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# High $PT$ Experimental Studies of Hydrothermally Altered Tuffs, Kuril Islands, Russia.

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## ABSTRACT

Experiments with tuff samples in close and open system from borehole on hillside of volcano Baransky (Kuril Islands) have been performed at high pressure ($P$) and temperature ($T$). Sampling depth varied from young superficial sediment layers to deeply hydrothermally altered layers (up to 1500 m). The main aim of studies was investigation of evolution of pore space during long sedimentation and further subduction in deep interior. It was found that the samples collected nearby surface were nonlinear enlarged with increasing temperature (up to 300 °C) under isobaric conditions ($P = 0.7$ GPa) whereas deep samples have linear expansion. Analyze of this results and additional studies of pore space showed that the nature of this process is found in deformation and reconstruction of rock framework.

## 1. INTRODUCTION

The sizeable part of upper of the Earth's crust is composed by volcanogenic and sedimentary rocks and their depth of bedding changes in wide limits – from hundreds meters on ancient sheets and to 10 and more kilometers in sediment flexures and basins. So an information about physical properties of volcanic-sediment rocks under variable $PT$ conditions is very important to interpretation of geophysical data and to tectonic and geodynamic reconstruction.

It may be to divide intratelluric rocks of crystalline basement onto primary-magmatic (orthorocks) and primary-sediment (pararocks) which metamorphysm shades often their primary nature. Under effect of high $PT$ parameters in deep conditions of crust, especially in its lower part considerable alteration of petrophysical properties of sedimentary cover takes place at a process of its deepening. It is important to mark zones of junction continent-ocean. Most often in this situation the compacting of volcanic-sedimentary is observed as well as an increase of velocity of elastic seismic waves.

Backward process connected with rising and an eroision lifts up on original ground or on near surface layers vastly metamorphized rocks which should be proved a dilation and drop of elastic properties at taking down stresses. Experimental laboratory investigations are the simplest path of receiving of information about changing of petrophysical properties of rocks under variable $PT$ conditions.

## 2. GEOLOGICAL SETTING AND SAMPLING

The region of investigation is the area of modern volcanic and hydrothermal activity on Iturup Island (South Kurils, Far East, Russia) (Figure 1). The samples investigated were collected from the borehole 1200 m depth located at the SW slope of volcano Baransky (central part of Iturup island). This is an andesitic volcano, situated within caldera of $Q_2$-$Q_3$ age, overlaying volcano-arched uplift structure of Grozny ridge. Detail geological description of the region and volcano is given in a paper of Rychagov (1993).

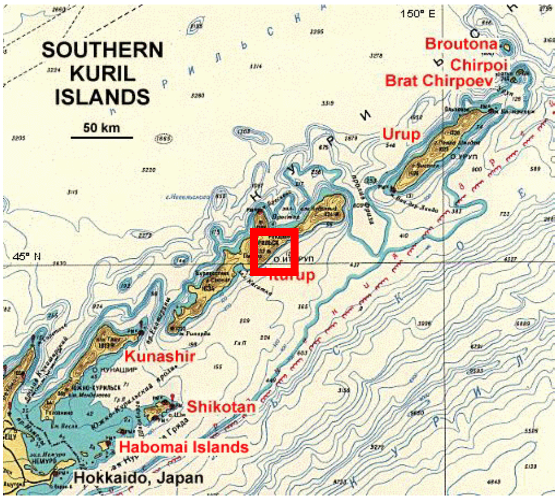


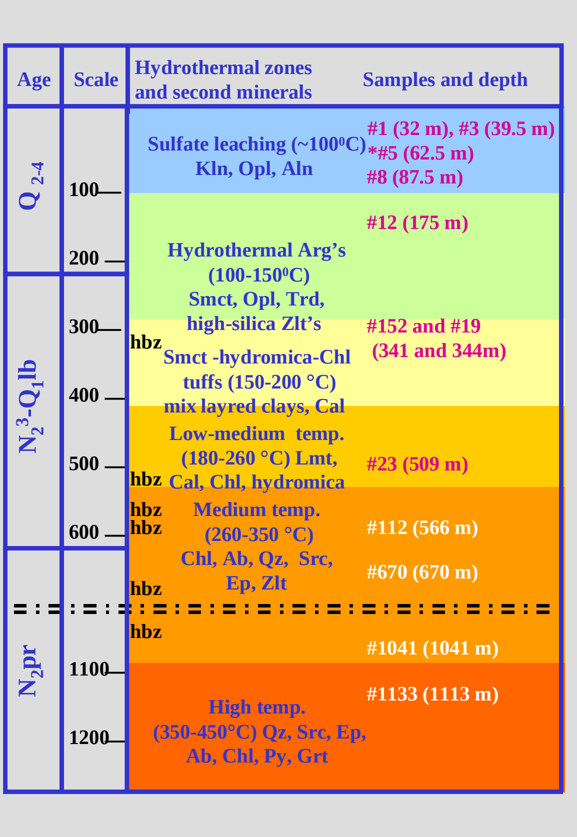
**Figure 1. The region of investigation**

