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Effects of Hydrothermal Alterations on Physical and Mechanical Properties of Rocks in the Geysers Valley (Kamchatka Peninsula) in Connection with Landslide Development

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ABSTRACT

The geothermal system of the Geysers Valley is composed of highly porous pumice-rich Quaternary tuffs. Thermal water altered and transformed them into hydrothermal rocks. Two hydrothermal facies are distinguished in geological section: low-temperature argillized propylites and hydrothermal argillites with high-silica zeolites. In some zones tuffs are totally altered into clayey soils. Mineralogical alteration of rocks decreases their physical and mechanical properties promoting the slope instability and triggering hazardous geological processes such as landslides. The most notable example is the catastrophic landslide in the Geysers Valley which occurred in 2007. This paper describes the hydrothermal alteration of volcanic rocks in the Geysers Valley and the relationship between petrophysical properties and secondary alteration.

1. INTRODUCTION

The Geysers Valley is located in the Kronotskiy State Natural Biosphere Reserve and is included in the UNESCO World Natural Heritage Site "Volcanoes of Kamchatka". It is a very attractive touristic site with tens of geysers and other geothermal manifestations. Besides geysers, the valley is known for the catastrophic landslide ocurred in June, 2007 (by different estimations the landslide volume is about 16-21 mln m^3). It should be noted that landslides are rather regular phenomenon in the valley (Dvigalo and Melekestev, 2009; Kiryukhin et al., 2010). In particular, a large landslide took place in January, 2014; other small landslides, mudflows and avalanches are also widespread. The main factors promoting landslides are geological conditions of the territory including lithology, tectonic faults, relief (steep slopes of the valley), high seismicity; and climatic particularities such as abundant atmospheric precipitation and snow melting. Hydrothermal alteration of rocks appears also to be a reason triggering landslides. Thermal water affects volcanic rocks and transforms them into hydrothermally altered rocks. Mineralogical alteration of rocks decreases their physical and mechanical properties.

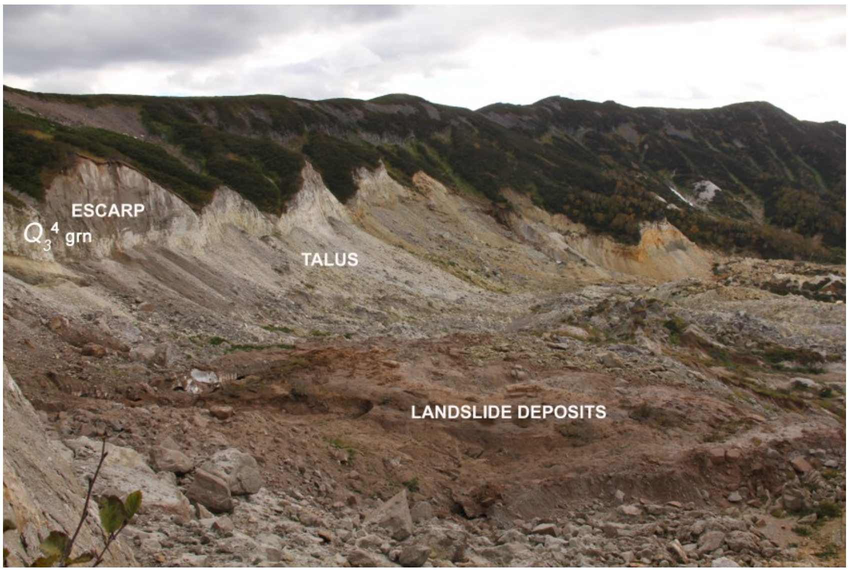

Figure 1: Landslide in the Geysers Valley occurred in 03.06.2007 (Photo taken in 2013). Escarpment is approximately 40-50 m high.

