Application of Lattice Green Function & Lattice Boltzmann Model to Lithosphere-asthenosphere permeability

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Abstract

This work develops a model to measure the permeability property of the deep lithosphere-asthenosphere [~ 660 Km] under coupled lithostatic pressure [~ 10 GPa] and temperature [~ 1500 ºC]. First, the new novel lattice Green function & lattice Boltzmann multi-scale [200 pm ~ 100 μm ~ 10 cm] flow driven pore-network model is obtained for the first time, and the role of free, supercritical [374 °C & 22.1 MPa] and constitutional state water [H+, (OH)-, (H_3O)+, 1500 °C & 1~10 GPa] is analyzed. Then, the permeability property of the deep lithosphere-asthenosphere [~ 660 Km] is predicted and their dependence on pressure, temperature and chemical composition is explored.

Keywords: Lattice Green function; Lattice Boltzmann method; Flow driven pore-network damage theory; Permeability of lithosphere-asthenosphere; Parallel CPU-GPU platform

1. Introduction

Permeability of lithosphere-asthenosphere is closely linked to the rheology, viscous-elastic and strength properties of the deep earth [0 ~ —660 Km], reflected dehydration-melting and phase-transition-melting properties of the rock/mineral and their dependence on pressure, temperature and chemical composition. Permeability physical property is important to understand the interior structure and material convection in the earth [1-4]. Brace et.al [5] studied the permeability of granite under 10~400 MPa condition; Chu et.al [6] found that permeability decrease with an increase in pressure from 1.5 Mpa to 22 MPa, and Morrow et.al [7] measured permeability under 10~200MPa confining pressures; Lockner et.al [8] studied permeability from the 12 Km deep well under confining pressure 10~300 MPa, and pore pressure 112-117 MPa; Darot et.al [9] measured permeability of granite specimens heated up to 650 °C for various confining pressure10~100 MPa; Gorbatsevich et.al [10] investigated permeability of deep-seated rocks under PT-conditions in the Kola Super deep Borehole [SG-3, 6~8 Km]; Gleeson et.al [11] used an extensive compilation of results from hydrogeologic models [>5 Km] and provided the first global picture of near-surface[100 m] permeability; Behnsen and Faulkner [12] measure water permeability of phyllosilicate powders at room temperature and varying confining pressure up to 160 MPa with a constant pore pressure of 10 MPa; Armitage et.al [13] studied vertical and horizontal permeability across a range of effective pressure 0~70 MPa; In-situ measurements of permeability in the Nankai accretionary prism were under taken during a recent IODP expedition [14].

But to the rock/mineral in the deep lithosphere-asthenosphere (~ 660 Km), it is hard to measure permeability through lab experiments manner and classical theoretical analysis way and traditional numerical method, especially when the water is located at supercritical state (374 °C, 22.1 MPa) and constitutional state (H+, (OH)-, (H_3O)+; 1500 °C, 1~10 GPa); In the lab experiment asperity, the existing design capacity and manufacturing ability can not provide such high pressure and temperature condition for the lab experiment apparatus and device; in the classical theoretical analysis asperity, the classical fluid-solid coupled mechanics/physics theory do apply to the ultra high temperature and pressure rock/mineral physical-chemical process in the deep earth; In traditional numerical method asperity, the traditional computational finite different element method and finite element method which based on the continue mechanics/physics can not calculate the lowest scale relationship between the molecular-ion scale rock/mineral structure and potential energy/force; All these reasons lead the permeability in the deep earth (~ — 660 Km) studies remain stagnate stage in the last 40 years.

In recent years, with the development of lowest level scales (atom-molecular-pico-nano-micro) computational porosity fluid flow mechanics/physics theory, especially for quantum lattice Boltzmann method[15-22] applied into physical transformation and chemical equilibrium/reactions problem, measuring/determining ultralow permeability in the deep lithosphere-asthenosphere became possible.

In this work, based on the quantum physical-chemical theory, the lattice Green function under coupled temperature and pressure potential is derived and combined with the previous work on the lattice Boltzmann distribution function [23-27], the new novel lattice Green function & lattice Boltzmann multi-scale flow driven pore-network model for measuring the permeability of rock/mineral in the deep earth is developed for the first time by the authors. Then, the permeability of lithosphere-asthenosphere under coupled LS (0~10 GPa), PS (0~600 MPa) and temperature (0~1500 ºC) is calculated and their dependence on pressure, temperature and chemical composition are analyzed, which can be helpful for understanding the strength weakening of the asthenosphere and the interaction between lithosphere-asthenosphere.

