang (1992) show that density of brines with PPM=300 000 (where PPM is NaCl concentration in parts per million) is on the average 20% higher than that of pure water, while bulk modulus is twice higher.

For T<100 ^{o}C, viscosity of aqueous solutions (e.g. Kestin et al., 1981) decreases rapidly with a temperature increase. However, at higher temperatures, viscosity of brines decreases rather slowly and is almost constant. The pressure dependence of viscosity is rather small.

Two other important types of pore fluids are hydrocarbon gases and liquids (oils). Their composition varies from rather light gases to dense organic residues. At high pressures, the physical properties of hydrocarbon gases and oils become rather similar (Batzle and Wang, 1992). Hydrocarbon gases are characterized by a specific gravity G (the ratio of the gas density to air density at T=15.6 ^{o}C and P=1 atm). Oil densities, which under room conditions can vary in the range 0.5-1.0 g/cm^3, are often characterized by API number (API=141.5/ρ_o-131.5, where ρ_o is reference density of oil in g/cm^3 at T=15.6 ^{o}C and P=1 atm). Usually, API varies in the range from about 10 (heavy oils) to near 100 (light condensates) (Batzle and Wang, 1992).

Let us mention briefly physical properties of hydrocarbon gases and liquids, which are important for the further consideration. Gas densities and velocities were calculated using the approximations of Thomas et al. (1970). Oil parameters were calculated after McCain (1973), Wang et al. (1988). References to the other studies and their overview can be found in the paper of Batzle and Wang (1992).

Density of gases increases with increasing P and decreasing T (Fig. 1a). For heavy gases, the dependence of density on pressure is almost linear, while for light gases (such as methane) at low temperatures a rapid increase of density occurs only for P<20-30 MPa. At 5 km depth, where hydrostatic pressure is about 50 MPa and T ~100-200^{o}C, density of very light gases (G=0.6) can vary from 0.3 to 0.4 g/cm^3, while density of heavy gases (G=1.2) does not change much due to temperature variations and is about 0.19-0.21 g/cm^3.

Fig. 1b shows the dependence of velocity in gases as a function of their density G. For heated gases at low pressure, velocity slightly depends on the gas composition. For P and T typical for the 5 km depth, velocity in heavy gases may differ by a factor of 2 for hot and cold regions. Viscosity of gases depends greatly on P and is slightly affected by temperature at T>100-150^{o}C.