2. GEOLOGICAL SETTING

The region is located in the East side of Uzon-Geyserny depression. Detail geology is described by Belousov et.al.(1983) and Sugrobov et.al. (2004). The valley of Geyizernya River cuts the volcanic massif, which is mainly composed of Quaternary tuffs. The most ancient Ustievaya Unit (Q_{1-2} ust) is exposed in the river mouth. It consists of lapilli lithic and crystal-rich andesite-dacite tuffs altered by propylitization. Secondary mineral assemblage includes calcite, chlorite, sericite, quartz. Ustievaya Unit is covered by Geysernya Unit (Q_3^4 grn) which is composed of ash-pumice tuffs. These tuffs are intensely altered with high-silica zeolites and smectites as shown by Naboko and Glavatskih (1978) and Vergasova et.al. (2010). “Yellow tuffs” Unit (Q_3^4 js) lies above. It consists of pumic-rich tuffs that have never been affected by hydrothermal activity. The landslide 2007 involvedn hydrothermally altered ash-pumic tuffs of Geysernya Unit, which contained clay horizons. The layers dip to the west-northwest at the angle of 20-25^0 along the slope, which promoted the occurrence of the landslide.

3. ANALYSIS AND TESTING METHODOLOGY

Twenty six samples of tuffs were taken in 2013 in the Geysers Valley from natural outcrops and then examined in laboratory.

In the laboratory, each sample was separated into several specimens (from 4 to 15) for physical and mechanical measurements. Specimens had cylindrical shape with a length-to-diameter ratio from 1:1 to 2:1. Several tests were carried out for each property, then, the mean values were calculated for each sample.

The following properties were determined: bulk density (ρ), grain density (ρs), open (no) and total (n) porosity, gas permeability (K_g), hygroscopic moisture (Wg), water absorption (W), velocity of ultrasonic P- and S-waves (Vp, Vs), elastic modulus (E), Poisson's ratio (ν), uniaxial compressive (σ_c) and tensile (σ_t) strength, softening coefficient (C_{soft}), angle of internal friction (ϕ), and cohesion (C). All measurements were performed in accordance to standard testing procedures of the International Society for Rock Mechanics (ISRM, 2007).

Property measurements were accomplished with petrological examinations. All samples were studied petrographically (optical microscope "Olympus" BX-41). Secondary minerals were also identified using X-ray diffraction (DRON-3). Microprobe analysis was conducted for a portion of the samples (electron microscopes Camebax SX-50 and LEO 1450VP with microprobe apparatus INCA 300) to study the morphology of pore space and chemical alteration that occurred during the hydrothermal process.

4. RESULTS AND DISCUSSION

4.1. Petrology and hydrothermal alteration

Thermal water alters parent rocks changing their composition, pore-space morphology and volume, and properties, finally transforming them into hydrothermal rocks. Two hydrothermal facies are distinguished in the Geysers Valley: low-temperature argillized propylites and hydrothermal argillites with high-silica zeolites.

Argillized propylites are developed in tuffs of Ustievaya Unit. They consist of quartz (30-50%), calcite (5-6%), Mg-chlorite (6-7%), Ca-smectite, illite, mixed-layer clay minerals and pyrite. Calcite and chlorite fill pores and microcracks (Fig.2a). Occasionally calcite forms porous intergranular cement between clasts. Quartz composes some sites and occurs as a fine-grained matrix with the grain size varying from 1 to 10 microns (Fig.2b). Clay minerals substitute porous pumice clasts (Fig.2c). Zeolites occasionally replace plagioclase (Fig.2d). Alteration has pseudomorphous character when primary tuff textures are maintained in spite of intense mineralogical alteration. The intensity of propylitization varies from medium to intense. Some samples are characterized by abundant microcracks filled with calcite and chlorite.