2. The mathematical model

As we know, when the fluid flow translates through ultralow permeability porous rock/mineral (UPPR/M) under ultrahigh pressure-temperature (UHPT), the dynamics viscous of fluid, effects of boundary layer and surface diffusion can not be neglected; the classical fluid-solid theory established on the continue mechanics do not suit for these complex rock/mineral physical-chemical process, and the molecular-ion scale potential energy/force can not be simulated through traditional finite different element and finite element method, the lattice green function & lattice Boltzmann method had be used to analyzed.

Put the typical nature core samples from upper-crust (0~20 Km), lower-crust (20~50 Km), upper mantle-lithosphere (50~150 Km) and lithosphere and asthenosphere (150~660 Km) into the parallel central processing unit & graphics processing unit (CPU&GPU) high performance computational system is the first step for the lattice Green function & lattice Boltzmann (LGF-LBM) model; Using micro XCT-400 CT system and focused ion beam system, the high resolution crosses-section images and micro surface images are obtained, then the 3D virtual digital rock are reestablished, and the LGF-LBM model are constructed. The left row (A1~E1), the medium row (A2~E2) and the right row (A3~E3) in the fig.1 show the initial CT data, the pretreated CT data (the threshold is arrange from 78~100) and the ES&NS model, respectively. In this process, the interior geometry architecture on low-level scales is translated from the pix RGB color format into the cell-mesh-grid model (cell-lattice green function method; grid-lattice Boltzmann method; mesh-LGF-LBM method).

Fig.1. LGF-LBM model for typical rocks/mineral of the deep earth.

A1~E1: represent center slice of physical object of granite. marble, sand, eclogite and olivine, respectively. A2~E2: represent relatively virtual digital models boundary of A1~E1. A3~E3: represent cross section mesh grid (1024×1024) for A1~E1.

Then, the initial/boundary conditions, the physical/chemical parameters of rock/mineral and water, and the low level scales geometry pore-solid structure are defined. The diameter and the length of the nature core samples are equal to 5cm and 10cm, respectively; the resolution of cross-section and the interval between cross-sections are equal to 2~10 μm. The general model was formulated by utilizing an automatic local amplification grid technique, and the initial ES&ES physical is equal to 1024×1024×1024 pixels, which does not include the extended variables (Fig. 2).

Fig.2. The physical objects and corresponding digital virtual physical 3D models

A~E: physical core samples of granite, marble, sandstone, eclogite and olivine, respectively; F~J: relatively digital virtual physical 3D models of A~E, respectively.

There are four different scales for the UPPR/M in the deep earth. First, the pore/void size is located at atom-molecular-pico-nano scale level, the fluid viscous (as function of pressure-temperature [P-T]), the effects of boundary layer, and the unsteady fluid flow (eddy flow and turbulent flow) can not be neglected; Second, when the P-T conditions are high enough, the water role in the rock/mineral includes free-supercritical-constitutional state, the fluid flow particles are composed of four components [H_2O, H+, (OH)-, (H_3O)+]. Third, the micro pore is composed of four types [multi-grain gap, polycrystalline space, crystal space and crystal internal space[28] and the deformation of the micro-structure had to be considered; Last, the fluid flow permeability and diffusion include intermolecular collisions and diffusion (Fick's laws of diffusion), molecular collisions with interface (Knudsen diffusion), molecular and interfacial adhesive and viscous flow (Darcy and Forchheimer flow). With the scale decrease, the surface stress component became domain, the effect of the body stress component reducing, and the classical N-S equation is no longer applies (Fig. 3).

Fig.3. Micro fluid flow translate in the ultralow permeability under UHPT

Olivine, resolution 2 μm, cell-node-grid scale 1024^3, 1.4 GPa and 600 °C.

The UPPR/M consists of six constituents, i.e. the particles of solid skeleton (the 1st component), bound liquid film (the 2nd component), static pore-liquid (the 3rd component, free state water), and dynamic pore-liquid I (the 4th component, free state water), dynamic pore-liquid II (the 5th component, supercritical state water) and dynamic pore-liquid III (the 6th component, constitutional state water).

Here summation from 1 to 3(1 to 6) over repeated lowercase (uppercase) subscripts is assumed, and a subscript comma denotes the partial differentiation with respect to the coordinates. The dynamic governing equations and constitutive relations of UPPR/M under electro-magneto-thermo-force (EMTE) field can be expressed as [29, 30]

$$A_L \tau^L_{ij,j} + B_L + \Sigma_{iJ,i} + f_J = 0 \tag{1}$$

where the extended porosity, the extended permeability, the extended stress and the extended body force of the UPPR/M can be defined as

$$A_L = \begin{cases} 1-(1-\alpha)\kappa & L=1 \\ \phi_2^P & L=2 \\ \phi_3^P & L=3 \\ \phi_4^P & L=4 \\ \phi_5^P & L=5 \\ \phi_6^P & L=6 \end{cases} \tag{2}$$