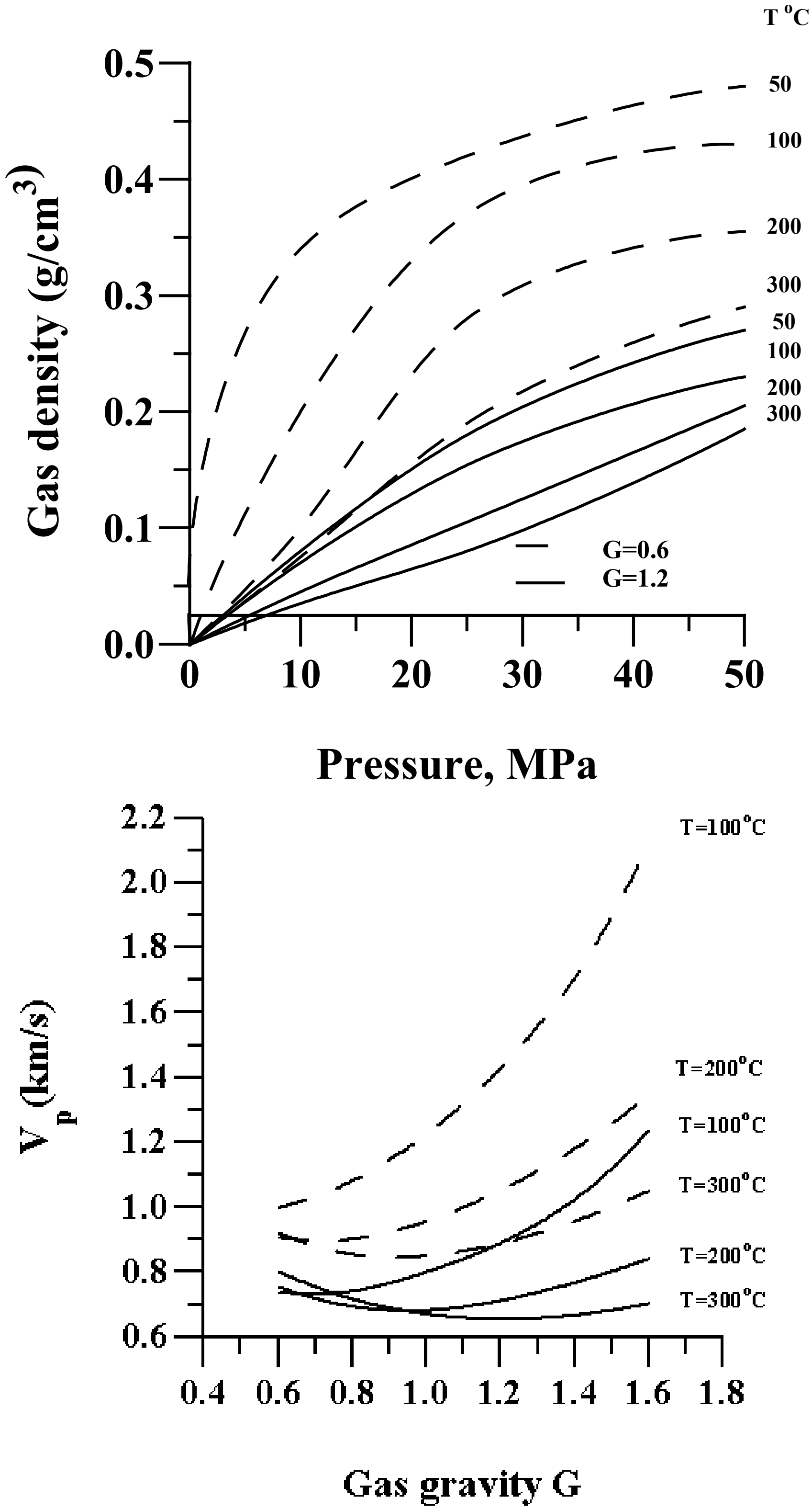

Fig. 1. Physical parameters of hydrocarbon gases.

a) Gas density versus pressure for different gas temperature and composition G.

b) Acoustic velocity in gases versus gas composition G for different P-T conditions. Solid lines for P=50 MPa, dashed - for P=100 MPa.

Under crustal conditions a large amount of hydrocarbon gas can be dissolved into oil. The maximum amount of dissolved gas under given P-T conditions and for definite gas and oil composition increases greatly with P, especially for large API numbers, and linearly depends on G value (Standing, 1962). The maximum amount of dissolved gas is obtained for very light oils with large API numbers.

Physical parameters of both dead (gas-free) and live (gas-saturated) oils, such as density and acoustic velocity, are almost linear functions of P and T, pressure effect being less pronounced than the temperature one. Under P-T conditions of the upper crust, acoustic velocities in oils can vary by a factor of 2-3 (for live and dead oils, respectively), depending on the thermal state of the region considered.

3. THE MODEL AND METHOD OF THE PROBLEM SOLUTION

When studying macroscopic physical properties of heterogeneous materials such as rocks, which appear to behave as statistically homogeneous above the scale of their inhomogeneity, it is useful to operate with average physical parameters describing the properties of the equivalent homogeneous medium. This approach is used in effective medium theories (EMT) that are applied widely to calculate effective parameters of rocks (e.g. Koplik, 1981; Sen et al., 1981; David et al., 1990).

Having at our disposal the algorithm for numerical calculations of effective parameters for thermal conductivity (Artemieva and Chesnokov, 1991) and elastic moduli (in a long-wave limit) (Chesnokov and Zatsepin, 1991) of a medium with ellipsoidal inclusions, earlier we showed the possibility of its application to permeable cracked solids (Artemieva and Zatsepin, 1992). The approach is based on an analogy between the Fourier's law for heat conductivity and the D'Arcy's law for permeable media; mathematical formulation of the problem is described in details in Artemieva and Zatsepin (1992).

As earlier, the model assumptions are the following. For simplicity the medium is assumed to be made of solid grains and identical fluid-filled cracks modeled by ellipsoids of revolution with small aspect ratio α ($\alpha \ll 1$ for penny-shaped cracks). Crack roughness is not accounted for in the model; its effect was considered by Gavrilenko and Gueguen (1989).

This model has been used for the calculation of elastic moduli of cracked low-porous liquid-saturated solids by a number of workers (O'Connell and Budiansky, 1974, 1976; Hudson, 1980, 1986) and provides a relatively good agreement with laboratory (Nur, 1971) and field (Crampin, 1984) experimental data. In our studies, we follow the method of Eshelby (1957) and use the first order approximation to estimate elastic moduli of the medium under external stress. For simplicity we considered 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 calculation scheme is based on the results of Chesnokov and Zatsepin (1991), where the general case of ellipsoidal inclusions initially (at external stress σ_e=0) distributed over the length L and aspect ratio α, with arbitrary (anisotropic) distribution functions (DF) over crack orientational angles θ and ϕ was considered. It provides the algorithm for the calculation of effective elastic moduli $C^*(\sigma_e, p_f)$ and DF of a crack ensemble $N = N(\alpha_0, L_0, \theta, \phi | \sigma_e, p_f)$ as a function of applied stress σ_e and fluid pressure p_f ($N=nL^3$ is dimensionless crack density (proportional to the number of cracks n in a unit volume) for given values of DF parameters, α_0 and L_0 are the initial values at σ_e=0 and p_f=0).

The key point of the approach for a study of macroscopic permeability of a rock is the effect of relatively long intergranular cracks of a size much greater than the dimensions of crystal grains. Under this assumption, macroscopic cracks are described as inclusions of an increased permeability compared with a background permeability of a solid (formed on a scale of crystal grains). It is assumed that rock containing no cracks has zero porosity.

We limit ourselves by a consideration of a very low permeable rock with low concentration of non-interacting, non-intersecting cracks. That is why the effects connected with the percolation of a crack system are not considered in the present study.

