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Geothermal monitoring as a way to predict volcanic eruptions and estimate geothermal energy resources

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Abstract. Geothermal monitoring is an effective tool for predicting volcanic eruptions, as well as for assessing the geothermal energy potential of geothermal areas. Increased magmatic activity, an indicator of which is the penetration of hot volcanic gases through faults, has been observed in recent years on the Elbrus volcano. Since Elbrus is a year-round resort of world importance, in order to control volcanic and seismic activity, forecast and reduce the risks of eruption and earthquakes, it is recommended to drill a observation well on the slope of Elbrus with the installation of an underground fiber-optic system for temperature and pressure monitoring. In combination with microseismic, gravimetric and inclinometric observations, satellite IR imaging and geochemical gas testing, the continuously obtained information on the thermodynamic conditions of the subsoil will provide a reliable complex for the operational forecast of natural geophysical disasters. Utilization of the geothermal energy of the magma chamber in the artificial circulation systems of small GeoPPs, water injection from the surface and obtaining superheated water and steam from producing wells will reduce the risks of eruption and at the same time provide the resort with environmentally friendly thermal and electric power. Technological justification for the construction of a GeoPP will also require exploratory drilling to the area of hot rocks, therefore information on the distribution of temperature and pressure along the wellbore is doubly valuable.

In geothermal fields that are under development, to assess the spatial heterogeneity of the filtration characteristics can be a useful method of “thermal interference testing” – as a complement or alternative to hydrodynamic interference testing. It is recommended to conduct such an experiment at the North Mutnovsky geothermal field.

Key words: Geothermal, monitoring, fiber optic measuring systems, Elbrus, Mutnovsky, volcano, prediction, volcanic eruptions, geothermal energy resources, thermal interference testing

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1. Introduction

Geothermal monitoring in the areas of modern volcanism is aimed at solving two main problems – the forecast of eruptions and the assessment of prospects for the development of geothermal energy. These two sets of tasks are closely interrelated. The study of the geothermal activity of volcanoes in the interparoxysmal stage provides a basis for the conclusion about the geological conditions, risks and economic efficiency of the development of geothermal energy near the volcano. On the other hand, active taking away of the heat of the magmatic chamber during the operation of the geothermal power plant (GeoPP) leads to continuous cooling of the interior beneath volcano, which can reduce the risks of eruptions. The artificial circulation system, which gives energy to GeoPP, may include dozens of injection wells with water injection from surface sources and dozens of production wells with the removal of superheated steam to the surface at a temperature of about 240-300°C. It is well known, the cost of electricity produced by GeoPP is few times lower than that obtained at diesel thermal power plants. The practical inexhaustibility of volcanic energy resources and the environmentally friendly nature of their utilization by means of closed-cycle system makes geothermal energy extremely unique and attractive.

2. Geothermal monitoring of the Mutnovsky volcano

Mutnovsky volcano, located about 70 km from the city of Petropavlovsk-Kamchatsky, is an ideal site for geothermal monitoring due to the presence of extensive fumarole fields (Bottom and Top fields), located in its Lower (North-East) crater, as well as modern Active funnel, which are within relatively easy reach for researchers and tourists. Regular studies of the thermal

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regime were started by B.G. Polyak and his colleagues in 1961, 1963 (Polyak, 1965, 1966; Vakin et al., 1966) and continued in 1980 and 1981 (Muravyev et al., 1983; Polyak et al., 1985; Vakin et al., 1986). Thermal imaging of fumarole fields using platinum resistance thermometers at various depth sections (15 cm, 50 cm and 100 cm), panoramic IR imaging of the sides of the Active funnel, as well as measurements of the temperature and flow rate of fumarole gas and hot springs, allowed us to estimate the thermal power of the fumarole fields of the North-Eastern crater (about 380 MW) and to draw a conclusion about the relative stability of the thermal regime of the volcano in the interparoxysmal stage. Thus, geothermal survey with an interval of 17-18 years on the Bottom field of the North-Eastern crater did not reveal any fundamental changes in the pattern of temperature distribution in the soil (Fig. 1). Only the relative heating of the soil was found in the 80-ies in the Northern part of the fumarole field, located near the exit of extrusions and necks, according to the binding to the detailed geological map of the volcano (Selyangin, 2016).