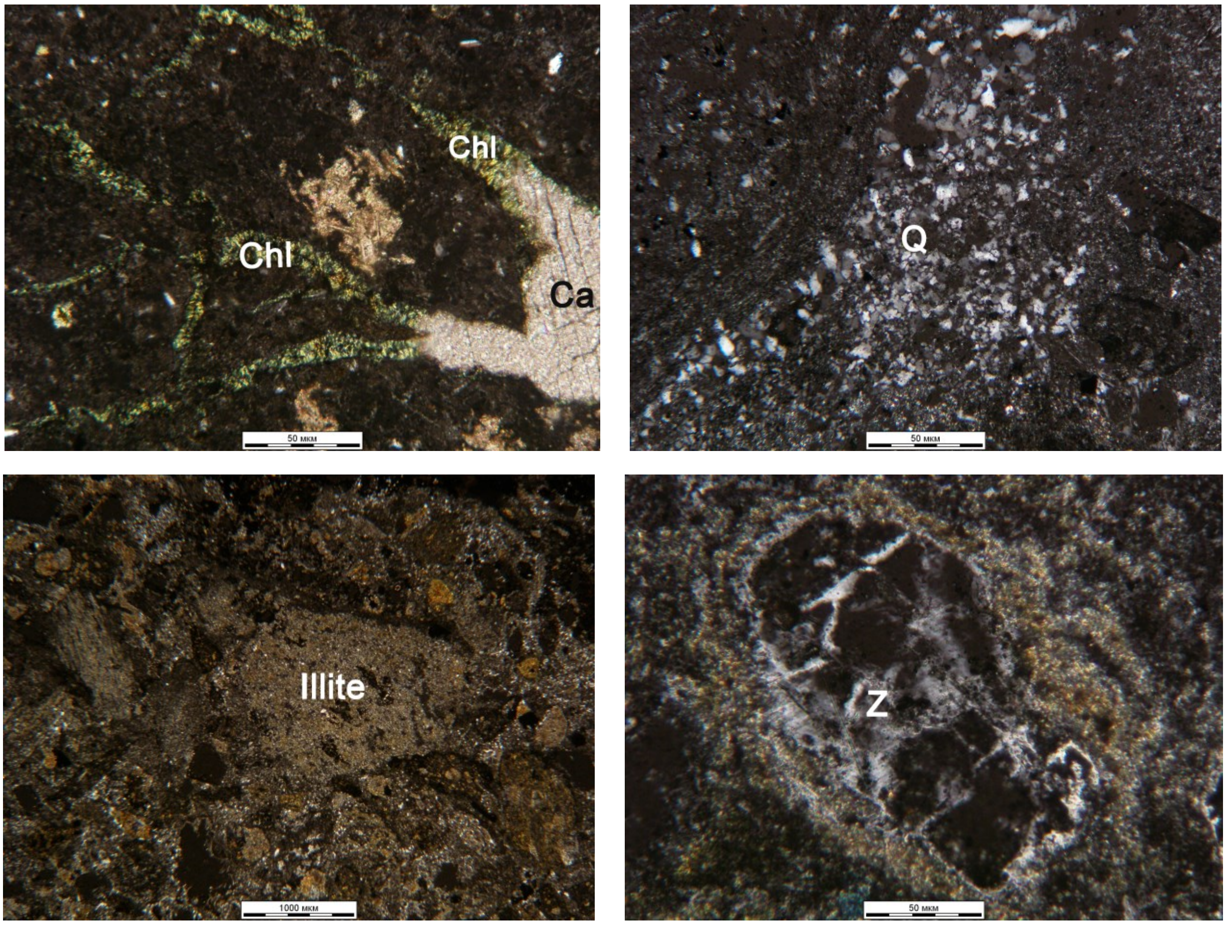

Figure 2: Photomicrographs of thin sections. A – chlorite and calcite fill in pores and microcracks; b - fine-grained matrix of secondary quartz; c – illite replaces pumice clasts; d – zeolites replace leached plagioclase. Chl – chlorite, Ca – calcite, Q – quartz, Z – zeolite.