Geological section is composed mainly of psammite-psephitic andesitic (rarely dacitic or andesite-basalts) tufogenic rocks of Upper Pliocene-Pleistocene age, alternating with andesites and andesite-basalt lavas and intersected by dykes. Highly porous and permeable tuffs host a great amount of groundwater heated by subintrusion suggested beneath volcano. Thermal fluids, circulating within hydrothermal system, are characterized by variable temperature (100-450 °C), pH (1.5-10) and chemical composition. They cause extensive alteration of hosting tuffs. Hydrothermal alteration has zonal character, which is described in the work of Rychagov et.al. (1994). The following zones are distinguished along geological section (going upwards): high temperature secondary quartzites with quartz, epidote, sericite, wairakite and garnet; medium temperature quartz-albite-chlorite tuffs with epidote and zeolites; low-medium temperature zeolite-chlorite and calcite-hydromica-chlorite tuffs; chlorite-smectite-hydromica tuffs; hydrothermal argillites with smectite clay minerals and high-silica zeolites; and the zone of sulphiric acid leaching with kaolinite, opal and alunite. Each zone has characteristic petrophysical features and differs from the other zones by physical and mechanical properties (Ladygin and Rychagov 1994; Frolova et. al. 1999, 2001; Ladygin et. al. 2000). The boundaries between zones are rather sharp. The main zoning is destroyed and intersected by so-called “hydrotherm boiling” zones with quartz-adular-wairakite mineral association. These zones are disposed on fractures areas with particular thermodynamic conditions.

## 3. SAMPLES DESCRIPTION

Samples studied can be divided in three groups by their age (Table 1).

**Table 1. Hydrothermal zoning along borehole 54 and scheme of sampling**



| Age | Scale | Hydrothermal zones and second minerals | Samples and depth |
|---|---|---|---|
| $Q_{2\text{-}4}$ | 100 | Sulfate leaching (~100°C)<br>Kln, Opl, Aln | #1 (32 m), #3 (39.5 m)<br>*#5 (62.5 m)<br>#8 (87.5 m) |
| | 200 | Hydrothermal Arg's<br>(100-150°C)<br>Smct, Opl, Trd,<br>high-silica Zlt's | #12 (175 m) |
| $N_2^3$-$Q_1$lb | 300<br>400 | hbz<br>Smct -hydromica-Chl<br>tuffs (150-200 °C)<br>mix layred clays, Cal | #152 and #19<br>(341 and 344m) |
| | 500 | Low-medium temp.<br>(180-260 °C) Lmt,<br>hbz<br>Cal, Chl, hydromica | #23 (509 m) |
| | 600 | hbz<br>hbz<br>Medium temp.<br>(260-350 °C)<br>Chl, Ab, Qz, Src,<br>Ep, Zlt<br>hbz | #112 (566 m)<br>#670 (670 m) |
| $N_2$pr | | hbz | #1041 (1041 m) |
| | 1100<br>1200 | High temp.<br>(350-450°C) Qz, Src, Ep,<br>Ab, Chl, Py, Grt | #1133 (1113 m) |

*Note*: hbz – “hydrotherm boiling” zone ; Kln kaolinite; Opl – opal; Aln – alunite; Smct – smectite; Trd – tridimite; Zlt – ziolite; Chl – chlorite; Cal – calcite; Lmt – lomontite; Ep – epidote; Src – sericite; Py – pyrite; Grt – garnet.