Throughout the history of the formation during the Holocene, Mutnovsky volcano was characterized by relatively frequent (with a periodicity of 4-60 years) phreatic-magmatic eruptions of medium and low power, with the predominant NW direction of explosions (Melekestsev et al., 1987). In 1980, just in time for field work on Mutnovsky, the nearby Gorely volcano, having with Mutnovsky common magmatic chamber, started to erupt. The increased heating of the soil at the Bottom field in 1980-81 fits into the tendency of increasing activity of volcanic processes, which eventually led to another episode of the explosive activity of Mutnovsky with a phreatic explosion on March 17, 2000 (Zelenskii et al., 2002).

A large amount of atmospheric precipitation in the area of the volcano provides a high level of natural soil moisture and groundwater supply. Water penetrating through cracks and channels to the depth of tens and hundreds of meters into the hot rocks area continuously flushes through volcanic rocks and is discharged in the form of steam hydrotherms and hot springs, creating prerequisites for the development of geothermal energy. These hydrogeothermal resources, in the form of superheated steam and hot groundwater, were discovered by drilling. In 1999 on the basis of the North-Mutnovsky geothermal field, the Upper Mutnovsky GeoPP with a capacity of 12 MW was put into operation, and in 2002 two power units of Russia's largest Mutnovsky GeoPP with a capacity of 50 MW were put into operation, which together cover about 17% of the electricity consumption of the Kamchatka territory; in the future, it is expected to include new power units with an increase in the capacity of Mutnovsky GeoPP to 200 MW (https://minzkh.kamgov.ru/shema-i-programma-razvitia-energetiki-kamcatskogo-kraa).

To control the risks of eruptions in the future, as well as to increase the efficiency of the GeoPPs, it is advisable to continue geothermal monitoring of the Mutnovsky