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 relatively weak external stress acting during such short periods of time (compared to geological time scales) that almost no fluid is evacuated from rock mass. In this case, the main contribution to changes of macroscopic physical properties of rocks is made by the elastic closure or 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.

Deformation of a permeable cracked solid displays in fact a time-dependent character. However, we make no attempt to model time evolution of macroscopic rock parameters under applied external stress or heating. 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.

In the present study, we considered granite with parallel microcracks saturated by different fluids (brines of various salinity, hydrocarbon gases and oils of different composition). However, for the other rocks with the same crack geometry the results will be qualitatively the same as those obtained for cracked granite. The model is specified by densities, seismic velocities and conductivities of the host rock and the saturating fluid, crack geometry (α) and crack density N, fluid temperature, initial pore pressure, and values of external uniaxial compression.

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. 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. Fluid parameters for different P-T conditions were described in the Part 2. Initial crack density N was assumed to be equal to 0.05 (for N>0.1 a medium is highly fractured and the EMT technique is not valid).

At the first step, the influence of external stress on crack geometry (including cracks volume) and hence, on pore-fluid pressure is considered. Then, the physical parameters of a saturating fluid (density, bulk modulus, acoustic velocity) are calculated for the given P-T conditions on the basis of data presented in the Part 2. When this problem is solved, the effective-medium theory is applied for the calculation of macroscopic parameters of the rock. As the result, the seismic and transport parameters of rocks are considered for different saturating fluids and under different stress conditions with account for P-T dependence of physical characteristics of pore fluids.

4. CRACK GEOMETRY UNDER EXTERNAL STRESS

External compressional stress applied to a cracked rock causes gradual closure of cracks. In terms of inclusion characteristics, the process of cracks closure results in changes of crack geometry and concentration (crack density). Under the assumption of a uniform strain in the volume of an inclusion, it is possible to determine the crack aspect ratio as a function of external stress.

The change in crack aperture depends on the elastic moduli of the saturating fluid which, in turn, depend on fluid temperature. That is why the variations of cracks aspect ratio, rock porosity and density under external stress also depend on the temperature of the saturating fluid.

External pressure or uniaxial compressional stress causes closure of microcracks that are not oriented parallel to the stress/pressure axis and results in a decrease of crack density and porosity. The rate of crack closure depends on the crack orientation, size (Artemieva and Zatsepin, 1992), and surface roughness (Batzle et al., 1980). As one could expect, numerical modeling revealed that cracks saturated with light gases, especially under high temperatures, are closed the first at comparatively low stress values (Fig. 2).

As pore-fluid pressure changes with a variation of crack aspect ratio (crack volume), a change of pressure in the saturating fluid occurs due to the action of external stress. In analogy with changes of crack geometry, variations of pore pressure under external compression are temperature dependent and are more pronounced for gases and gas-saturated oils (Fig. 3). Variations of pore pressure result, in their turn, in changes of fluid density, acoustic velocity and other parameters, all of which are (as it was shown above) pressure dependent.