$$B_L = \begin{cases} \left[(1-\kappa)\rho_1 + \alpha\kappa\rho_2\right]\ddot{U}(x_i,t)_{1i} - \sum_{N=1}^{5}\left\{\nu_N\delta_N^2\chi^{-1}\chi_N^{-1}\left[\dot{U}(x_i,t)_{(N+1)i} - \dot{U}(x_i,t)_{Ni}\right]\right\} & L=1 \\ \phi_2^P\rho_2\ddot{U}(x_i,t)_{2i} - \sum_{N=2}^{5}\left\{\nu_N\delta_N^2\chi^{-1}\chi_N^{-1}\left[\dot{U}(x_i,t)_{(N+1)i} - \dot{U}(x_i,t)_{Ni}\right]\right\} & L=2 \\ \phi_3^P\rho_3\ddot{U}(x_i,t)_{3i} - \sum_{N=3}^{5}\left\{\nu_N\delta_N^2\chi^{-1}\chi_N^{-1}\left[\dot{U}(x_i,t)_{(N+1)i} - \dot{U}(x_i,t)_{Ni}\right]\right\} & L=3 \\ \phi_4^P\rho_4\ddot{U}(x_i,t)_{4i} - \sum_{N=4}^{5}\left\{\nu_N\delta_N^2\chi^{-1}\chi_N^{-1}\left[\dot{U}(x_i,t)_{(N+1)i} - \dot{U}(x_i,t)_{Ni}\right]\right\} & L=4 \\ \phi_5^P\rho_5\ddot{U}(x_i,t)_{5i} - \nu_5\delta_5^2\chi^{-1}\chi_5^{-1}\left[\dot{U}(x_i,t)_{6i} - \dot{U}(x_i,t)_{5i}\right] & L=5 \\ \phi_6^P\rho_6\ddot{U}(x_i,t)_{6i} + \nu_6\delta_6^2\chi^{-1}\chi_6^{-1}\dot{U}(x_i,t)_{6i} & L=6 \end{cases} \tag{3}$$

$$\sum\nolimits_{iJ} = E_{iJKl}Z_{Kl} = \begin{cases} \sigma_{ij} & J=j=1,2,3 \\ D_i & J=4 \\ B_i & J=5 \\ \vartheta_i & J=6 \end{cases} \tag{4}$$

$$f_J = \begin{cases} f_j & J=j=1,2,3 \\ -f_e & J=4 \\ -f_m & J=5 \\ -f_\vartheta & J=6 \end{cases} \tag{5}$$

The more detailed explanation to the equation (4) and (5), please refer to the author's previous work[31, 32]. The drained porous solid frame and the drained bound liquid film have the same displacement and pressure; the static pore-liquid, the dynamic pore-liquid I have the same displacement. The pressure of saturated porous solid frame is the sum of static pore-liquid, dynamic pore-liquid I, dynamic pore-liquid II and dynamic pore-liquid III components pressure. The elastic wave are composed of volume wave, spin wave and deflection wave parts, and can be written as

$$\frac{\partial^2\varepsilon_{kk}}{\partial x_m\partial x_m} = \frac{1}{c_L^2}\frac{\partial^2\varepsilon_{kk}}{\partial^2 t} \quad c_L^2 = \frac{\lambda+2\mu}{\rho} \tag{6}$$

$$\frac{\partial^2\omega_k}{\partial x_m\partial x_m} - \frac{\eta}{\mu}\frac{\partial^4\omega_k}{\partial x_m\partial x_m\partial x_n\partial x_n} = \frac{1}{c_T^2}\frac{\partial^2\omega_k}{\partial^2 t} \quad c_T^2 = \frac{\mu}{\rho} \tag{7}$$

$$\frac{\partial^2 e_k}{\partial x_m\partial x_m} - \frac{\eta}{\mu}\frac{\partial^4 e_k}{\partial x_m\partial x_m\partial x_n\partial x_n} = \frac{1}{c_T^2}\frac{\partial^2 e_k}{\partial^2 t} \quad c_T^2 = \frac{\mu}{\rho} \tag{8}$$

The motion equation of UPPR/M under transient dynamic wave loading can be written as

$$\left(C_{ijkl}e_{kl} - M_{ij}\left[\phi(U_i-u_i)\right]_{,i}\right)_{ij,j} = \rho\ddot{u}_i + \rho_f\left(\frac{\partial\left[\phi(U_i-u_i)\right]}{\partial^2 t}\right)_{,i} \tag{9}$$

$$\left(M\left[\phi(U_i-u_i)\right]-M_{ij}e_{ij}\right)_{,i}=\rho_f\ddot{u}_i+M_{ij}\left(\frac{\partial\left[\phi(U_j-u_j)\right]}{\partial^2 t}\right)_{,j}+r_{ij}\left(\frac{\partial\left[\phi(U_j-u_j)\right]}{\partial t}\right)_{,j} \tag{10}$$