Hydrothermal argillites with high-silica zeolites are associated with Geysernaya Unit. Secondary mineral assemblage consists of Mg-Na-smectites, zeolites (clinoptilolite, mordenite, heulandite, analcime), and silica minerals (tridymite, and cristobalite). Glassy matrix of tuffs is mainly recrystallized to smectites. SEM image clearly shows transformation of volcanic glass to smectite with cellular microstructure (Fig.3). Zeolites fill pores in pumice clasts (Fig.4a) and partially substitute plagioclase (Fig.4b). SEM image illustrates the leached “skeletal” crystal of plagioclase, and rectangular-tabular microcrystals of clinoptilolite growing in pores (Fig.4b). Mordenite is also developed in pores forming fiber-needle or sheaf-like crystals (Fig. 5a,b).

“Yellow tuffs” Unit consists of coarse-grained pumice-rich tuffs. They are only weakly altered (due to weathering) with smectites developing in pumice clasts.

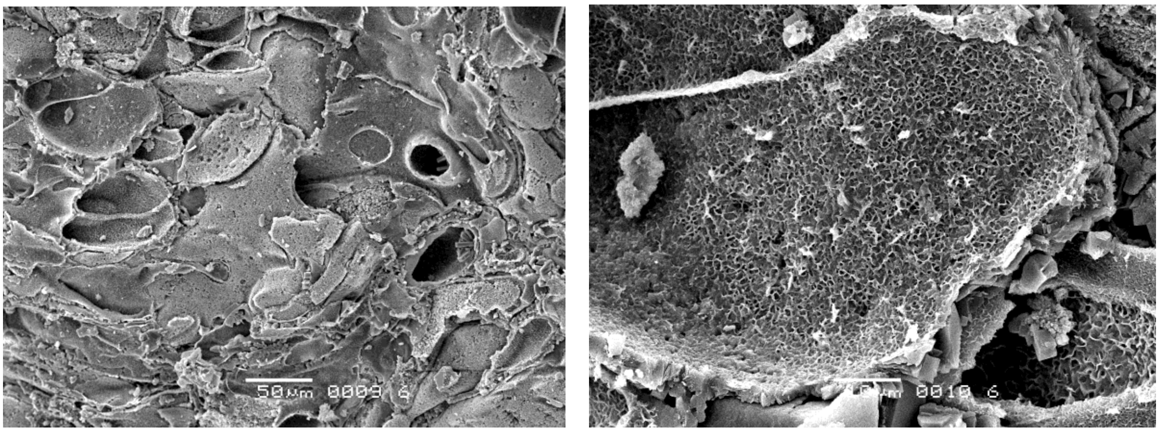

Figure 3: SEM images of argillized tuffs. Volcanic glass is replaced by smectite with cellular microstructure

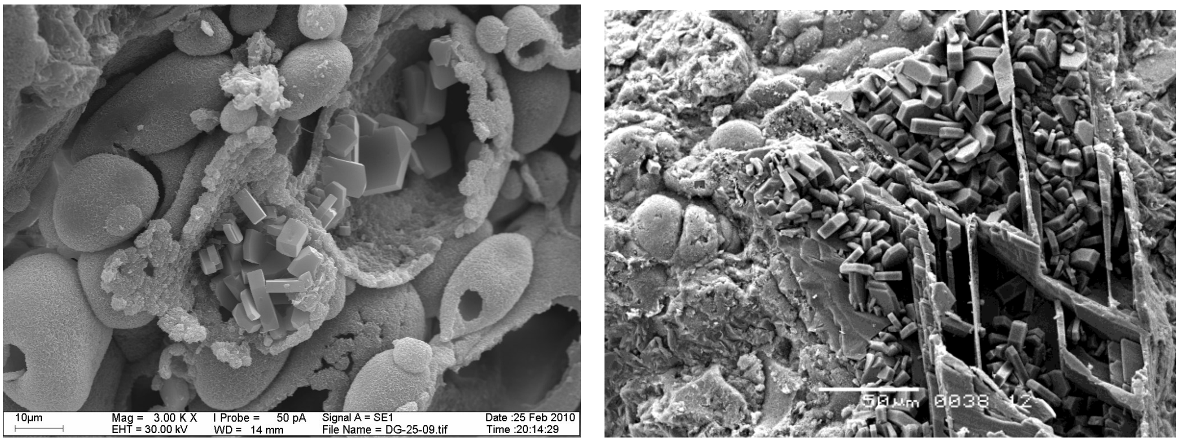

Figure 4: SEM images of argillized tuffs. a –tabular crystals of clinoptilolite growing in pores of pumice clasts; smectites replace volcanic glass; b - leached crystal of plagioclase substituted with clinoptilolite