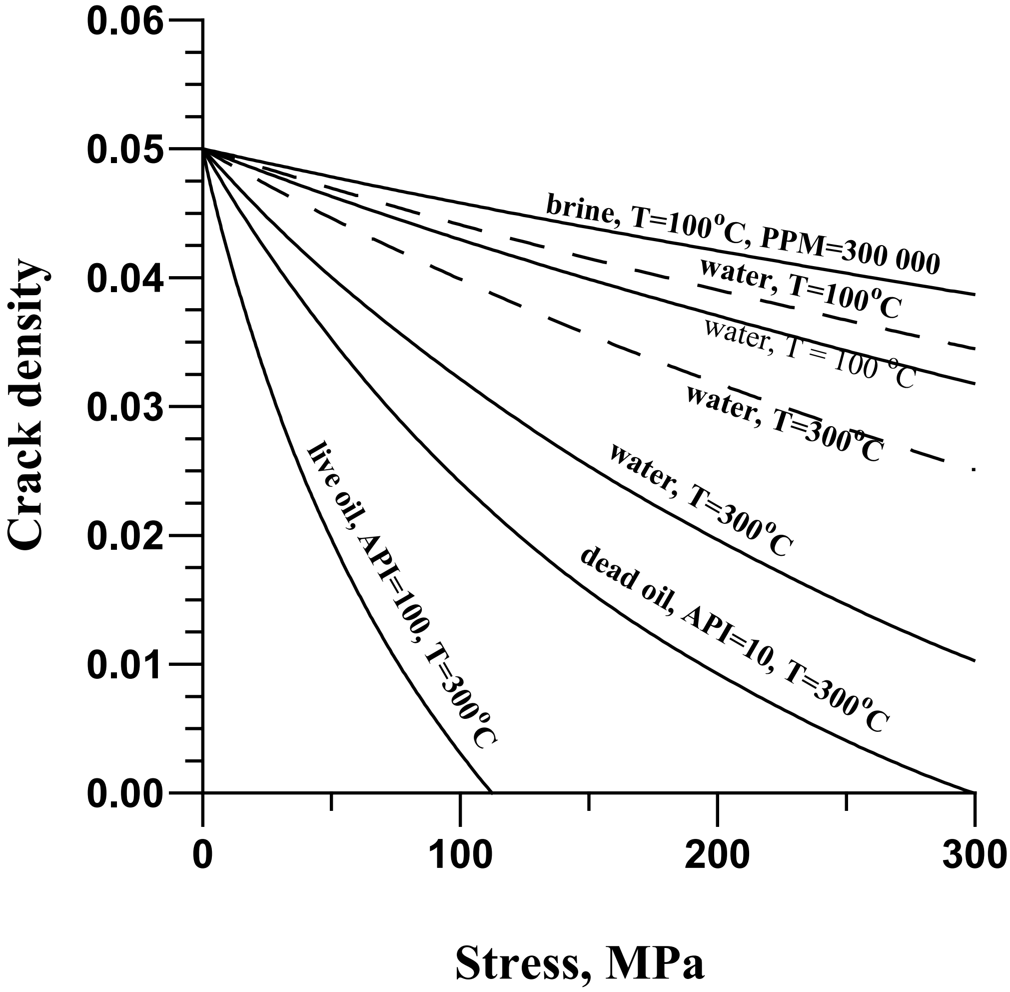

Fig. 2. Crack density of granite with fluid saturated parallel cracks versus uniaxial differential compression. Initial fluid pressure 50 MPa (solid lines) and 200 MPa (dashed lines). Parameters of the model are given in text.

5. MACROSCOPIC PARAMETERS OF FLUID-SATURATED ROCKS

When physical parameters (density, elastic moduli, etc.) of the saturating fluid in pre-stressed rock were recalculated for the new crack volume (and hence pressure), the effective-medium theory was applied to estimate the macroscopic properties of the rock. As the result, seismic and transport parameters of rocks were considered for different saturating fluids and under different stress and fluid pressure conditions taking into account the P-T dependence of physical characteristics of pore fluids.

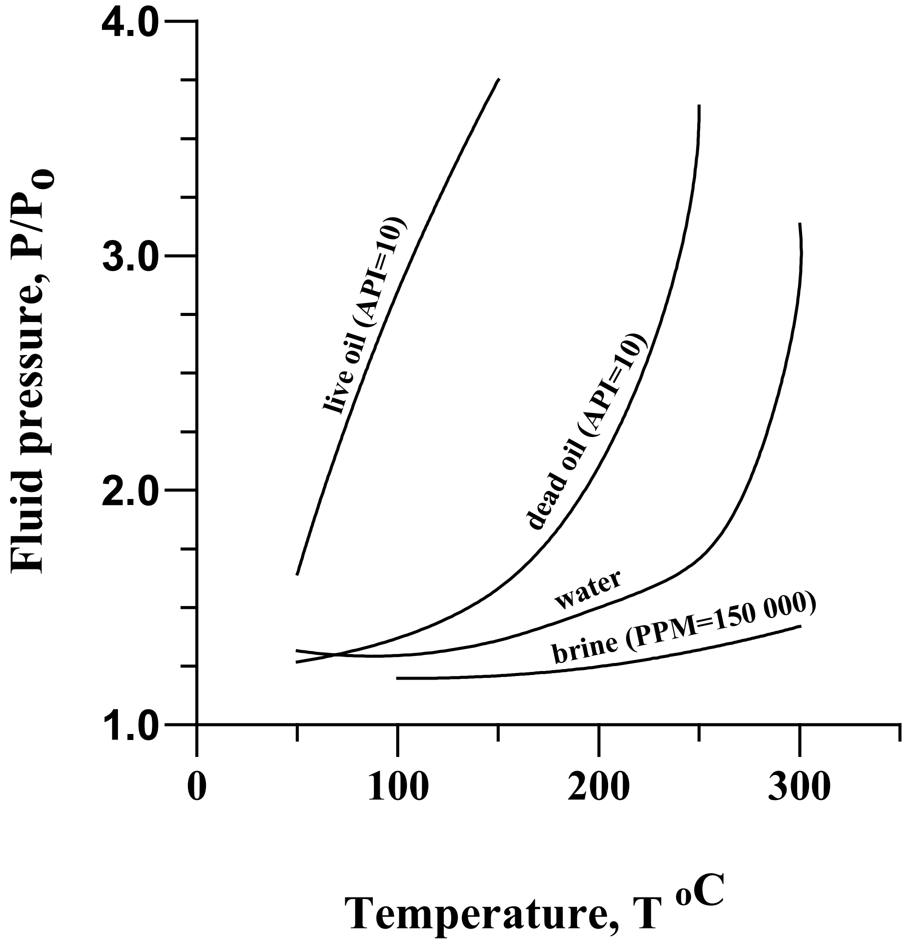

Fig. 3. Pore-fluid pressure normalized by its initial (prior to compression) value (50 MPa) versus fluid temperature. Model is the same as in Fig. 2. Uniaxial compression 300 MPa.

First, we will consider rocks saturated with different fluids and then compare their characteristics for different external conditions. If the rock (in our modeling, granite) is saturated by brines, shear velocities V_s will depend almost linearly on applied stress (as far as stress is not high enough to close all cracks) and fluid (and rock) temperature and will be inversely proportional to brine salinity. A notable reduction of effective permeability (up to 10% at P=300 MPa for brines at T=300^{O}C, PPM=150000) occurs with approximately 3% increase of V_s.