The constitutive relation equation of UPPR/M under transient dynamic wave loading can be written as

$$\left[\left(\lambda+\frac{Q^2}{R}\right)\delta_{ij}u_{i,i}+\mu\left(u_{i,j}+u_{j,i}\right)+Q\delta_{ij}U_{i,i}\right]_{,j}+F_i=-\omega^2\left(\rho_{11}u_i+\rho_{12}U_i\right)-i\omega^2 b\left(u_i-U_i\right) \tag{11}$$

$$\left[Qu_{i,i}+RU_{i,i}\right]_{,i}+F'_i=-\omega^2\left(\rho_{11}u_i+\rho_{22}U_i\right)-i\omega^2 b\left(u_i-U_i\right) \tag{12}$$

Then the wave displacement in UPPR/M can be defined as

$$U(x_i,t)_{iL}=\Phi^1(x_i,t)_{iL,i}+\varepsilon_{ijk}\Phi^2(x_i,t)_{jL,k} \tag{13}$$

where

$$\begin{aligned}
&\Phi(x_i,t)^{\alpha}_{iL}\\
&=-A^{\alpha}_i E(\omega t)\left\{\begin{array}{l}\delta_{3i}\left[\begin{array}{l}E(-2\omega^{\alpha}_L x_1x_2x_3\sin\theta^{\alpha}_{1L}\cos\theta^{\alpha}_{2L})+E(-2\omega^{\alpha}_L x_1x_2x_3\cos\theta^{\alpha}_{1L}\sin\theta^{\alpha}_{2L})\\+E(-2\omega^{\alpha}_L x_1x_2x_3\cos\theta^{\alpha}_{1L}\cos\theta^{\alpha}_{2L})+E(-2\omega^{\alpha}_L x_1x_2x_3\sin\theta^{\alpha}_{1L}\sin\theta^{\alpha}_{2L})\end{array}\right]\\+E(-2\omega^{\alpha}_L x_3\cos\angle(x_3,x_2)^{\alpha}_{pL})+E(-2\omega^{\alpha}_L x_3\cos\angle(x_3,x_1)^{\alpha}_{pL})\end{array}\right\}\\
&\times\left[\begin{array}{l}E(\omega^{\alpha}_L x_1\sin\angle(x_3,x_2)^{\alpha}_{pL})+E(\omega^{\alpha}_L x_2\sin\angle(x_3,x_1)^{\alpha}_{pL})+E(2\omega^{\alpha}_L x_1x_2\sin\theta^{\alpha}_{1L}\cos\theta^{\alpha}_{2L})+E(2\omega^{\alpha}_L x_1x_2\cos\theta^{\alpha}_{1L}\sin\theta^{\alpha}_{2L})\\+E(2\omega^{\alpha}_L x_1x_2\cos\theta^{\alpha}_{1L}\cos\theta^{\alpha}_{2L})+E(2\omega^{\alpha}_L x_1x_2\sin\theta^{\alpha}_{1L}\sin\theta^{\alpha}_{2L})\end{array}\right]
\end{aligned} \tag{14}$$

$$\theta^{\alpha}_{1L}=\begin{cases}\angle(x_3,x_2)_{pL}+\angle(x_3,x_1)_{pL} & \alpha=1\\ \angle(x_3,x_2)_{pL}-\angle(x_3,x_1)_{pL} & \alpha=2\end{cases} \tag{15}$$

$$\theta^{\alpha}_{2L}=\begin{cases}\angle(x_3,x_2)_{sL}+\angle(x_3,x_1)_{sL} & \alpha=1\\ \angle(x_3,x_2)_{sL}-\angle(x_3,x_1)_{sL} & \alpha=2\end{cases} \tag{16}$$

$$\omega^{\alpha}_L=\begin{cases}\omega/v^L_P & \alpha=1\\ \omega/v^L_S & \alpha=2\end{cases},\ E()=e^{i()} \tag{17}$$

If we defined that solid skeleton component and liquid components are parallel and subjected to the same strain, the time-dependent rigidity modulus components G_L of UPPR/M is defined as

$$G_L=(1-f)G_0+\alpha f(v^L_s\varepsilon^{-2}_L)_{,t} \tag{18}$$

The permeability tensor can be defined as

$$\kappa_{ij}=-\frac{V_i\mu}{g\phi_{,j}}=-\frac{V_i\mu}{gJ_i} \tag{19}$$

The more detailed introduction can be found elsewhere in the literature[33-36].