**I group** - Q $_{2\text{-}4}$. This group includes 5 samples of psephitic and psammitic tuffs variably altered by hydrothermal process. Samples 54-1, 54-3 and 54-5 were taken form the upper zone of sulfate leaching. Sample 54-1 (32 m) belongs to the upper subzone of sulfate leaching - opalites. It is composed of secondary opal, tridymite and Fe-oxides totally substituting primary grains of volcanic glass, crystaloclasts of plagioclases and pyroxenes. This is highly porous (38%) rock with low density (1.57 g/cm$^3$). In spite of high porosity the rock is characterized by “rigid” structure entailing relatively high sonic velocity ($V_p$=3 km/s) and uniaxial strength (~30 MPa). Samples 54-3 (39.5 m) was taken from the horizon overlaying by impermeable lava flow, which is represent water-confining layer. Tuff is almost fresh, relatively dense (2.09 g/cm$^3$) and strongly cemented (55 MPa). Samples 54-5 (62.5 m) represents kaolinite subzone of the sulfate leaching zone. Primary clastic fragments only slightly altered while the matrix is totally substituted by opal and clay. The rock is highly porous (36 %) and low dense (1.68 g/cm$^3$); $V_p$ – 2.65 km/s, strength – 20 MPa.

Samples 54-8 (87.5 m) and 54-12 (175 m) belong to the zone of hydrothermal argillites. These tuffs are only slightly altered and partially substituted by opal, smectite (mixed layered smectite-hydromica) and tridymite. They are characterized by relatively high petrophysical characteristics: density 2.22 and 2.25 g/cm$^3$; porosity 21 and 17%; $V_p$ 3.8 and 3.85 km/s; strength 55 and 62 MPa, respectively.

High content of hygroscopic moisture varying in a range 1-3 % is typical for the first group samples.

**II group** – $N_2^3$-$Q_1$lb. This group includes 4 samples. Samples 54-152 (341 m) and 54-19 (344 m) represents volcano-sedimentary stratum extensively altered by hydrothermal process. The main second minerals are mixed layered clays (smectite-hydromica), chlorite and calcite, which totally substitute primary crystals as well as develop in the pores and fill the fractures. These rocks are highly porous (38 and 31%), low dense (1.74 and 1.93 g/cm$^3$), with low sonic velocity (2.25 and 2.6 km/s) and strength (21 and 17 MPa). Samples 54-23 (509 m) and 54-152 (566 m) represent psammitic tuffs. Sample 54-23 belongs to the zone of low-medium temperature alteration with laumontite, chlorite, wairakite, quartz, leucoxene, calcite, epidote, prehnite. Although the rock is altered to a certain degree but the primary clastic structure can be recognized. Petrophysical properties are following: density 2.22 g/cm$^3$, porosity 19%, $V_p$ 2.75 km/s, strength 56 MPa. Sample 54-152 represents the zone of “hydrotherm boiling”. This tuff is intensively substituted by quartz, adular and epidote. Development of quartz entails density to be high 2.46 g/cm$^3$ as well as low porosity 13 %, high sonic velocity 4.4 km/s and extremely strong cementation with strength being 150 MPa.

**III group** – $N_2$pr. This group consists of 3 samples. Samples were taken from tuff stratum, which has been affected by high temperature and pressure during a long time. Samples 54-670 and 54-1041 represent tuffs altered by medium temperature thermal fluids. Second minerals among which are quartz, chlorite, wairakite, calcite, pyrite, epidote partially substitutes primary minerals, fill pores and fractures. Tuffs are characterized by following properties: density 2.31 and 2.24 g/cm$^3$, porosity 17 and 21 %, $V_p$ = 3.75 and 3.45 km/s, strength ~60 and 50 MPa. Sample 54-1133 (1133 m) was collected from the deepest horizon, where hydrothermal process is characterized by extremely high temperature (350-450 °C). Primary tuff totally re-crystallized by high temperature fluids. The rock has massive structure and consists of quartz, sericite, epidote. This is dense (2.46 g/cm$^3$), low porous (12%) rock with high $V_p$ 4 km/s and strength 90 MPa.

Groups II and III are characterized by low content of hygroscopic moisture (not exceed 0.5 %).

## 4. EXPERIMENTAL EQUIPMENT AND METHODS

Experiments with compress and heating samples of tuffs have been carried out in open and close system. First type experiment is assumed a possibility of free leakage a water or its vapor from a rock specimen regardless the nature of the water (free or bounded). The second type of experiments has been carried out in hermetically closed jacket.

Always two samples from chosen of investigated samples of tuff for high pressure testing were prepared. For closed system the sample was drilled (a diameter and length are 10 mm). For open system the sample was prepared the same volume but its form was irregular.

### 4.1 The experiment in “close system”.

The samples of tuffs were tested in a piston-cylinder type high pressure apparatus (channel diameter – 12 mm) with external heater. This type apparatus assumes to control a process of pressing and heating. The scheme of this device is demonstrated at figure 2. A sample of tuff (1) covered in lead jacket (2), and both of them together named as cell, was compressed into tungsten carbide alloy cylinder with supporting steel ring (3) by means of pistons and anvils into hydraulic press what exactly holds acting force (*F*).

