Stress-time context of fault permeability at the Krasnokamensk Area SE Transbaikalia

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Abstract. The main aim of the contribution is to combine data on the consecutive stages of deformation, inflow and migration of palaeofluids and accumulation of mineral filling with uranium traces within the faulted-fractured environment at the Krasnokamensk Area, SE Transbaikalia, Russia. Object of examination is a framework of fault zones transecting the Proterozoic-Paleozoic granitic unit to the extent of northwestern part of uranium-bearing Streltsovskaya caldera of Mesozoic age. Considerations of stress- and permeability-time relationships in faulted-fractured zones were taken with account of stress and strain dependencies within fluid saturated rock massifs at crustal seismogenic level. Stress-time consecution of fault zone permeability was developed using set of fieldwork and lab tests including structural-geological survey, fault slip data analysis, mineral-chemical diagnostics, microstructural observations, and radiographic studies. Practical applications of obtained data for solving uranium mining and environmental issues are indicated in conclusion.

1. Introduction

Crystalline rocks, such as granites, are hosted economic uranium deposits and practically viewed as suitable settings for constructing underground facilities with a view to spent nuclear fuel (SNF) long-term storage or high-level wastes (HLW) disposal. The evaluation of mineral resources and safety of the facilities directly depends on the identification of the most probable pathways of fluid flow in connection with spatial-temporal evolution of radionuclide transport conditions. Some aspects of tectonic, geochemical and microstructural context of uranium migration in granites of the Krasnokamensk Area were distinguished previously¹. There were studied three specific sites located at different places and elevation outside (SNF storage potential Sites No. 1 and No. 5) and inside (the Antey uranium deposit) the Streltsovskaya caldera. It was shown that time scale context has crucial importance for modeling of the main features, events and processes existing at different geometric scales arranged in 3D space of variously deformed and altered fractured porous granites. This context was studied by the example of fault zone framework at the Proterozoic-Paleozoic granitic unit (potential Site No. 1) exposed within the northwestern part of the caldera.

In the general case, it is suggested² that the deformation in fluid-saturated rocks develops in the framework of a seismic cycle consisting of four stages (Fig. 1): (i) preseismic, when stresses accumulate steadily against the background of nonlinear deformation of rocks; (ii) coseismic, when deformation occurs immediately after relaxation of stresses (an earthquake); (iii) postseismic, with
nonlinear deformation of rocks during some time after stress relaxation; (iv) interseismic (the stage of seismic quiescence), when the deformation is close to linear.

Fig. 1. Hypothetical stress- and displacement-time relationships into the fault zones of seismogenic crustal level. Four stages of seismic cycle: $\alpha$ – interseismic, $\beta$ – preseismic, $\gamma$ – coseismic (earthquake), $\delta$ – postseismic.

At the interseismic stage, the fault cores undergo less dilatancy and are less permeable in comparison with zones of their dynamic effect, where fluids accumulate and slowly diffuse. At the coseismic stage, a considerable volume of these fluids is squeezed out from the compressed fractures and leaks into the disturbed core of the fault, where favorable conditions are created for drainage and circulation of solutions and precipitation of solid matter. Against this background when in a local domain of the geological medium the fluid pressure approaches $P_f = \sigma_e + TS$ ($\sigma_e$ – effective stress, $TS$ – tensile strength) the tensile cracks develop along heterogeneities (plane $\sigma_1\sigma_2$) favorably oriented in the stress field. The spatiotemporal cyclic relationships between pore pressure and favored paths of fluid migration are considered in the fault valve (pumping) model, which causes the stage-by-stage formation of mineral assemblages in the process of solid matter deposition. The efficiency of the fault valve mechanism of mineral formation is determined by the geometry of pore-fracture space, stressed-strained state of rocks, physicochemical parameters (composition) of solutions and their equilibrium with host rocks.

The first successful attempts to link hydraulically active fracture formation and fluid flow state during tectonic events were made in the University Nancy-1. It was suggested to use fluid inclusions in minerals (mainly quartz) as markers of thermobaric and physicochemical conditions of fluid migration, and fluid inclusion plains (FIPs) as structural indicators of changes in geometry of fluid-conducting fractures and geotectonic setting of permeability. FIPs start to form as tensile microcracks which change orientation in response to rearrangement of the stress field. They are oriented perpendicular to the least compression axis $\sigma_3$ while vector of maximum permeability lies in plane $\sigma_1\sigma_2$ forming direction of dominant fluid migration. The new tectonic setting gives rise to a new stage of deformation that is inevitably reflected in the orientation of FIPs of the second generation, etc.