The lattices point in $\Re^d$ can be defined as

$$\left\{\sum_{i=1}^{d} n_i a_i : n_1,......,n_d \in \mathbb{Z}\right\} \subseteq \Re^d \tag{20}$$

the lattice Green function on the lattices point can be written as

$$p_n(x:z) = \sum_{n=0}^{\infty} p_n(x) z^n = \frac{1}{\pi^d}\int_x^{\pi} ......\int_x^{\pi} \frac{d\kappa_1......d\kappa_n}{1-z\lambda(\kappa)} \tag{21}$$

$$\lambda(\kappa) = \sum_{x\in\Re^d} p_i(x) e^{ix\bullet\kappa} \tag{22}$$

When the resolution between any two grids in the D3Q27 [31] numerical model is high enough to reach the quantum physical-chemical scale level (atom-molecular-ion level, around 200 pm), the lattice grid in the D3Q27 can be defined as lattice point $\Re^d$. The relationship between distribution function [31] in the D3Q27 and the structure function in the lattice Green function can be established, and the improved D3Q27 lattice Green function & lattice Boltzmann can be used to exploring the lattice points extended physical-chemical process, and the permeability in the UPPR/M can be calculated.

3. LGF-LBM model for lithosphere-asthenosphere permeability

3.1 Mathematical calculations versus AUTOLAB 200C experience system

Based on the LGF-LBM model, the ultralow permeability of the deep earth under UHPT can be measured. We choose a tight sandstone core samples from the Ordos Basin Triassic formation of China, the rock depth, the diameter, the length, the density, the confining pressure, the PS, the temperature is defined as 862.76~864.36 m, 25.4 mm, 25~30 mm, 2.359~2.426 g/cm^3, 0~200 MPa, 0~10 MPa, 35~45 °C respectively, the more detail parameters of the tight sandstone core sample are shown in Tab.1.

Tab.1. Mineral composition, porosity and matrix density of the tight sandstone samples

The diagonal component of permeability tensor obtained as LGF-LBM model and experimental approach are given in the Tab. 2~4. The regular black color values represent the LGF-LBM model results, the value with outside border represent experimental results. From the diagonal component of permeability in x, y (DC-XYZ), we can see that the LGF-LBM model approach results are consisted with fluid pulse experimental results on the Inc AUTOLAB 200C system.

Tab.2. Diagonal component in x-direction as function of effective pressure and temperature

Tab.3. Diagonal component in y-direction as function of effective pressure and temperature

Tab.4. Diagonal component in z-direction as function of effective pressure and temperature

3.2 Upper-crust (0~20 Km)

The P-T conditions are 0~400 °C and 0~1.4 GPa, the water is free-supercritical state, the fluid transport in the multi-grain gap and polycrystalline space, the dehydration-creep-consolidation-enhance process existed, the permeability increases with LS, PS and temperature increasing (LS is most important, PS is second and temperature is least important); the permeability of sandstone and marble are located at 10~100 uD and 0.1~2 uD respectively, and the PA of marble is more apparent than sandstone (Fig.4).

Fig.4. Permeability of sandstone (left) and marble (right) as function of lithostatic pressure (0 ~ 1.4 GPa), pore pressure (0 ~ 200 MPa) and temperature (0 ~ 400 °C)

A~C: represnet diagonal element of sandstone in x, y and z direction, respectively; D~F: represent diagonal element of marble in x, y and z direction, respctively.

Sandstone: The diagonal component in x, y and z direction (DC-XYZ) varies 60~155 uD, 30~98 uD and 10~30 uD respectively; The permeability increases slowly at 0~0.65 GPa, increases sharply at 0.65~1 GPa, increases rate slow down again at the range of 1~1.4 GPa; The temperature has little influence and can be neglected at 0~0.6 GPa, has positive influence but still not obvious at 0.6~1 GPa, became obviously when the effective pressure over 1 GPa.

Marble: The DC-XYZ varies 0.5~2 uD, 0.1~1.8 uD and 0.1~1.3 uD respectively; the effect of LS increases fast in x, y and z direction is 0.7~1.1 GPa, 0.5~1.1 GPa and 1.2~1.4 GPa respectively, the most positive influence effective stage in x, y and z direction is 1.0~1.4 GPa, 1.3~1.4 GPa and 1.2~1.4 GPa respectively.

3.3 Lower-crust (20~50 Km)

The P-T conditions are 400~900 °C and 0~1.4 GPa, the water is supercritical state and constitutional state, the fluid flow transport in the polycrystalline space and crystal space, and the dehydration-phase transient process existed, the permeability increases with LS, PS and temperature increasing (LS is most important, PS is second and temperature is least important). The permeability of marble and granite are located at 0.1~2.0 uD and 0.03~1.6 uD respectively, and the PA of granite is greater than marble (Fig.5).

Fig.5. Permeability of marble and granite as function of lithostatic pressure (~ 1.4 GPa), pore pressure (~ 200 MPa) and temperature (400 ~ 900 °C).