The effect of brines temperature and salinity on velocity and permeability variations is almost of the same order as the effect of uniaxial compression. For brines of average salinity, an increase of T from 100^{O}C to 300 ^{O}C will result in a 1% growth of V_s and a 3-4% reduction of effective permeability.

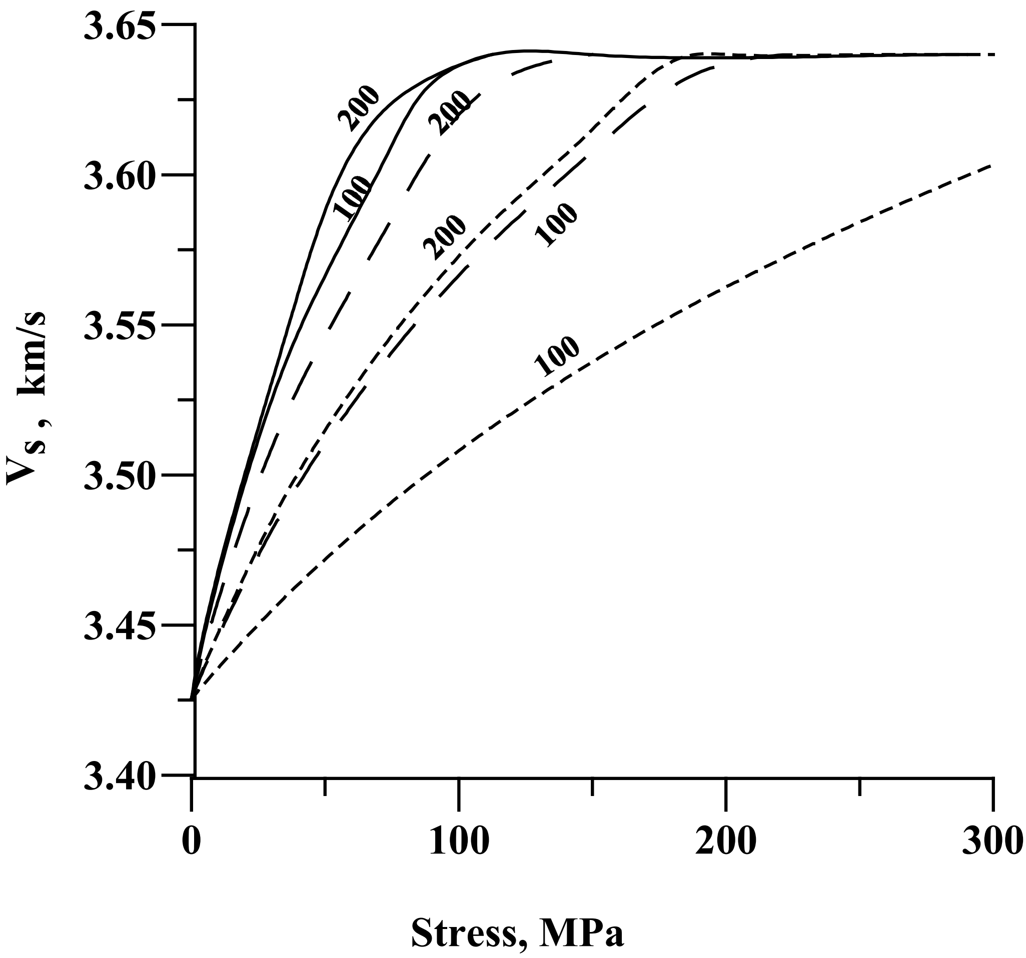

Fig. 4. Shear velocities in granite with parallel cracks saturated with different hydrocarbon gases versus uniaxial differential compression for direction normal to crack orientation. Gas temperature $100^{O}C$ and $200^{O}C$. G=0.6 for solid lines; 1.2 for long dashes; 1.6 for short dashes.

When calculating the effective permeability of the rock, we did not account for the temperature dependence of fluid viscosity, because (see Part 2) the viscosity of all the considered fluids remains almost constant at $T>100^{O}C$.

Unlike permeability and shear velocities, thermal conductivity is not so sensitive to the variations of the fluid parameters. As it has been shown earlier (Artemieva and Zatsepin, 1992), one can hardly speak about a significant effect of stress on thermal conductivity for cracks with aspect ratio $\alpha<0.01$.