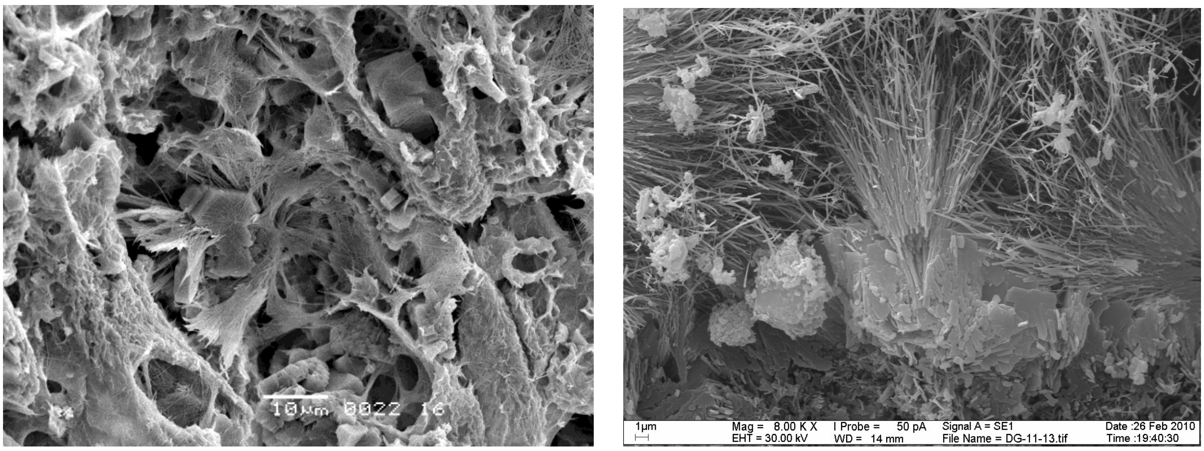

Figure 5: SEM images of argillized tuffs. a – fiber crystals of mordenite and tabular crystals of clinoptilolite; b - fiber-needle and sheaf-like crystals of mordenite

4.2 Influence of hydrothermal alteration on petrophysical properties

All studied tuffs are highly porous, hygroscopic, and weak, but their properties are quite variable. Three tuffs Units, mentioned above, differed in their petrophysical properties (table 1). Properties depend mainly on rock primary features (composition, structure, grain size, heterogeneity) and hydrothermal alteration.

Table. 1. Physical and mechanical properties of tuffs (average values)

Unit	Number of samples	ρ, g/m^3	n, %	W, %	W_g, %	K_g, mD	V_p, km/s	E, GPa	σ_c, MPa	C_{soft}	ϕ, ^{0}	C_{dry}/C_{sat}, MPa	Secondary Minerals
Ustievaya ($Q_{1\text{-}2}$ ust)	5	1.69	39	28	1.3	0.67	2.77	10.71	15.8	0.34	43	3.21/1.26	Quartz, Chlorite, Calcite, Illite, Illite-Smectite, Zeolites
Geysernaya (Q_3^4 grn)	20	1.17	57	42	2.7	3.67	2.11	4.46	10.7	0.37	45	2.06/0.73	Mg-Na Smectite, Clinoptilolite Mordenite, Heulandite
"Yellow tuffs" (Q_3^4 js)	1	1.15	59	-	2.8	-	1,55	2,15	1,1	-	39	0,3	Smectite