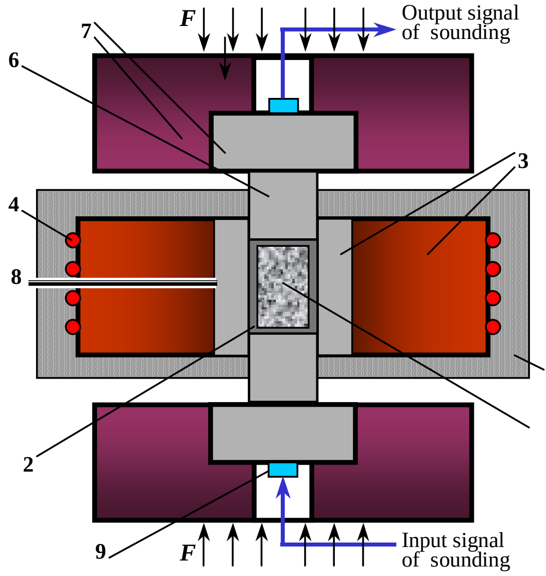


**Figure 2. Scheme of high pressure apparatus at loading in c1osed system: 1 – a rock sample; 2 – lead jacket; 3) – tungsten carbide alloy cylinder with supporting steel ring; 4) – wire heater; 5) – heater insulation; 6) – tungsten carbide alloy pistons (up and down); 7) – tungsten carbide alloy anvils with supporting steel supporting rings; 8) – thermocouple; *F* – acting force; – a circuit of ultrasonic sounding ("input and output signals").**

A temperature of a sample is controlled by means of resistive wire heater (5) and thermocouple (8) measured a temperature near device center. By means of up and down ultrasonic transducers (9) with a resonant frequency ≈1 MHz elastic properties of a sample at high pressure and temperature were studied (pulse method). The data of temperature and acting force of press continuously were collected in a memory of computer by means of analog-digital converter and special software and then they displayed on monitor for controlling the slowly changeable *PT*-parameters during an experiment. Another special computerized recording scheme supplies for measuring travel time of ultrasonic pulses and thus with data about length changing it serves for elastic property change estimation.

Overall basic description of testing techniques and basic algorithm for exact calculating of sample volume in this type piston-cylinder high pressure apparatus have been given in Kalinin et all (1997). In this method an exact determination of volume changes of jacket material under pressure loading. We modified these methods both a temperature and a pressure correction of jacket volume.

The procedure of a pressure and a temperature loading includes following steps that was illustrated on figures 3 and 4. Figure 3 demonstrates the scheme of cell loading (sample and jacket) with including of both piston constrictions. This process is typical for all tested samples. Obviously that residual deformation of sample is always observed. On the figure 4 the temperature dependence $D = 1\text{-}\Delta V/V_0$ of sample in pure form is drawn. All calculations are performed according method described in Kalinin (1997). I.e. a volume changes of lead jacket, deformation of loading parts (pistons and anvils) and widening of cylinder is excluded. Have a note that a density of sample at any PT conditions is $\rho=\rho_0/D$ ($\rho_0$ – initial density).

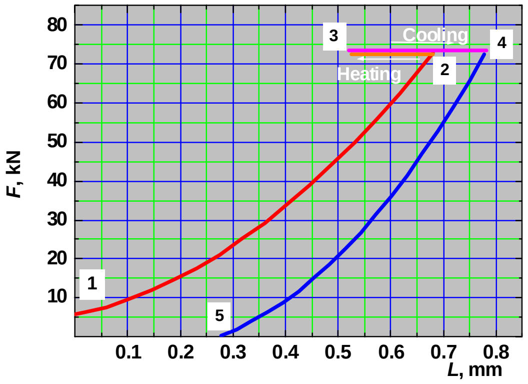


**Figure 3. Scheme of loading and heating samples in piston-cylinder high pressure apparatus. *F* – acting force; *L* – alteration of mutual closing of both pistons.**