Hence, three complementary aspects were taken into account during consideration of stress- and permeability-time relationships in fault zones of the area under investigation:

(a) Deformation of fluid saturated rock massifs within crustal seismogenic level is essentially nonlinear during tectonic events and variation of stressed-strained states;
(b) There is coupling between main phases of fluid inflow into and mineral accumulation inby different domains of fault zones due to fault valve (pumping) effect against the backdrop of seismic deformation cycle leads to local mixture of hydrothermal and meteoric solutions;
(c) Local mineral associations into fault zones do not have univocal correlation due to various $P$-$T$ conditions in distant domains (dilational jogs vs frictional fault planes) along even single fault zone.

2. Methods and Results
The SNF storage potential Site No. 1 occupies ~45 km$^2$ at the northwest part of the Streltsovskaya caldera where 20 outcrops (reference points) were investigated. The fieldwork procedures were realized as follows: (1) Structural-geological and mineral-petrographic survey of the main fault zone domains, their architecture, morphology, component strikes, dips, mineral filling, etc; (2) Determination of the mean principal stresses orientation, fault kinematics (dextral or sinistral displacements), and faulting regime (normal, strike-slip, and thrust) using fault slip data analysis; (3) Sampling of positioned lumps for studying rock mineral-chemical composition, FIPs characterization.
and fission-track radiography (FTR) analysis. The lab tests included: (1) Optical microscopy and mineral-chemical studies (XRF and ICP-MS) of rock varieties, nature and intensity of hydrothermal-metasomatic alteration and oxidizing transformation; (2) Microfracture space digitalization for distinguishing stress dependent FIPs and open micro discontinuities; (3) Evaluation of content and specific features of uranium distribution in rock varieties using FTR data. Some structural, mineral-chemical, and radiographic data are mentioned in 1. Hereafter we would like to focus on stress-time context of fault permeability at the area under investigation.

This area is situated within the Archaean-Proterozoic anticline that was repeatedly intruded by magmatic melts during Late Proterozoic with formation of a granitic gneiss cupola subjected to subsequent granitic injections during Caledonian and Variscan tectonic-magmatic cycles (TMC). Later on, during Early Jurassic to the Early Cretaceous period of regional tectonic-magmatic activation (TMA) the central part of the cupola underwent subsidence due to eruption of a large volume of acid volcanic products from several palaeovolcanoes, devastation of the magmatic chamber and, as a result, formation of the piecemeal-type Streltsovskaya caldera with three main units of volcanic and sedimentary rocks. Concerned granitic Site No. 1 situates at the NW flank of the caldera and its tectonic position is determined by intersection node of the NE-SE, NNE-submeridional, NW-SE and W-E long-lived interblock regional fault zones.

Five elements of internal constitution of the Site No. 1 are identified: (1) original magmatic foliation of granitic rock; (2) NE-SW fault zone of initial ductile deformation (schistosity); (3) NNE-submeridional fault zone of semibrittle deformation; (4) NE-SW, NNE-submeridional, and NW-SE normal and strike-slip faulted-fracture zones; (5) steeply- and gently dipping fractured zones of various strike.

Contour, dimensions and inner structure of granitic massif are defined using strike and dip components of original magmatic foliation: in latitudinal cross-section this is a cupola with steeply-dipping limbs and saddle shaped central part; in meridional cross-section this is a buckle folding structure results from lateral compression. The main peculiarity of the NE-SW fault zone of about 10 m width is ductile rock deformation stated in schistosity, blastic elongation of quartz and feldspar grains into the mylonite quartz-chlorite-carbonate matrix. The width of NNE-submeridional fault zone of semibrittle deformation is about 20 m. The main peculiarities of the zone are several sutures (about 25 cm width) with cataclastic material of quartz-feldspar composition, crush breccias and some necking stage boudinage. Normal and strike-slip faulted-fracture zones of NE-SW, NNE-submeridional, and NW-SE directions consist as a rule of one suture (about 1 m width) with precise striation (indicators of displacement) at the planes and cataclastic material (gouge) as fault filling. The main fault planes are accompanied by veins of milky-white quartz (about 5 cm width) and tensile fractures with quartz-carbonate aggregates.