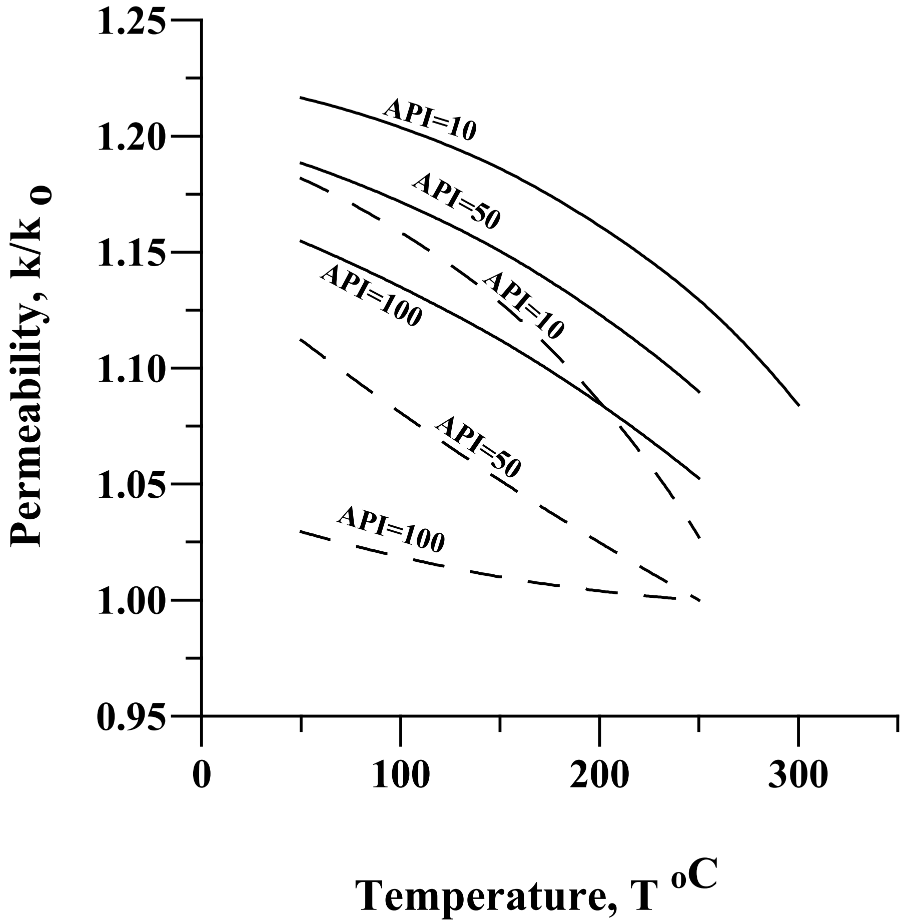

Fig. 5. Permeability of granite with parallel cracks saturated with different oils versus fluid temperature for fluid flow along cracks. Oil density API=10, 50, 100. Initial pore pressure 50 MPa, uniaxial stress 150 MPa. Solid lines correspond to dead (gas-free) oils, dashed lines - for live (gas-saturated) oils.

Here we want to note, that for the considered model of a rock with identical parallel cracks, all macroscopic physical parameters are highly anisotropic at low stress values. However, as stress increases, a reduction of crack aperture occurs accompanied by porosity decrease and the macroscopic characteristics of a rock mass tend to the values typical for the host rock.

Macroscopic parameters of a gas-saturated rock (Fig.4) depend greatly on gas density G and are less sensitive to temperature variations. A difference in permeability of rocks saturated with light (G=0.6) and heavy (G=1.6) gases may be as much as 15%, while shear velocities in granites saturated with the same gases may differ by 3-4% for differential stress being 100 MPa and P-T values typical for the upper crust.

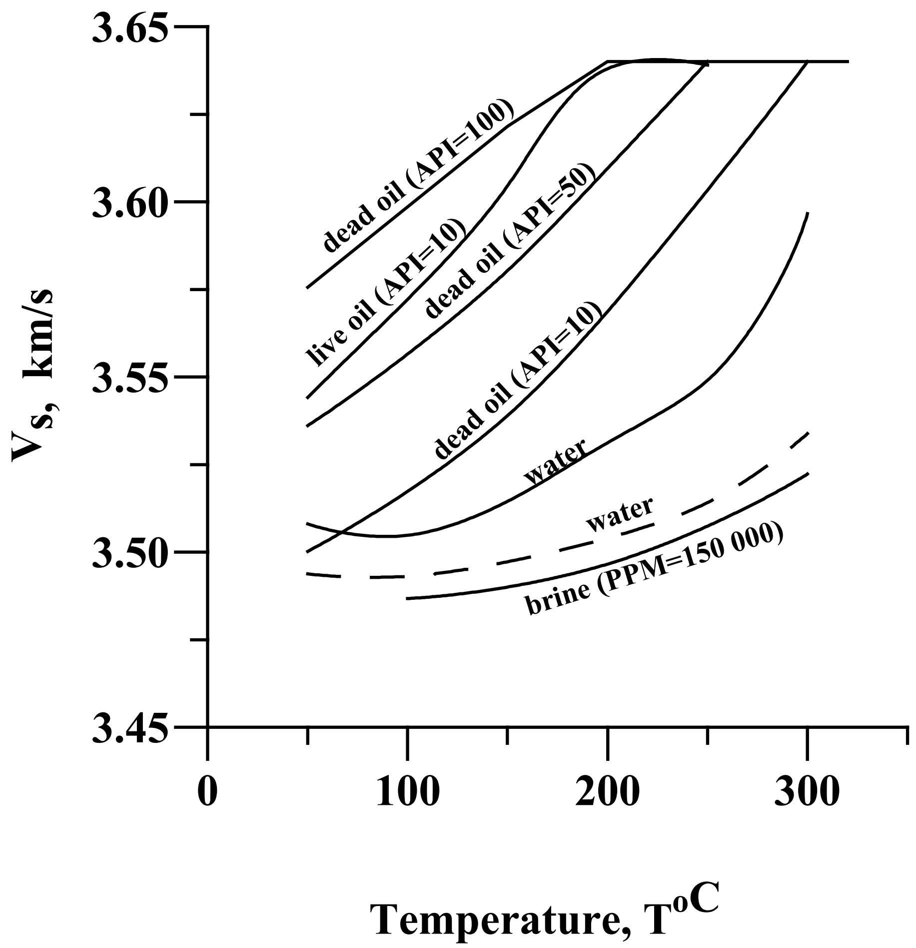

Fig. 6. Shear velocities in granite with parallel cracks saturated with different fluids versus fluid temperature for direction normal to crack orientation. Initial pore pressure 50 MPa (solid lines) and 200 MPa (dashed lines); uniaxial stress 300 MPa.