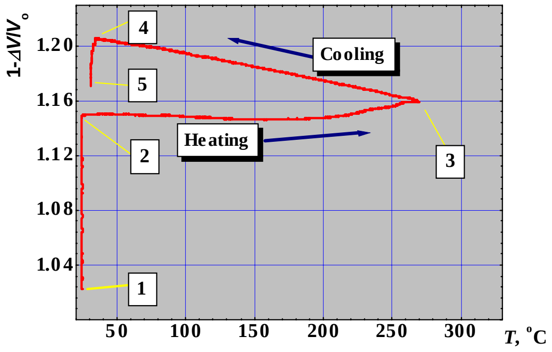


**Figure 4. Typical curve of sample pressing and heating for tuffs.**

Here we will explain a meaning of point numbers (1-5) on the figures 3 and 4. A point 1 is a value of *D* at *P*=0.04 GPa and *T*=20 °C (room temperature). This *P* value is minimal for a start loading of high pressure cell – "a pressure of first touch". Then the pressure up to *P*=0.76 GPa (the experiment value) at 20 °C (point 2). This value of pressure will be held under controlled heating to point 3 (approximately 1.5 hour). On reaching the highest experiment temperature a current is switched off and the high pressure equipment is forced cooled by the ventilator up to point 4. Then between points 4 and 5 the pressure slowly is reduced to minimal value. Note, that it is observed deficiency the volume of a sample (see value *D* at point 5).

### 4.2. The experiment in "open system".

This type of an experiment has been carried out in recess type anvil high pressure device. The scheme of this apparatus is drawn on a figure 5. Between two opposite tungsten carbide alloy anvils (1) with spherical recesses lens-shaped tablet (3) made from lithographic stone is pressed. In a central part the tablet the cylindrical coaxial hole was drilled for high pressure cell. The cell includes graphite heater (6) and high pressure generating medium in cell (sodium chloride) (5) pressed with a rock sample (4). The pressure in the cell controlled by the acting force *F* and in an experiment is determined by means of a measure of resistance of special bismuth wire included in a break of graphite heater circuit. A phase transformation in bismuth (Bi-I–Bi-II) ($P$= 2.55 GPa) is a reference for reading pressure in a cell. After reaching the phase transformation in bismuth wire the force is changed according linear law to required value (commonly decreases to required pressure) and then a force is held a pressure. Our experiments are performed at 1.4 and at 1.7 GPa. The temperature is controlled by the changing electric power and measured by a tungsten-rhenium thermocouple (7). Upper and lower anvils are cooled by a special system with running water.

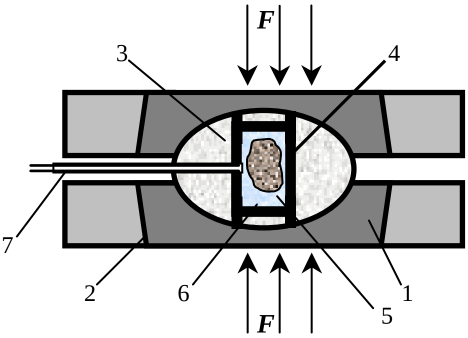


**Figure 5. The scheme of high pressure apparatus at loading in open system: 1 – a tungsten carbide alloy anvil with recess and supporting steel rings (2) (up and down); 3) – high pressure generating medium in cell (lithographic stone);4) – a rock sample; 5) – high pressure generating medium in cell (sodium chloride); 6) – graphite heater; *F* – acting force.**

After compression and heating to required temperature (400 °C) the samples stand 1÷2 hours. Then a power was switched off. So after switching off a power the samples are practically quenched (less than 5 seconds).

As the experiments in open system are performed simpler so we made several experiments with every type of rock. This procedure improved an accuracy of density determination since more volume of sample was used.

### 4.3. Density determination before and after loading.

In Section 3 we reported about physical properties of tested samples. As regards the densities and porosities, it is necessary to note that above values are get by standard methods usually applied for rock investigations. Sample dimensions were as core diameter.

Tested at high pressure samples are appreciably smaller. So as to decrease errors of observation we used modified pycnometer method and analytical balance. Volume of the pycnometer was 5 cubic cm. We made some experiments with familiar substances which neighbor to tested sample densities (pure aluminium, quartz glass) and estimated data errors at the most 5%.

In tests with close system we have additional possibility to verify density data before and after loading as we determined theirs on the basis of weighing of geometrically right samples (cylinders).

The samples tested in open system pressed with salt as medium supplied hydrostatic pressure in experiments. So we dissolved salt jacket then dried and covered by thin film of glue for further density determination.

The procedure of glue covering the samples tested in close system we made before density determination also. That guards against water penetration in pore space of pressed samples at pycnometer method.

### 4.3. Studies of pore space alteration after *PT* experiments.

One of the most common density measurements involves the determination of the geometric space occupied within the envelope of a solid material including any interior voids, cracks or pores. This is called geometric, envelope or bulk density and only equals true density when there are no internal openings in the material being measured.

One of sample we studied more than our “standard’ methods. We wished to try alterations in pore space – their evolution under *PT* effects.