A~C: represnet diagonal element of marble in x, y and z direction, respectively. D~F: represent diagonal element of granite in x, y and z direction, respctively.

Marble: The DC-XYZ varies 0.67~2.3 uD, 0.12~1.9 uD and 0.015~1.4 uD respectively. The effects of temperature on PA are significant at 400 ~ 900 °C, the PA increased sharply when the temperate is higher than 400 °C, which reflects that the water properties over 400 °C is different from below 400 °C.

Granite: The DC-XYZ varies 0.03~1.6 uD, 0.04~1.0 uD and 0.03~0.48 uD respectively. Compare with PA in upper-crust zone, the permeability fast-increasing region of granite move from 0.65~1 GPa to 1~1.4 GPa, which reflected physical properties difference between upper crust and lower-crust. The effect of temperature to the permeability became highly significant when LS is higher than 1.0 GPa, the PA has marked rise at 550°C point, especially for diagonal element in y and z direction.

3.4 Upper mantle-lithosphere (50~150 Km)

The P-T conditions are 400~900 °C and 1~5 GPa, the water is constitutional state, the fluid flow transport in the crystal space and crystal internal clearance. The permeability increases with LS, PS and temperature increasing (temperature is most important, LS is second and PS is least important). The permeability of granite and olivine are 0.27~4.1 uD and 0.04~0.39 uD, respectively (Fig.6).

Fig.6. Permeability of granite and olivine as function of lithostatic pressure (1 ~ 5 GPa), pore pressure (200 ~500 MPa) and temperature (400 ~ 900 °C)

A~C: represnet diagonal element of granite in x, y and z direction, respectively. D~F: represent diagonal element of olivine in x, y and z direction, respctively.

Granite: The DC-XYZ varies 0.55~4.0 uD, 0.27~1.57 uD and 0.27~1.18 uD respectively. The effect of temperature on the permeability anisotropy (PA) is significant, and increased sharply when the temperate is higher than 400 °C.

Olivine: When temperate is higher than 400 °C varies 0.08~0.38 uD, 0.06~0.24 uD and 0.04~0.26 uD, respectively. There are existed two PA properties dramatic changes region at 400 °C and 600 °C point respectively.

3.5 Lithosphere and asthenosphere (150~660 Km)

The P-T conditions are 900~1500 °C and 5~10 GPa, the water is constitutional state, the fluid flow transport in the crystal space and crystal internal clearance. The permeability decreases with LS and PS increasing, and its increase with temperature increasing, temperature is most important, LS is second and PS is least important (Fig.7).

Fig.7. Permeability of olivine and eclogite as function of lithostatic pressure (5 ~ 10 GPa), pore pressure (400 ~800 MPa) and temperature (900 ~ 1200 °C)

A~C: represnet diagonal element of olivine in x, y and z direction, respectively. D~F: represent diagonal element of eclogite in x, y and z direction, respctively.

Olivine: The DC-XYZ varies 0.022~0.078 uD, 0.017~0.068 uD and 0.011~0.051 uD respectively. There are three-temperature inflection points (1st point is 400 °C, 2nd point is 550~600 °C, 3rd point is 900 °C), the PA increase sharply at the first two points.

Eclogite: The DC-XYZ varies 0.0032~0.048 uD, 0.0029~0.062 uD and 0.0023~0.053 uD respectively. The temperature effects manner on olivine PA is similar on eclogite.

5. Discussion and conclusion

In this paper, we explored the water (free water, supercritical water and constitutional water) transport and dehydration in UPPR/M of the deep earth under UHPT, and analyzed the correlation between permeability under UHPT. Combined with high resolution 3D virtual digital technology, the multi temporal-spatial scale flow driven pore-network dislocation-crack damage theory, the novel new LGF-LBM model for measuring permeability of the deep earth is developed for the first time.

Compared with permeability results of the tight sandstone on the Inc AUTOLAB 200C system under coupled LS (0~200 Mpa), PS (0~60 MPa) and temperature (0~180 ºC), the accuracy, reliability and advantage of LGF-LBM model is validated.

The permeability of the deep earth (0~660 Km) under coupled LS (0~10 GPa) and temperature (0~1500 ºC) is measured (Tab.5), and its variation as function of pressure, temperature and chemical composition is discussed (Fig.8). We provide a new approach to understanding the mechanism of rheology and strength variation of asthenosphere and interaction between lithosphere and asthenosphere.

Tab.5. Permeability anisotropy of the deep earth under UHPT from LGF-LBM model

Fig.8. Permeability distribution as LS, PS and temperature of the deep earth from LGF-LBM model

1A~1C: DC-XYZ of sandston as function of LS (0 ~ 1.4 GPa), PS (0 ~ 200 MPa) and temperature (0 ~ 400 °C), respectively; 1D~1F: DC-XYZ of marble as function of LS (0 ~ 1.4 GPa), PS (0 ~ 200 MPa) and temperature (0 ~ 400 °C), respectively.