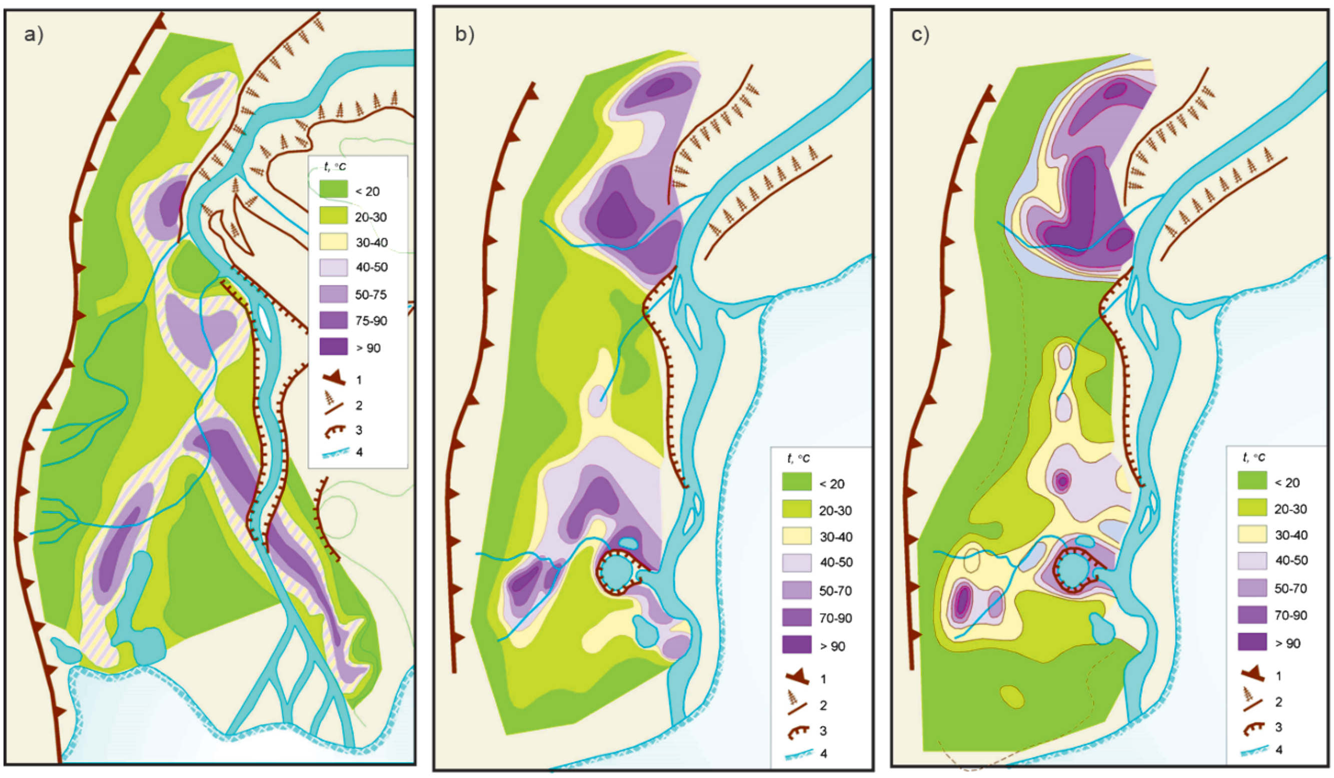

Fig. 1. Subsurface soil temperature at a depth of 15 cm on the Bottom fumarole field, NE crater, Mutnovsky volcano, in 1963, 1980 and 1981 (Polyak, 1965; Muravyev, et al., 1983)

field at a qualitatively new level. Dozens of wells in the North Mutnovsky geothermal field are currently out of operation due to insufficient flow of coolant. This means that the circulation system is inefficient and needs to be optimized. The stopped deep wells (depth over 2000 m) are excellent candidates for transfer them to the category of observational with installation in them of systems of underground monitoring with sensors of temperature and pressure. The network of such support wells will create the basis for the method of hydraulic monitoring. This method is based on the analysis of the time of passage and changes in the amplitude of the pressure pulse transmitted from the perturbing well to the reacting (observation) wells. It is widely used in the development of oil and gas fields to assess the anisotropy of filtration properties and to identify hydrodynamic relationships between wells (Stewart, 2011). The pressure pulse created by suspending production or, conversely, by pumping water into a previously inactive well is recorded by digital downhole gauges with a sufficiently high resolution of pressure (0.03 kPa) and temperature (0.005°C). Such metrological parameters are standard for modern downhole quartz gauges (www.slb.com). If the pressure change is not recorded for a long period of time, significantly exceeding the estimated time, the hydrodynamic connection between the wells is absent. If a change in pressure is noted, the studies continue to produce a response curve. Quantitative interpretation of the interference testing data is performed using a hydrodynamic interpretation programs such as Saphir™ or PanSystem™.

Although modern downhole gauges automatically measure both pressure and temperature, in practice, only the pressure parameter is used for hydrodynamic interpretation by oil companies. The temperature is mainly used to adjust the rheological properties of reservoir fluids. This is due to the fact that the heat pulse is subject to relatively rapid relaxation due to heat exchange with all host rocks, while the pressure pulse propagates only within the reservoir and in the absence of hydrodynamic barriers can be registered at a distance of 1-1.5 km from the disturbing well. However, in the author’s opinion, in case of application of the method of interference testing on the geothermal field, both measured parameters can be effectively used: pressure and temperature. Preconditions of success of the use of such «thermodynamic» interference test are following:

- The identity of the equations of thermal conductivity and diffusivity makes it possible to apply similar algorithms for the interpretation of hydrodynamic and thermal interference testing data.
- The high permeability of the reservoir at the geothermal field and, consequently, the rapid filtration of the coolant from the perturbing well allows us to expect that the amplitude of the thermal pulse at the observation well will be large enough (>1°C) for reliable quantitative interpretation.
- Relatively close distances between wells (about 100-200 m) also contribute to the rapid passage of the pulse.
- It is possible to create a high amplitude pulse by pumping water with a contrasting temperature (cold water – in hot rocks).
- The efficiency of the experiment can be improved by the use of chemical markers (tracers) when injected into active well.