For that we investigated sample No 54-3 by adsorption method generally usable for materials pressed from powder. This technique is described in monograph (Lowell and Shield, 1984). We used apparatus AUTOSORB-1 designed for surface area and pore size analyze at temperature of liquid nitrogen. Absorbate molecules quickly find their way to the surface of every pore in the solid (the adsorbent). These molecules can either bounce off or stick to the surface. Gas molecules that stick to the surface are said to be adsorbed. The strength with which adsorbed molecules interact with the surface determines if the adsorption process is to be considered physical (weak) or chemical (strong) in nature. It is clear that we investigated only physical adsorption.

Before performing gas sorption experiments, solid surfaces must be freed from contaminants such as water and oils. Surface cleaning (degassing) is the most often carried out by placing a sample of the solid in a glass cell and heating it under a vacuum. Once clean, the sample is brought to a constant temperature by means of an external bath. Then, small amounts of a gas (the absorbate) are admitted in steps into the evacuated sample chamber.

The parts of sample 54-3 – initial and two subjected *PT* (open and close system) tested by this method.

## 5. RESULTS AND DISCUSSION

As it should be expected the densities of all studied samples were increased under effect of high pressure and temperature. The porosity was decreased and the density approached to mineral density.

We partly investigated mineral alteration of tuff compositions. But in this paper we do not show this result because of this is required more volume and more strong method experiment technique.

We accentuate that the first aim of all *PT* experiments is the studying of density alteration. Second purpose is experimental observation of process of sample compaction at temperature effect at constant temperature.

So the results are divided on three part: 1 – experiments in open system, 2 – experiments in close system, 3 – tests of porosity studies.

The results of open system experiments are demonstrate at table 2.

**Table 2. The densities of samples tested in open system.**

| Sample No. | *Kp*, % | $\rho_{In}$ | $\rho_M$ | $\rho_{PT}$ | $\Delta\rho_{Exp}$, % |
|---|---|---|---|---|---|
| 54-1 | 38.4 | 1.57 | 2.55 | 2.17 | 38.1 |
| 54-3 | 19.9 | 2.09 | 2.61 | 2.53 | 21.0 |
| 54-5 | 36.4 | 1.68 | 2.64 | 2.09 | 24.4 |
| 54-8 | 22.6 | 2.19 | 2.83 | 2.33 | 6.3 |
| 54-12 | 16.7 | 2.25 | 2.70 | 2.35 | 4.4 |
| 54-152 | 38.3 | 1.74 | 2.82 | 2.46 | 41.1 |
| 54-19 | 30.9 | 1.97 | 2.85 | 2.30 | 16.9 |
| 54-23 | 19.3 | 2.22 | 2.75 | 2.48 | 11.8 |
| 54-112 | 13.4 | 2.46 | 2.84 | 2.60 | 5.9 |
| 54-670 | 17.5 | 2.31 | 2.8 | 2.43 | 5.4 |
| 54-1041 | 21.4 | 2.24 | 2.85 | 2.48 | 10.8 |
| 54-1133 | 12.1 | 2.46 | 2.8 | 2.46 | 0.0 |

*Note*: *Kp*, % – porosity of initial samples; $\rho_{In}$ – initial density (before loading), g/cm$^3$; $\rho_M$ – mineral density; $\rho_{PT}$ – residual density after *PT* tests, g/cm$^3$ ; $\Delta\rho_{exp}$ – increment of density, %;

The experiments in open system are performed for specially selected samples. The main idea was to use samples near surface (quite young tuffs) and deep sediments (more than 500 m). Density alterations were demonstrated at the table 3.

**Table 3. Measured and calculated densities in close system.**

| Sample No | $\rho_{In}$ | $\rho_{PT}$ | $\rho_2$ | $\rho_3$ | $\rho_4$ |
|---|---|---|---|---|---|
| 54-1-1 | 1.6 | 2.01 | 1.98 | 1.85 | 2.07 |
| 54-3-1 | 2.19 | 2.28 | 2.51 | 2.50 | 2.60 |
| 54-23-1 | 2.21 | 2.31 | 2.33 | 2.30 | 2.37 |
| 54-670-1 | 2.36 | 2.72 | 2.58 | 2.50 | 2.62 |
| 54-1133-1 | 2.33 | 2.36 | 2.41 | 2.33 | 2.42 |

*Note*: $\rho_{In}$ – initial density of samples; $\rho_{PT}$ – residual density after *PT* tests. $\rho_2$ – the density of sample at $P$=0.7 GPa, $T$=25 °C (point 2), $\rho_3$ – density at $P$=0.7 GPa, $T$= 270-290 °C (point 3), $\rho_4$ ($P$=0.7 GPa, $T$=30 °C, point 4). About number of "points" see above.