Reconstruction of geodynamic circumstances throughout Pre-Mesozoic and Mesozoic tectonic-magmatic events shows that activation (reactivation) of interblock regional fault zones occurred on a step-by-step basis during succeed TMCs: Proterozoic (terminated about 600 Ma), Caledonian (~520-430 Ma), Variscan (~360-210 Ma), and Late Mesozoic (~150-100 Ma). Preferred faulting regimes of TMCs were indicated using fault slip data analysis combined with paleogeomorphological analysis and data on relative age of fault infill.

It was founded that magmatic body formation took place during Proterozoic TMC in regime of general tension with complementary component of submeridional compression. The main indicator of this regime is original magmatic foliation of the granitic rocks. During Caledonian TMC the principal axes of stress \( \sigma_1 \) and \( \sigma_3 \) were subhorizontal while the principal axis of stress \( \sigma_2 \) was oriented in subvertical direction (Fig. 2). This is characteristic feature of the strike-slip faulting regime. This regime was gradually changed by normal faulting regime with ENE-WSW direction of general tension axis during Variscan TMC. However at the time border between Paleozoic and Mesozoic eras, probably during \( T_3-J_2 \) time, all geological structures in SE Transbaikalia underwent inversion of tectonic movements due to global reorganization of the stress-strain field. In this connection the strike-slip faulting regime (transpression, \( \sigma_v=\sigma_2 \approx \sigma_3 \)) prevailed. As a result most intensive strike-slip
displacements and shearing were developed along NNE-submeridional and WNW-latitudinal fault zones.

Figure. 2. Dynamics of faulting regime changes at the NW granitic frame of Streltsovskaya caldera. Stereograms (L-hemisphere) present projections of 38 fault planes, direction of displacement (thin arrows) and averaged course of stress principal axes ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) during Caledonian (a) and Variscan (b) TMC, and Late Mesozoic TMA (c). Dominant directions of fluid flow (planes $\sigma_1 \sigma_2$) are shown as dotted lines.

In the tectonic context it is very important to define orientation in space the $\sigma_1 \sigma_2$ plane, which assigns direction of prevailing fluid flow and migration of the matter along pathways. The dynamics of fluid permeability of the fault zones was reconstructed using spatial distribution and orientation of FIPs (the AnIma video screen method) in connection with data on faulting regimes. Comparative analysis shows that orientation of FIP and fault networks coincides. That denotes the unified mechanism of their formation during different tectogenenic events. Three groups of FIPs prevail: NE-SW, NNE-submeridional, and NW-SE (Fig. 3). Herewith the NE-SW-trending FIPs form considerable cluster within the NE-SW fault zone of initial ductile deformation (schistosity). Preliminary microthermometric measurements show that constituent fluid inclusions are characterized by increased salinity that affirmed data on ancient origin of this zone.

Figure 3. Rose-diagrams of FIPs orientation within the Site No. 1 at the NW granitic frame of Streltsovskaya caldera. 20 outcrops (reference points) and NE-SW fault zone (dotted line) of initial ductile deformation (schistosity) are shown.

Intending changes in faulting regime, dominant directions of fluid flow at fault scale (planes $\sigma_1 \sigma_2$) and relationships between rock mechanical basis of discontinuity formation at macro and micro scale, it is possible to conclude that emphasized groups of FIPs were formed throughout different tectonic-magmatic cycles. For instance, NE-SW-trending FIPs were fashioned during Proterozoic TMC (FIPs 1) into the NE-SW fault zone of initial ductile deformation (schistosity) as well as during Late Mesozoic regional TMA (FIPs 4) inside the reactivated brittle segments of the zone. NNE-submeridional and NW-SE-trending FIPs were gradually formed most likely during Caledonian (FIPs 2) and Variscan (FIPs 3) TMCs due to planes $\sigma_1 \sigma_2$ were positioned along these directions.

