Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Structure-Properties Correlations in Original and Hydrothermally Altered Rocks: Experimental and Pore-Scale Modeling Study

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Keywords: X-ray computer microtomography, hydrothermal processes, andesite, basalt, Kamchatka, Nizhne-Koshelevskoe thermal field, conditions modeling. µXRF-spectrophotometer.

ABSTRACT

Reactive transport and hydrothermal alteration of rocks depend not only on boundary conditions, e.g., pressure, temperature and solution chemistry, but is also influenced by original rock structure. By structure we mean not only pore morphology and connectivity, but also spatial correlations of pore space and chemical elements/mineral phases. In this work we combine detailed structure information obtained using X-ray microtomography scanning with high resolutions, element mapping with µXRF-spectrophotometer, laboratory measurements on rock samples, and pore-scale modeling to characterize structure-properties correlations in original and hydrothermally altered rocks. We use such modern methods as local porosity theory analysis (connectivity of the pore space), correlation functions (spatial correlations between pore space and different mineral phases), different pore-scale modeling approaches to determine permeability and connect such properties to structure data (spatial correlations and pore morphology estimated from pore-network extractions). Pore-scale modeling techniques were found to be invaluable tools in characterizing changes in physical properties of altered rocks based on 3D structure information obtained using non-destructive microtomography scanning.

1. INTRODUCTION

Nowadays the priority is put on the development of renewable energy sources, including the heat generated within the Earth. This is of special importance in areas of active volcanism, where the traditional sources of energy can be hardly produced and delivered to (Naboko, 1974; Kristmannsdottir and Armannsson, 2003; Kelly, 2011). Taking into account the contemporary methods of the resource development (the re-injection of waste thermal water into the reservoir), the extraction of geothermal heat is determined by economic effectiveness and reliability together with the ecological security of the atmosphere and natural water resources. The composition, structure and properties of hydrothermally altered volcanogenic and volcanogenic-sedimentary rocks are studied worldwide in relation to the construction of geothermal power plants (Lucko et al., 2009; Frolova et al., 2010). Nevertheless, a little attention is paid to the fact of constant change of these characteristics in real time, which can negatively affect the exploitation of geothermal field. Building new geothermal power plants and the modernization of existing ones broaden the scientific base of the hydrothermal processes research and raise a question on the possibility of carrying out some natural experiments. Some articles regarding the experiments with studies of minerals (Frolova et al., 2011) and rocks (Karpov, 1976) conversion under hydrothermal processes have been published since the middle of the XX-th century. Still our understanding of hydrothermal alteration and its influence on physical properties of rocks are limited. The progress of science and technology lead to the creation and usage of more and more advanced methods of investigating the composition, structure and properties of the rocks, for example, the X-ray computer microtomography (µCT) and pore-scale modelling (Korost and Gerke, 2012). The computer microtomography is especially attractive because it is a method of non-destroying analysis, which provides opportunity to study the same sample before (initial) and after the autoclave modelling of hydrothermal processes (modified). The aim of our work is to identify the regularity of volcanogenic rocks changes under the influence of waters of different composition by high temperatures and pressure during laboratory experiments (to model the conditions of hydrothermal alterations) with the parallel application of standard methods to access physical and mechanical properties of rocks, computer microtomography, pore-scale modeling and statistical structure characterization based on a collection of volcanic rocks of Koshelevsky volcano (Southern Kamchatka).

2. COMPREHENSIVE METHOD OF STUDYING CHANGES IN THE COMPOSITION, STRUCTURE AND PROPERTIES OF ROCKS UNDER THE INFLUENCE OF HYDROTHERMAL PROCESSES

We propose following systematical study of changes in composition, structure and properties of volcanic rocks under the influence of hydrothermal processes in real time in the deep and surface conditions, which consists of different experimental blocks: 1) field study of hydrothermal fields (temperature survey, geochemical sampling), sampling thermal water, sediments and samples of unaltered rocks, 2) laboratory study of the chemical and mineral composition, structure, physical and physic-mechanical properties of the investigated rocks, chemical composition of the thermal waters and sediments; 3) *in situ* research aimed at understanding the changes in the composition, structure and properties of volcanic rocks in real time by putting into hydrothermal environments: a) thermal waters and wells, b) in hydrothermal clay soils, 4) laboratory experiments in autoclaves using natural and model solutions at temperatures and pressures characteristic of the studied hydrothermal systems. This provides us with significant sample data base. All samples are then a subject of laboratory measurements of numerous physical properties, structure imaging, X-ray microtomography and pore-scale modeling and structure characterization.