The processes of sample compactions during pressure and temperature effects are demonstrated on the figure 6. The samples No 54-1 and 54-3 (depths are 32 and 39.5 correspondingly) have been expanded under heating at pressure 0.7 GPa vastly nonlinear. This fact is obviously may be observed on lower branches of loops. On the other hand the deep samples are expanded more linear with temperature. Process of cooling at high pressure is accompanied by linear compaction for all samples. Partially this result is observed for the sample No 54-23. This sample was collected from low-medium zone of borehole. The widths of loops for "upper" samples are wide.

Such effects may be explained that in samples with depth upper than 500 m irreversible processes are passed. Those processes are accompanied with deformation of pore space and alteration its forms ant types.

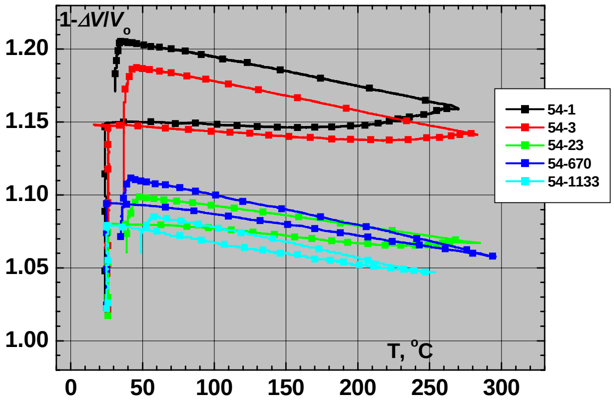


**Figure 6. A compression of tuff samples in closed system. Detailed explanations of sample number explanation are in a text of paper.**

This observation was verified in tests with nitrogen vapor absorption for sample 54-3. Table 4 demonstrates these results. We used three piece of sample. The first was sample taken out from initial core sample. The second was subjected to high *PT* effects in close system. The last was subjected to high *PT* effects in open system. Note that in general *PT* parameters in experiments with open system were higher than in close system. It was found that the specific volume of mesopores (a radius of pores 0.01÷0.5 µm) is decreased to 1/3 from initial. This fact is confirmed by results of porosity calculations by another methods. At another hand volume-part of specific surface of micropores (radius < 0.01 µm) decreased more than 3 times in spite of their volume is negligible. Thus firstly mesopores were shrank and changed shape to more complicated, secondly micropores partially closed down. Nevertheless numeric results show that in spite of the pressure and temperature of effect are higher in open system than in close the value of specific area and volume are in first type experiment.

**Table 4. Specific volume and area of pore space in sample 54-3.**

| Sample No | $\rho$ | $V_{обр}$ | $v_{микр}$ | $(1/\rho)/v$ | $S_{micr}$ | $S_{mezo}$ | $\Delta v$ |
|---|---|---|---|---|---|---|---|
| 54-3 (Int) | 2.09 | 0.0631 | 0.088 | 18.4 | 7.4 | 33.9 | 21 |
| 54-3 (Cls.) | 2.28 | 0.0552 | 0.028 | 6.4 | 0.6 | 11.9 | 3.4 |
| 54-3 (Opn.) | 2.53 | 0.0528 | 0.036 | 9. 1 | 1.9 | 14.4 | 5.2 |

*Note:* $\rho$ – sample density g/cm$^3$; 1/$\rho$ – specific volume of sample (cm$^3$/g) $V_{обр}$ –its volume cm$^3$; $S$ – specific area of all pores, m$^2$/g; $v_{микр}$ – specific pore volume cm$^3$ ; $S_{микр}$ – specific area of micropores m$^2$/g; $S_{мезо}$ – specific area of mezopores m$^2$/g; $\Delta v=f/(P/P_0)$ – width of hysteresis loop absorption and desorption (conventional unit); Int – initial sample; Cls – close system; Opn – open system.

In addition to numerical results which is obtained using AUTOSORB-1 it may be analyze hysteresis loop of adsorption and desorption of nitrogen vapor versus ratio of gas pressure to pressure of saturated vapor nitrogen. The hysteresis loops for tested samples were drawn on the figure 7. Obviously that a volume of adsorbed gas is very different for each of three cases. The initial sample is characterized by the largest volume and the widest hysteresis loop.