Propylitized tuffs of Ustievaya Unit are characterized by higher density (1.69 g/cm^3), elastic modulus (10.7 GPa), P-wave velocity (2.77 km/s), compressive strength (15.8 MPa), cohesion (2,2-3,9 MPa) and angle of internal friction (38-51^0) in comparison with argillized zeolitic tuffs of Geysernaya Unit (ρ=1.17 g/cm^3, E=4.5 GPa, V_p=2.1 km/s, σ_c=10,7 MPa, C=0,7-4,2 MPa, φ =24-58^0). "Yellow tuffs" Unit is the most porous and weak (σ_c=1,1 MPa, C=0,3 MPa, φ=39^0). All tuffs are unstable in water saturated environment. In particular, compressive strength decreases in 60-70%, cohesion also decreases from 3.21 to 1.26 MPa for Ustievaya Unit and from 2.06 to 0.73 MPa for Geysernaya Unit. Entire transformation of tuffs into Mg-smectite decreases cohesion down to 0,02 MPa and angle of internal friction to 19^0.

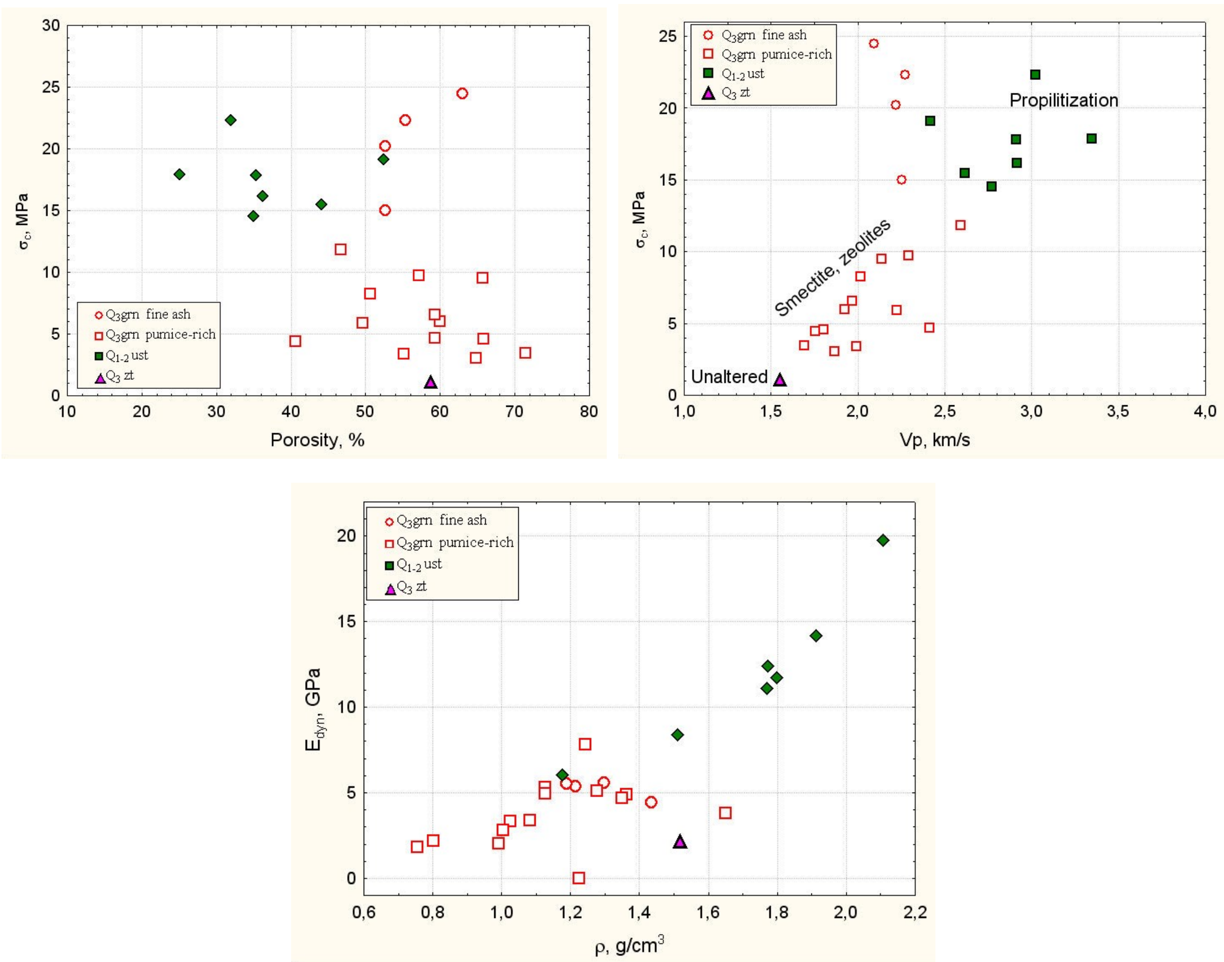

Figure 6: Scatterplots: a – Uniaxial compressive strength versus porosity; b – Uniaxial compressive strength versus P-wave velocity; c – Elastic modulus versus bulk density

The plot between compressive strength and porosity shows inversely proportional relationship (Fig.6a). The fine-ash vitreous tuffs (Q_3^4grn) are out of the common trend. They are highly porous (50-60%) but characterized by relatively high strength (20-25 MPa), whereas the strength of