2.1 In situ field studies at natural geothermal fields

At selected sites for field studies temperature survey are conducted, they allow us to select various areas of thermal field which will be our study cites. Samples are put into wooden cups with drilled holes and placed into various natural environments (Fig.1).

Physico-chemical parameters of the solutions including temperature, pH, Eh, and salinity are measured at each site. Samples of thermal waters and soils are also taken to determine their chemistry later in lab and to use natural solutions in autoclave experiments. To study changes in the composition, structure and properties of rocks without the active effects of the thermal waters, some samples were put into hydrothermal clay soils within excavated pits (Fig. 2c) at depths corresponding to the zones of the sulfuric acid and carbon acid leaching. Locations of field sites were determined using GPS.

a) b) c)

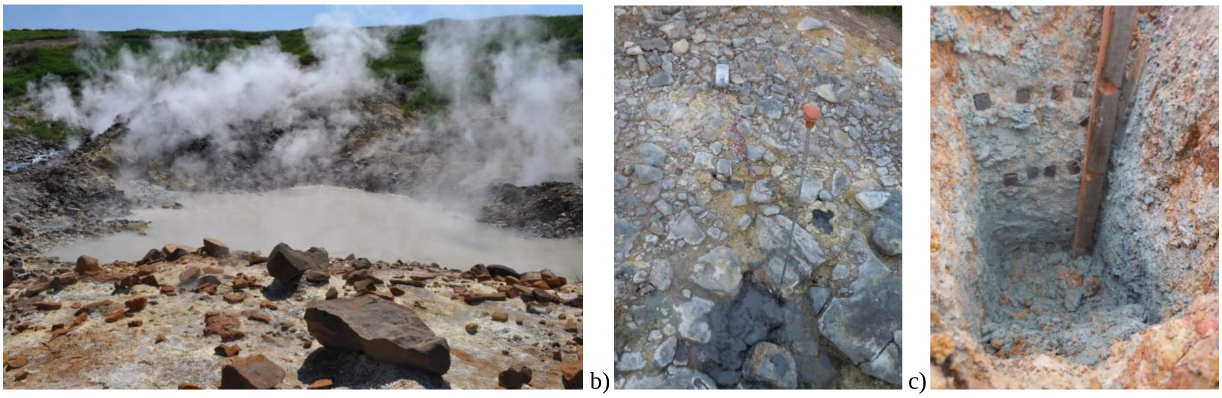


Figure 1: Experimental cites at Lower-Koshelevsky thermal anomaly: a) HK-15; b) HK-9; c) HKG-3

2.2 Laboratory determination of composition, structure and physical properties

The mineral composition of the studied volcanic and volcano-clastic rocks was determined in thin sections using a polarizing microscope, spot chemical analyzes of minerals and study the morphology of the pore space using a scanning electron microscope. For an illustration of the changes we provide pictures of original and modified rocks and their thin sections. To determine the composition of new minerals a quantitative X-ray analysis is conducted. Composition of ore minerals can be clarified by studying magnetic properties of samples (stepwise thermal demagnetization to temperatures of 540-700 °C). Chemical analysis of rocks is determined by X-ray crystal diffraction spectrometer; element mapping is performed with the help of µXRF-spectrophotometer. To study the physical and physico-mechanical properties of rock samples required preparations using stone-cutting machine to obtain rectangular parallelepipeds and also were polished. After preparation following properties are measured: bulk and mineral density, total porosity, open porosity, water absorption, propagation velocities of elastic waves (longitudinal and transverse), magnetic susceptibility, uniaxial compression strength and tensile. All measurements are performed according to standard methods described in conventional textbooks and manuals.