2A~2C: DC-XYZ of marble as function of LS (0 ~ 1.4 GPa), PS (0 ~ 200 MPa) and temperature (400 ~ 900 °C), respectively; 2D~2F: DC-XYZ of granite as function of LS (0 ~ 1.4 GPa), PS (0 ~ 200 MPa) and temperature (400 ~ 900 °C), respectively.

3A~3C: DC-XYZ of granite as function of LS (1 ~ 5 GPa), PS (200 ~500 MPa) and temperature (400 ~ 900°C), respectively; 3D~3F: DC-XYZ of olivine as function of LS (1 ~ 5 GPa), PS (200 ~500 MPa) and temperature (400 ~ 900°C), respectively.

4A~4C: DC-XYZ of olivine as function of LS (5 ~ 10 GPa), PS (400 ~ 800 MPa) and temperature (900 ~ 1500°C), respectively; 4D~4F: DC-XYZ of eclogite as function of LS (5 ~ 10 GPa), PS (400 ~800 MPa) and temperature (900 ~ 1500°C), respectively.

Acknowledge

Results described in this paper are obtained on the Deepcomp7000 of Supercomputing Center, Computer Network Information Center of Chinese Academy of Sciences, and Minneapolis Supercomputing Institute (MSI) of University of Minnesota, respectively.
Project SinoProbe-07 of China and the National Natural Science Foundation of China (D0408/4097409) supported this work.

NOTE:

Due to the limit of conference international space, all figures and tables are shared through following link:

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References

1. D.Connolly, J.A., et al., *Permeability of asthenospheric mantle and melt extraction rates at mid-ocean ridges.* Nature, 2009. **462**: p. 209-212.
2. Crone, T.J., M. Tolstoy, and D.F. Stroup, *Permeability structure of young ocean crust from poroelastically triggered earthquakes.* Geophysical Research Letters. **38**.
3. Hebert, L.B. and L.G.J. Montesi, *Generation of permeability barriers during melt extraction at mid-ocean ridges.* Geochemistry Geophysics Geosystems. **11**.
4. Rapp, R.P., *AMPHIBOLE-OUT PHASE-BOUNDARY IN PARTIALLY MELTED METABASALT, ITS CONTROL OVER LIQUID FRACTION AND COMPOSITION, AND SOURCE PERMEABILITY.* Journal of Geophysical Research-Solid Earth, 1995. **100**(B8): p. 15601-15610.
5. Brace, W.F., J.B. Walsh, and W.T. Frangos, *Permeability of Granite under High Pressure.* Journal of Geophysical Research, 1968. **73**(6): p. 2225-&.
6. C.L.Chu, C.Y.Wang, and W.Lin, *Permeability and frictional properties of San Andreas Fault Gouges.* Geophysical Research Letters, 1981. **8**(6): p. 565~568.
7. Morrow, C., L.Q. Shi, and J. Byerlee, *Permeability and Strength of San-Andreas Fault Gouge under High-Pressure.* Geophysical Research Letters, 1981. **8**(4): p. 325-328.
8. Lockner, D., et al., *Laboratory-Determined Permeability of Cores from the Kola Superdeep Well, Ussr.* Geophysical Research Letters, 1991. **18**(5): p. 881-884.
9. Darot, M., Y. Gueguen, and M.L. Baratin, *Permeability of Thermally Cracked Granite.* Geophysical Research Letters, 1992. **19**(9): p. 869-872.
10. GORBATSEVICH, F.F., S.V. IKORSKY, and A.V. ZHARIKOV, *STRUCTURE AND PERMEABILITY OF DEEP-SEATED ROCKS IN THE KOLA SUPERDEEP BOREHOLE SECTION (SG-3)* Acta Geodynamica et Geomaterialia, 2010. **7**(2(158)): p. 145~152.
11. Gleeson, T., et al., *Mapping permeability over the surface of the Earth.* Geophysical Research Letters, 2011. **38**.
12. Behnsen, J. and D.R. Faulkner, *Water and argon permeability of phyllosilicate powders under medium to high pressure.* Journal of Geophysical Research-Solid Earth, 2011. **116**.
13. Armitage, P.J., et al., *Experimental measurement of, and controls on, permeability and permeability anisotropy of caprocks from the CO2 storage project at the Krechba Field, Algeria.* Journal of Geophysical Research-Solid Earth, 2011. **116**.
14. Boutt, D.F., et al., *Scale dependence of in-situ permeability measurements in the Nankai accretionary prism: The role of fractures.* Geophysical Research Letters, 2012. **39**.
15. Keehm, Y., T. Mukerji, and A. Nur, *Permeability prediction from thin sections: 3D reconstruction and Lattice-Boltzmann flow simulation.* Geophysical Research Letters, 2004. **31**(4).
16. Bosl, W.J., J. Dvorkin, and A. Nur, *A study of porosity and permeability using a lattice Boltzmann simulation.* Geophysical Research Letters, 1998. **25**(9): p. 1475-1478.
17. Sun, W.C., et al., *Connecting microstructural attributes and permeability from 3D tomographic images of in situ shear-enhanced compaction bands using multiscale computations.* Geophysical Research Letters, 2011. **38**.
18. Renard, F., et al., *Synchrotron 3D microtomography of halite aggregates during experimental pressure solution creep and evolution of the permeability.* Geophysical Research Letters, 2004. **31**(7).
19. Bai, L.P., D.R. Baker, and R.J. Hill, *Permeability of vesicular Stromboli basaltic glass: Lattice Boltzmann simulations and laboratory measurements.* Journal of Geophysical Research-Solid Earth, 2010. **115**.
20. Y.H.Liu, *A lattice Boltzmann model for blodd flows.* Applied Mathematical Modelling, 2012. **36**(7): p. 2890-2899.