Integrated consecution of the faulting periodicity and hydrothermal events at the NW granitic frame of the caldera is presented at stress-time diagram (Fig. 4). The periodicity of structural, deformation and hydrothermal processes coincides on a first approximation with stages of the seismic cycle when long-continued period of the stress accumulation (I) concurs with interseismic stage while relatively compact sequence of stress relaxation (II) accedes with preseismic, coseismic, and postseismic stages. The level of structural destruction (dotted line in Fig. 4) is governed by magnitude of compression, tension and shearing stress, ultimate yield and shear strength of rocks, fluid pressure and thermal gradient.
Figure 4. Stress-time dependence of fluid permeability for the fault zones: A – NE-SW, B – NNE-submeridional, C – NW-SE. Periods of stress accumulation (I) and relaxation (II) are accompanied by inflow of multiple-aged fluid portions committed to FIPs generations (from 1 to 4) during various tectonic-magmatic cycles (TMC) and regional tectonic-magmatic activation (TMA).

To reveal linkage between fracture repartition and uranium distribution in spatial-temporal context the fission-track radiography technique was utilizes (Fig. 5). Obtained data clearly indicate mobilization of significant part of uranium into the shearing core of NE-SW fault zone of initial ductile deformation (T17b) and NNE-submeridional zone of oblique-slip movements (T4) while outside the master planes of the faults (T20) the uranium distribution is in stockwork-like manner.

Figure 5. Uranium distribution patterns for variously deformed granitic rocks from reference points (T). Uranium content (C_U) is measured using ICP-MS (CRPG, Nancy).

The main concentrators of uranium are accessory and mafic minerals, and in a less degree, thin veinlets along grain boundaries. Intensive accumulation of uranium (probably in sorbed form) in oxidizing surface conditions is connected with Fe-Mn and Ti oxyhydroxides which fill microfracture networks.

Conclusions

Thus, the example of granitic environment of the Krasnokamensk Area shows long-term circulation of uranium-bearing fluids within the fault zones from Late Proterozoic and Paleozoic to Mesozoic and probably Cenozoic. The periodicity of the uranium-bearing hydrothermal solutions inflowing into the fault zones is connected with alternative repulsion phases of structural and deformation processes during tectonic-magmatic cycles coupled with preseismic, coseismic, postseismic and interseismic stages of the seismic cycle. For considering the stress- and permeability-time relationships for faulted-fractured zones a set of fieldwork and lab tests were used including structural-geological survey, fault slip data analysis, mineral-chemical diagnostics, microstructural (FIPs) observations, and radiographic studies. This approach allowed us to suggest the following results and practical applications:

1. Four main geodynamic cycles characterizing by inherent stressed-strained state of the rock massifs were identified namely Proterozoic, Caledonian, Variscan, and Late Mesozoic. The generation and activation (reactivation) of interblock regional fault zones occurred on a step-by-step basis during these cycles.

2. The main phases of the hydrothermal solution inflow to the optimally oriented segments of the fault zones accede with coseismic and postseismic stages of the seismic cycle while durable processes of hydrothermal-metasomatic alteration and mineral deposition concur with interseismic stage of transient and low-amplitude displacements.

3. Intersection nodes of the NE-SW fault zone of initial ductile deformation and the NNE-submeridional oblique-slip zones form areas of long-term volumetric circulation of uranium-bearing solutions. Here there are prerequisites for revealing Proterozoic-Early Paleozoic vein-disseminated uranium mineralization modified, probably, during Variscan episode of the caldera basement formation and/or during Mesozoic regional TMA.
Practical applications of obtained data on stress- and permeability-time relationships into the fault zones for solving uranium mining and environmental issues at the Krasnokamensk Area are as follows:

1. Consideration of Pre-Mesozoic, Mesozoic, Cenozoic and current faulting regimes and stressed-strained state of the granitic massifs allows us to develop conceptual and numerical rock mechanical models for localization the rock fall critical areas and organization of the mining operational safety monitoring.

2. Definition of intersection nodes of the regional long-lived and multiply activated fault zones allows us to identify the areas for long-term volumetric circulating of uranium-bearing solutions and thus to identify localities for further surveying with the aim of reconnaissance the uranium mineralization which is more ancient than Mesozoic (135 Ma) economic ores of the Streltsovkaya caldera.

3. Detection of hydraulically inactive blocks outside the intersection nodes of the regional fault zones allows us to recognize localities most favorable for constructing underground facility with a view for SNF long-term storage into the granitic environment.

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