2.3 Autoclave method to model hydrothermal alteration under high pressure and temperature conditions

To model natural hydrothermal conditions we use claves (Fig. 2) consisting of titanium alloy, containing from 2 to 6 rock samples each, filled with natural or artificial (model) solutions. Closed autoclaves kept in an oven at a temperature characteristic of the studied hydrothermal system. The temperature can be regulated by means OWEN TPM 10 with ±1 ºC accuracy and monitored by thermocouples. After the end of each experiment autoclaves were cooled down and disclosed. The pH of resulting solution was measured immediately.

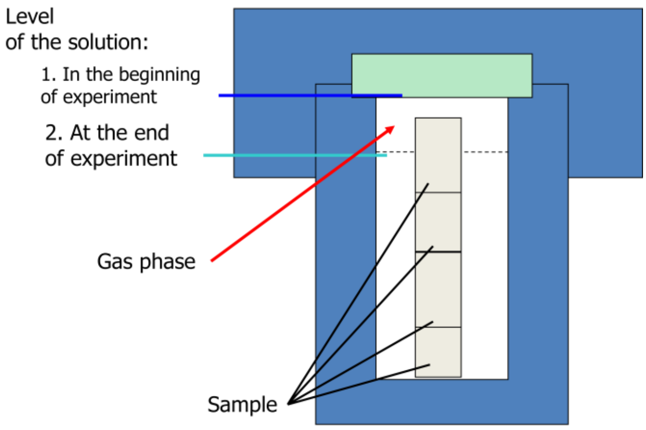


Figure 2: Autoclave scheme

2.4 X-ray microtomography, pore-scale characterization and modelling study

To determine the percentage of the heavy minerals and obtain detailed 3D information on pore space structure some rock samples were scanned using X-ray computer microtomography device (µCT). Using specialized software, one can build any sample section or their combination to create 3D computer model (Fig.3a,b). Such visualizations and necessary segmentation association of each voxel with some metrial, e.g. pore, heavy mineral or solid material) and some quantitative estimates (porosity, area, etc.) are obtained from 3D scans using SkyScan and ImageJ software. Using a specially designed software packages (Korost and Gerke, 2012) we extract pore-network model of the pore space using maximal inscribed ball method (Dong, Blunt 2009); pore space is divided into volume contorlling pore-bodies and permeability controlling pore-throats (Fig. 3c). In addition to the statistics of pore size distributions we calculate absolute permeabilities (Oren et. al., 1998).

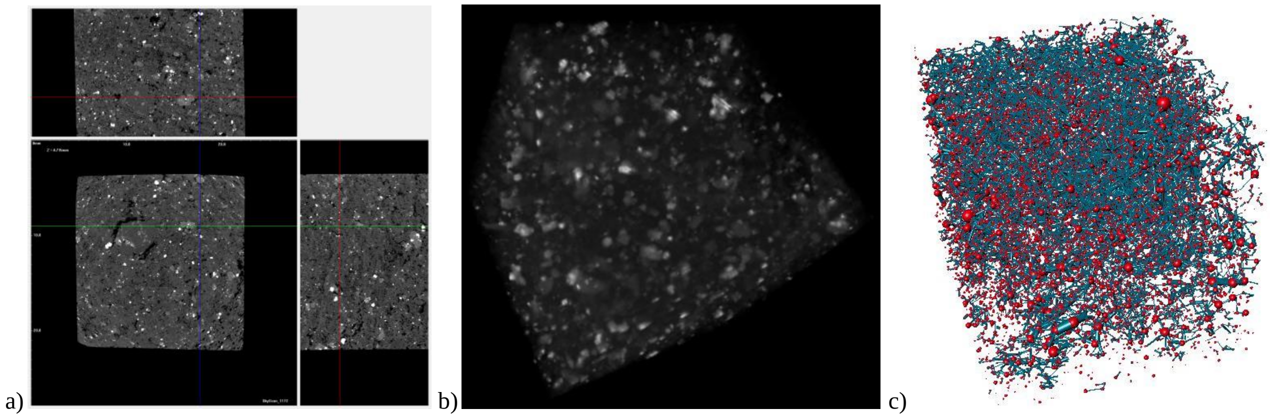


Figure 3: Images basalt samples: a) orthogonal sections (intial sample HK-100-1-34); b) visualization of the location of heavy minerals in a sample of basalt HK-102-30; c) pore-network model of basalt sample HK-102-30 (red - pore-bodies, blue - pore-throats)