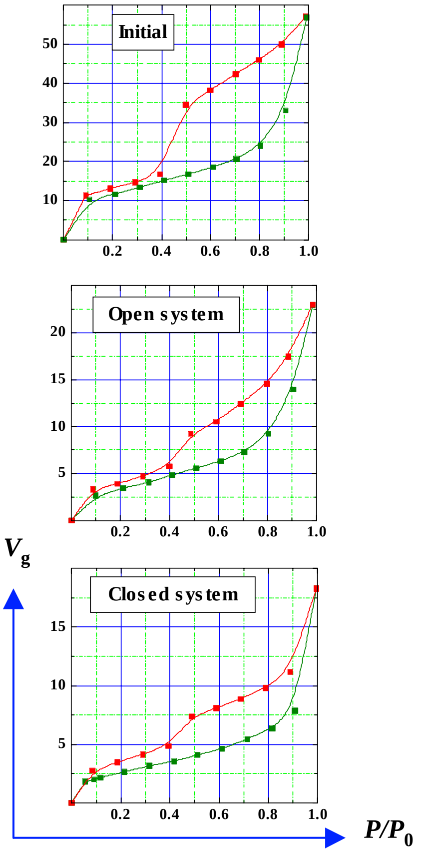


**Figure 7. Hysteresis of adsorption (green line) and desorption (red line) of gas volume *Vg* in tested three samples. $P/P_0$**

As a matter of fact that form and width of hysteresis loop for real substances are expected very complicated and individual for ones. On figure 8 there are drawn idealized shape for different type of pore space. According Lowell and Shield (1986) type **A** hysteresis is due principally to cylindrical pores open at both ends. In this type hysteresis is caused by condensation producing a cylindrical meniscus with one radius of curvature equal to the pore radius, less the thickness of previously condensed film, and the other radius is the length of pore or essentially infinite. The type **B** hysteresis is associated with slit-shaped pores or the space between parallel plates. Type **C** hysteresis is produced by a mixture of tapered or wedge-shaped pores but with narrow necks at one or both open ends. Type **E** hysteresis results from "bottleneck" pores. In pores of this shape, emptying of the wide portion will be delayed during desorption until the narrow neck can evaporate. Therefore, the desorption curve exhibits a small slope at high relative pressures and a large slope where the wide part of pore empties.

We compared obtained loops for initial sample and tested in open and close system with shape for idealized cases (Figure 7). The shape of the hysteresis for initial sample looks like a combination of types **A** (desorption curve), **B** (sorption) and **C** (sorption)**.** After pressing in both systems the hysteresis width was decreased. Moreover undoubtedly the loop shapes were modified. We concluded that contribution of type **A** pores was less and in close system results type **E** was became apparent. This means that large pores (mezopores) were deformed and changed to "bottleneck" pores.

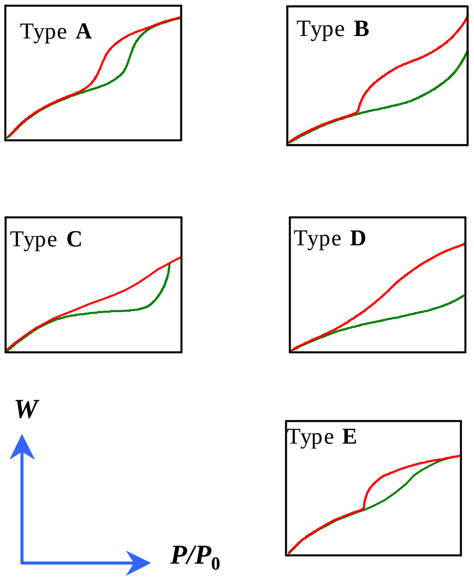


**Figure 8. Idealized presentation of five type of hysteresis of adsorption (green) and desorption (red line) processes. *W* – weight of adsorbed monomolecular gas layer, *P* – current pressure, $P_0$ – saturated vapor pressure. See comments in a text.**

Earlier in a paper of Saltykovsky (2004) we report about alteration of mineral composition in tested composition. So we do not focus on this problem here.

## CONCLUSIONS

The main effect of tuff sample compacting occurs due to closing of pores as a result of deformation at high *PT* parameters.

The reason of residual porosity near 5-15 % was to all appearance elastic reestablishment of pore space due to removing stresses.

At *PT* experiment conditions (*T* up to 400 ºC and *P* from 0.7 to 1.7 GPa) considerable alteration of mineral composition is not observed.

Maximum compacting took place in the samples, which had minimum initial densities or maximum initial porosity.

Passed in hydrothermal system of Baransky volcano high-temperature processes decreased compacting of tuffs at high PT experiments.

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