Compressional stress of about 100 MPa (such stress values could be expected, for example, for thrust faulting (Gretener, 1977)) is high enough to close almost all cracks of $\alpha = 10^{-3}$ saturated with gas (a weaker stress will be enough to close cracks with smaller aspect ratios (Artemieva and Zatsepin, 1992)). Only cracks saturated with relatively cold heavy gases (or liquids) can remain open under such compression (Fig. 4).

Difference in effective parameters of cracked granite saturated with different oils is rather essential. (To examine the pure effect of the influence of the fluid composition on macroscopic rock parameters, here we considered the same as above model of cracked saturated granite, though such situation seems to be uncommon in nature.) Study of effective permeability of such rock revealed that it is more sensitive to changes in oil composition than to stress or temperature variations. For pressures and temperatures typical for the upper crust, permeability of granite saturated with heavy and light gas-free oils differs by about 8%, while difference in permeability of a cracked rock saturated by gas-free heavy oil or live light oil may be as much as 15-20% (Fig. 5). Similar effect should be expected for other types of host rock with the same crack geometry.

For uniaxial stress of 150 MPa, a temperature effect on permeability of oil saturated rocks is essential only for dense oils, because such value of compression is large enough for almost entire closure of cracks filled with light gas-saturated oils. For such fluids, effective permeability practically does not depend on oil temperature at T>200^{O}C and is close to the background permeability of a host rock formed at the scale of crystal grains.

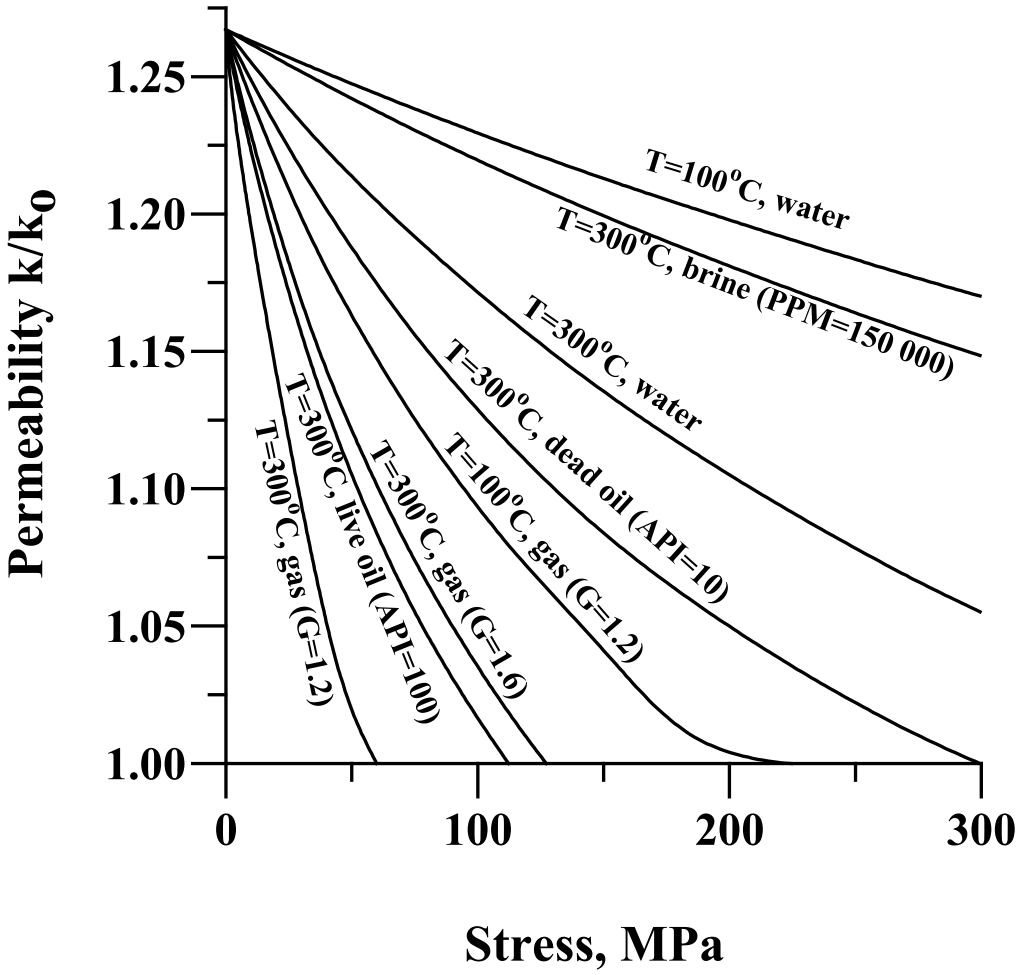

Fig. 7. Permeability of granite with parallel cracks saturated with different fluids versus uniaxial differential compression for fluid flow along cracks. Fluid temperature 100^{O}C and 300^{O}C. Initial pore pressure 50 MPa (solid lines).