Developed methodology consists of four blocks and allows parallel investigations in field and laboratory experiments and optimal combination of modern methods to study composition, structure and properties of rocks. The methodology has been tested on a large collection of andesites and basalts rocks samples from Koshelevsky volcano, and tuffs from Pauzhetskoe geothermal field (Southern Kamchatka) and basalts from volcano Krafla (Iceland).

3. SAMPLE COLLECTION

Examples of petrographic thin section (sample HK-1/09-1 and-1c) for andesite with porphyritic structures are shown in Fig. 4a. The background mainly consists of phenocrysts represented by plagioclase, pyroxene and ore minerals (probably magnetite). The matrix is composed of plagioclase, clinopyroxene, ore mineral and glass. Scoria (Fig. 4b) has a porphyritic structure mainly composed of basalt (SiO_2 50.30-50.75%). Composition of the basalt (Fig. 4c) is quite similar, but with higher SiO_2 content: 50.75% -53.10%. Plagioclase phenocrysts, pyroxene (clinopyroxene predominates) and ore minerals (magnetite) are also observed in thin-section (Fig.4c). Mineral composition is represented by plagioclase, clinopyroxene, olivine, ore mineral and glass structured hyaline.

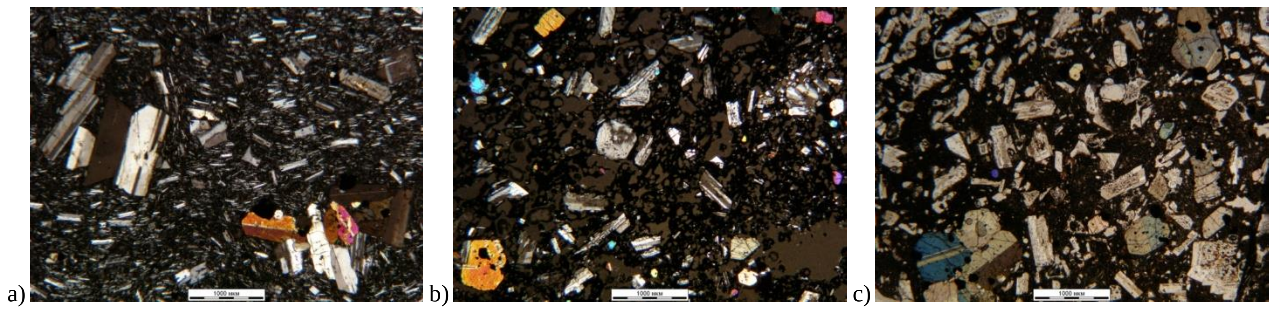
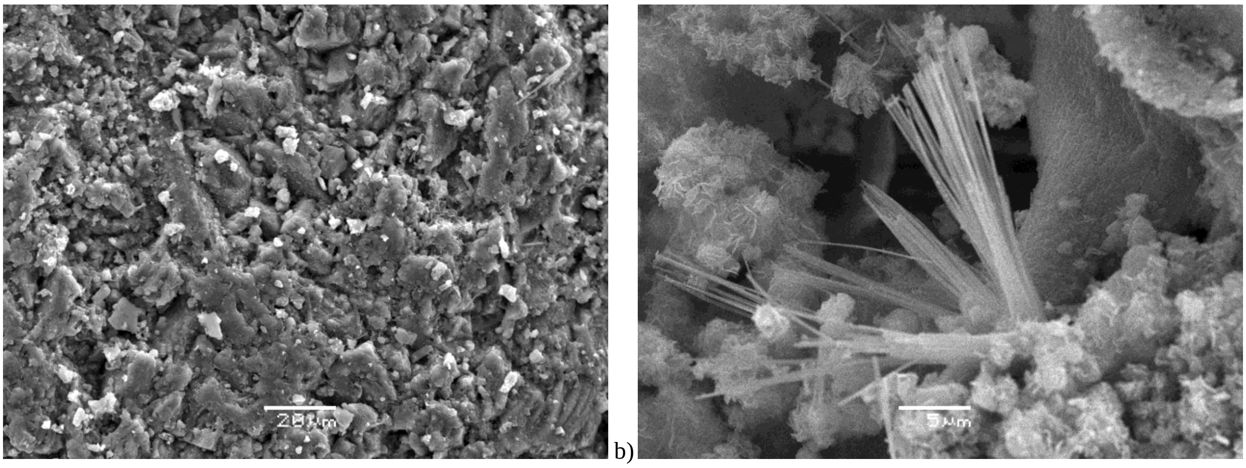