21. Leclaire, S.b., M. Reggio, and J.-Y. Trépanier, *Numerical evaluation of two recoloing operators for an immiscible two-phase flow lattice Boltzmann model.* Applied Mathematical Modelling, 2012. **36**: p. 2237-2252.
22. B.Yan, j.Y.Zhang, and G.W.Yan, *A lattice Boltzmann model for the eddy-stream equations in two-dimensional incompressible flows.* Applied Mathematical Modelling, 2011. **35**: p. 2358-2365.
23. Zhu, B.J. and Y.L. Shi, *Three-dimensional flow driven pore-crack networks in porous composites: Boltzmann Lattice method and hybrid hypersingular integrals.* Theoretical and Applied Fracture Mechanics, 2010. **53**(1): p. 9-41.
24. Zhu, B.J., et al., *Analysis of 3D fluid driven crack propagation problem in co-seismic slip under P- and S-waves by hybrid hypersingular integral method.* Computer Methods in Applied Mechanics and Engineering, 2009. **198**(30-32): p. 2446-2469.
25. H.H.Cheng, et al., *Extended hybrid pressure and velocity boundary conditions for D3Q27 lattice Boltzmann model.* Applied Mathematical Modelling, 2012. **36**: p. 2031-2055.
26. B.J.Zhu and Y.L.Shi, *Study of tight sandstone permeability from lattice boltzmann & digital rock model.* Chines Journal of Theoretical and Applied Mechancis, 2013. **45**(3): p. 384-394.
27. Bo-Jing, Z., et al., *Application of digital rock technology to saturated rock friction mechanism under high pressure and temperature.* process in Geophysics, 2013. **28**(4): p. 100~111.
28. Poiriet, J.-P., *Creep of crystals: High-temperature deformation processes in metals, ceramics and minerals.* Cambridge university press, 1985.
29. Aboudi, J., *Micromechanical analysis of fully coupled electro-magneto-thermo-elastic multiphase composites.* Smart Materials & Structures, 2001. **10**(5): p. 867-877.
30. Perez-Aparicio, J.L. and H. Sosa, *A continuum three-dimensional, fully coupled, dynamic, non-linear finite element formulation for magnetostrictive materials.* Smart Materials & Structures, 2004. **13**(3): p. 493-502.
31. B.J.Zhu and T.Y.Qin, *3D modeling of crack growth in electro-magneto-thermo-elastic coupled viscoplastic multiphase composites.* Applied Mathematical Modelling, 2009. **33**: p. 1014-1041.
32. B.J.Zhu. and T.Y.Qin, *Application of hypersingular integral equation method to three-dimensional crack in electromagnetothermoelastic multiphase composites.* International Journal of Solids and Structures, 2007. 44(18-19), 5994-6012.
33. B.J.Zhu, et al., *Porosity and permeability evolution and evaluation in anisotropic porosity multiscale-multiphase-multicomponent structure.* Chinese Science Bulletin, 2012. **57**(4): p. 320~327.
34. Dmitriev, N.M., *Surface porosity and permeability of porous media with a periodic microstructure.* fluid Dynamics, 1995. **30**(1): p. 64~69.
35. C.Y, K., F. J.D, and C. J.L.A, *Image analysis determination of stereology based fabric tensors.* Geotechnique, 1998 **48**: p. 515~525.
36. Koo, J. and C. Kleinstreuer, *Liquid flow in microchannels: experimental observations and computational analyses of microfluidics effects.* JOURNAL OF MICROMECHANICS AND MICROENGINEERING, 2003(13): p. 568~579.