Data shown in Fig. 6 and 7 allow to compare results obtained for different composition of pore fluids and reveal some general features. For the fixed values of initial pore pressure and temperature, seismic velocities increase almost linearly with stress, if stress is not high enough to close all cracks and rock porosity is far from zero.

For the same model of rock, characterized by the same values of initial (prior to stress) crack density, crack geometry, pore-fluid pressure and temperature, cracks filled with gas or gas-saturated oil are less "stiff" and will be closed the first. That is why, under the external compression, velocities will be higher in such rocks, intermediate in oil-saturated rocks, and the lowest in rocks saturated with brines of high salinity because their porosity will remain the largest. The effect of fluid composition on effective permeability of a saturated rock will be opposite (Fig. 7). Temperature variations will lead to changes of seismic velocities and permeability in the same direction as stress do (Fig. 6).

Under external compression, increasing fluid temperature results in decrease of fluid density and bulk modulus and is accompanied as well by crack density decrease due to gradual crack closure (Fig. 2). Under undrained conditions closure of cracks, in its turn, results in increasing fluid pressure and reverse changes of fluid density and elastic parameters. Thus, macroscopic properties of a heated saturated rock under external stress depend in a rather complex way on external stress-temperature conditions and on P-T dependence of physical properties of the saturating fluid.

As one may see in Fig. 6, at T~200^{O}C (which corresponds to the depth of about 5-10 km) only cracks saturated with heavy oils or brines of different salinity can remain open, while microcracks filled with gases, light or gas-saturated oils are closed, if initial (prior to the action of external stress) pore-fluid pressure is 50 MPa. However, an increase of initial pore pressure to 150-200 MPa allows to shift the point of such cracks closure to T~300^{O}C. However, even at T=200-300^{O}C, cracks saturated with water or brines at low values of initial pore-fluid pressure remain open and close gradually with a temperature increase.

Contrary to shear velocity, permeability of a rock decreases with increasing temperature. Thus, an increase of T from 100^{O}C to 200^{O}C is enough to reduce permeability of granites by 5-6% if they are saturated with oil, and by only 1% if the saturating fluid is brine. The same change of effective permeability can result from an increase of differential compression from 100 to 150 MPa (Fig. 7). On the whole, differential stress of about 100 MPa is high enough to close only cracks saturated with light or heated gases. However, an increase of water (or brine of low salinity) temperature from 100^{o}C to 300^{o}C may result in 10-15% reduction of effective permeability of cracked granites.

6. CONCLUSIONS

The overall physical parameters of cracked saturated rocks were considered under different stress and temperature conditions within the limits of undrained behavior. The pressure and temperature dependence of physical characteristics of pore fluids was taken into account. The results of numerical estimations were obtained on the basis of the effective-medium treatment and showed a significant dependence of macroscopic parameters of heated rock under external stress on physical properties of pore fluids. The results of the present study show that temperature of a saturating fluid is an important parameter controlling effective permeability and seismic velocities of cracked rock. For example, one needs to increase differential stress by about 50 MPa to get the same effect on macroscopic parameters as gives a fluid temperature increase from 100^{o}C to 200^{o}C.

It is likely, that in the upper crust, at the depth of about 5-10 km, cracks saturated with gases and live oils cannot remain open if differential compressional stress exceeds 100 MPa. Only rocks saturated with brines of increased salinity may remain highly permeable under high values of compression. However, this conclusion is true only for “short” geological time intervals when one can neglect fluid evacuation from rock and consider the closed system.

The above presented results refer to a case of a low-porosity rock. Meanwhile, it is likely that rocks within the upper parts of the crust may contain a dense network of interacting and intersecting cracks. In this case, the present approach is not valid, and percolation theory should be used to estimate effective permeability of the rock. It seems to be interesting to include temperature dependence of fluid parameters into the analysis of percolating networks. As far as author knows, such problem has not been considered yet.

In our model it was assumed that cracks are of elliptical form, and all macroscopic effects result from a gradual closure of such cracks due to uniaxial compressional stress. However, the results may be different for more realistic crack geometry, with an account for processes at crack tips. Moreover, if compression is so quick that a fluid is not evacuated from a crack volume, a sharp increase of pore-fluid pressure may occur leading to hydraulic fracturing of rock. This phenomenon, as well as thermal microcracking of rock was not considered in the present study.

Unfortunately, the author could not find any experimental data to verify the results of numerical modeling. An experimental (field or laboratory) testing of the above described results should be of a great importance, especially for estimations of rock permeability in the burial sites of radioactive and toxic wastes.

7. ACKNOWLEDGMENTS

I devote this paper to the memory of my father, Prof. Mikhail E. Artemjev, without whose strong influence I would never, probably, become a geophysicist and whose constant interest to my work stimulated all my studies.

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