Figure 4: Thin-sections: a) andesite; b) scoria; c) basalt

Due to their mineral content the studied rocks can be divided into three groups: 1) andesite (HK-1/09-1 and - 1c) - the most dense (bulk, 2.50-2.51 g/cm³) with a minimum density of the solid component (2.68-2.69 g/cm³), porosity (6-7 %) and the moisture absorbent (0.1-0.2 %) with a maximum uniaxial compression strength (151-168 MPa); 2) basalts (NK- 100-1 and -3) - medium density (2.23-2.25 g/cm³), porosity (21-24 %), absolute permeability (0.3 $*10^{-11}$ m^2 such higher values up to 10^{-10} m^2 for a typical highly porous basaltic tuff (Zhatnuev et al., 1996, Ostapenko et al., 1987, Saar and Manga, 1999, Smith and Sharp, 2006)), a hygroscopic moisture content (0.4-0.5 %) and strength (39-55 MPa); 3) scoria (NK-102 and NK-110) - the lowest density (1.73-1.07 g/cm³) and strength (7-12 MPa), maximum porosity (40-65%), the length of the channel (0.37 mm) and their number in a single pore (5.8) by the average values of absolute permeability (3.9×10^{-11} m^2) and hygroscopic moisture content (0.6-0.7 %) with minimum velocities of the elastic waves (longitudinal 2.65-2.75 km/s and transverse 1.65-2.00 km/s).

4. RESULTS

In the experiments studied unaltered volcanics rocks sampled in the Western Koshelevsky volcano. Due to the contact with bicarbonate water (pH 6.8, T = 95 °C) the andesites gradually decomposed to montmorillonite clay in Lower Koshelevsky thermal field (Lucko et al., 2009). These lead, for instance, to a reduction of the density of the andesite to 2,05 g/cm^3 as well as a slight decrease in the density of solid particles (up to 2,65 g/cm^3) whereas the porosity (23%) and the moisture absorbent (1%) increase. The example of newly formed minerals is shown for andesite and scoria in Fig.5. These changes were also reflected on 3D images of samples (before and after alteration) and resulted in shrinkage of pore-throats wgich, in turn, lead to significant reduction in simulated absolute permeabilities.



a) b)

Figure 5: The newly formed minerals: a) chlorite within andesite, b) actinolite (sample of scoria NK-102-30).

Four samples were selected for studies using computer x-ray microtomography and were scanned before and after hydrothermal alteration. We have obtained permeability values which are in a good agreement with average values associated with geological materials under study. Porosities observed on 3D images are lower than those obtained experimentally due to scanning resolution limitations. But as all large interconnected pores are resolved, our permeability predictions are robust. High-performance computing in conjunction with X-ray microtomography can serve as a fast and accurate tool for predicting numerous physical properties of various natural porous materials and, thus, compete with traditional laboratory methods. In addition to absolute permeability values in future we are planning to use pore-scale modelling to obtain mechanical properties, water/vapor relative permeabilities and some other properties. Pore-scale modelling is especially useful in many geothermal applications as numerous laboratory techniques are invasive or results in serous alterations in rock structure. Based on laboratory measurements, pore-scale modelling and statistical measures of rock structure using correlation functions (Gerke et al., 2014) we have created a database of structure-property relations for different initial and altered rocks, some examples relevant to engineering geology are shown in Fig.6-7.