pumice-rich, coarse-grained tuffs with the same porosity is below 10-12 MPa. The plot on Figure 6b shows correlation between uniaxial compressive strength and P-wave velocity with a correlation coefficient equal to 0.65. As seen on the plot, the fine-ash vitreous tuffs are placed above the common trend. A linear regression is obtained between elastic modulus and bulk density with a correlation coefficient equal to 0.84 (Fig.6c).

Physical and mechanical properties correlate well with content of secondary minerals. Some empirical relations are shown in Figure 7. As expected, quartz increases ultrasonic velocity and elastic modulus (Fig.7a), in contrast, zeolites decrease mechanical properties (Fig.7b) and grain density (Fig.7d). A linear regression is established between elastic modulus and quartz content (Fig.7c). The correlation is high with a correlation coefficient equal to 0.82. The rise of quartz content from 10 to 50% leads to the increase of elastic modulus from 2-5 GPa to 12-20 GPa. The relationship between elastic modulus and P-wave velocity, on one side, and zeolite content, on the other, is described by a logarithmic equation (Fig.7d). Also occurrence of zeolites notably decreases grain density from 2.7-2.8 g/cm^3 to 2.4-2.6 g/cm^3 because of the low density of zeolites (2.1-2.3 g/cm^3) (Fig.7e).