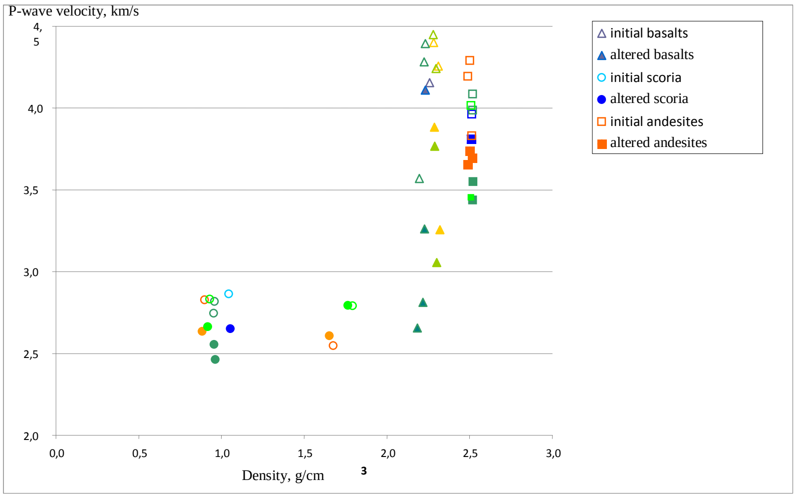


Figure 6: The ratio of the velocity of longitudinal waves in the studied rocks and their density

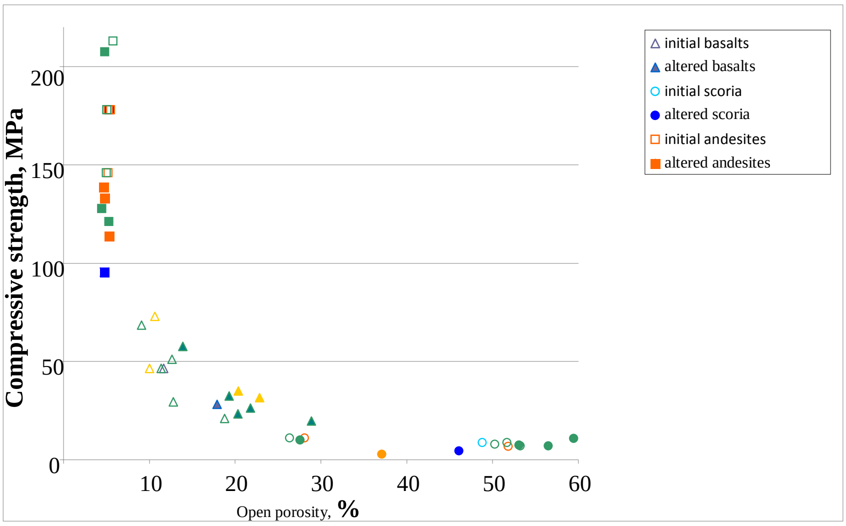


Figure 7: Dependence of uniaxial compression strength of rocks from their open porosity

5. CONCLUSIONS

New data on the nature of the changes in the properties of rocks during hydrothermal process was obtained and analyzed for a huge collection of rock samples:

1. Pore structure and connectivity is the most important factor affecting the degree of alteration and was lowest for samples with low porosity and permeability values.

2. If the time of interaction, temperature and pressure are all the same, pH of the solution has second significant impact on changes in the properties of rocks and increases in acidic conditions.

3. Hydrothermal alteration affects all main physical and mechanical properties.

4. Pore-scale modelling based on X-ray microtomography scans is a promising method for fast, reliable and non-destructive study of relationships between hydrothermal alteration, rock structure and physical properties. However at the moment our results are limited only to absolute permeability, in future we are planning to significantly improve the list of simulated properties.

5. Composition, structure and physical properties of studied volcanic rocks were changed under the influence of temperature, pressure and solution chemistry in a very short period (in geological terms). Similar changes are taking place in modern hydrothermal systems and reservoir where waste water is pumped.

This work was supported by RFBR grant № 13-05-01176_a and RSF grant 14-17-00658 (pore-scale modelling of multi-phase flow).

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