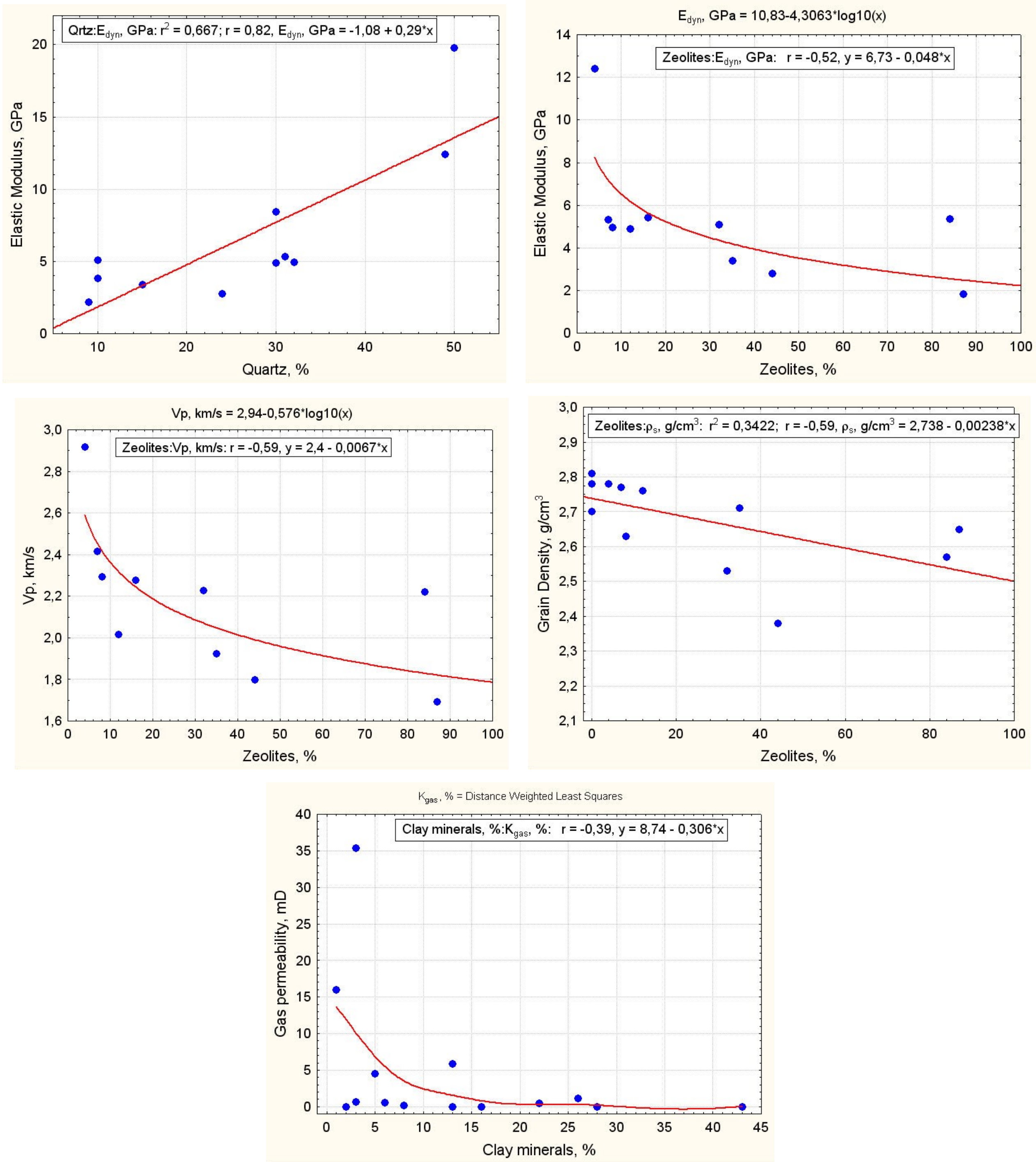

Figure. 7: Relationships between properties and content of secondary minerals. a – Elastic modulus vs. quartz, b – Elastic modulus vs. zeolites, c – P-wave velocity vs. zeolites, d – Grain density vs. zeolites, e – Gas permeability vs. clays

Gas permeability is controlled to some extent by the content of clay minerals (Fig.7e). Gas permeability is quite variable in tuffs with low clay content whereas tuffs with high clay content are characterized by low permeability.

5. CONCLUSIONS

The Geysers Valley geothermal system is hosted in Pleistocene hydrothermally altered pumice-rich tuffs. Tuffs are highly porous, hygroscopic, weak, and unstable in saturated state but their properties are quite variable. Petrophysical properties depend mainly on rock primary features (composition, structure, grain size, heterogeneity) and hydrothermal alteration. Two hydrothermal facies are distinguished in geological section: low-temperature argillized propylites and hydrothermal argillites with high-silica zeolites; in some zones tuffs are totally altered into clayey soils. Propylitized tuffs are characterized by higher density, elastic modulus, P-wave velocity and compressive strength in comparison with argillized zeolitic tuffs. Some physical and mechanical properties correlate well with the content of secondary minerals. In particular, quartz increases ultrasonic velocity and strength, in contrast, zeolites decreases mechanical properties and grain density of tuffs. Clays of the smectite group are widespread in the Geysers Valley due to transformation of volcanic glass under the action of thermal water. They cause significant decrease of rock mechanical properties especially in water saturated conditions. Thus, cohesion decreases by two orders and the angle of internal friction by 2-3 times.

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