Comparison of the results of classical hydrodynamic and thermal methods of interference testing in the framework of the same experiment will allow to evaluate the effectiveness of the latter, and if successful, to recommend it for use at sites where hydrodynamic interference testing is ineffective, for example, in gas fields.

In our case, interference testing at the Mutnovsky geothermal field can be recommended in order to create a hydrodynamic model of the field, determine the filtration and capacitive properties of the natural reservoir, identify high conductivity zones and impermeable barriers, plan geological and technological measures to improve the efficiency of development.

3. Geological risks in the area of mount Elbrus

The main sources of potential emergencies in the area of Elbrus are, along with climatic, geological factors: volcanism and seismicity. Accelerated melting and collapse of glaciers, snow avalanches and mudflows are also largely determined by the heating of soils, the release of warm gases and sources on the slopes of Elbrus, as well as seismic activity. The frequency of catastrophic eruptions of mount Elbrus is several hundred years. The last strong eruption with a radius of dispersion of volcanic bombs to 700-800 km occurred about 1800 years ago (Bogatikov et al., 1998; Rogozhin et al., 2001; Izmeneniya okruzhayushchei sredy i klimata..., 2007). In recent years, once again there has been an increase in the level of seismicity and heating of the surface of the volcanic cone, which may indicate the activation of processes in the magmatic chamber (Izmeneniya okruzhayushchei sredy i klimata..., 2008; https://geocenter.info/article/sejsmicheskaja-aktivnost-vulkana-elbrus). The volcanic structure of Elbrus is characterized by the absence of extensive fumarole fields and obvious signs of modern volcanic activity in the crater, but there are indirect signs of activation of the volcano in recent years. Few small fumaroles on the saddle and the side of the crater have been revealed, marked by a warming of the soil to +21°C on the Western side that led to the emergence of a colony of green moss at the height of 5621 meters, while the surrounding air is cooled to -20°C and below (Likhodeev, 2013). Analysis of the Earth's surface temperature in the area of the summit craters of Elbrus according to NOAA satellites, the temperature of mineral springs in the vicinity of the volcano, indicate a pronounced thermal anomaly associated with the volcano, and magnetotelluric and gravimetric data indicate the presence of a subsurface magmatic chamber and a deeper parent vent under the volcanic structure (Bogatikov, 2006).

Scientists from the Institute of Physics of the Earth have been carried out for a number of years comprehensive geophysical studies, including regime measurements of the temperature in the tunnel built on the slope of the Elbrus within the framework of the Neutrino project, as well as measurements of the temperature of fumarole, the surface of the volcano slope and the temperature of the bottom layer of the water of the newly formed lake at the foot of the Small Azau glacier (Global'nye izmeneniya prirodnoi sredy..., 1997; Rogozhin et al., 2001; Likhodeev, 2013; Gorbatikov et al., 2018; etc.). The geothermal gradient of 160 mK/m was established by measurements on the walls of the gallery. The researchers conclude that the development of thermal processes on the surface of the volcanic construction of Elbrus led to the intensive melting of some glaciers in recent years. The depth of the lower (parental) magmatic chamber is estimated at a depth of 20 to 40 kilometers. According to the updated data, the upper magmatic chamber beneath the volcanic construction is located in the range of depths of 1-10 km below sea level, its dimensions are within 8-9 km, and the temperature of the upper edge of the chamber is about 850 °C (Likhodeev, 2013).

Microseismic sounding (MSS) studies along the submeridional profile through the Eastern summit of the Elbrus have confirmed the presence of two magmatic foci in the distinct region of low shear wave velocities (Gorbatikov et al., 2018). The depth of the upper hearth is estimated at 7-13 km below sea level, and the lower – at depths from 18 to 40 km, and to depths above 50 km there is no distinct lower boundary of the hearth. Despite the certain value of all existing methods of observing the temperature regime of the Elbrus volcano, they do not solve the problem of the operational forecast of the eruption. Perhaps, only satellite IR-surveying under condition of regular repeated researches can give the reliable short-term forecast. However, such studies are expensive and performed with long interruptions, so that with the sudden development of the process, observers can easily miss the moment of a sharp increase in the activity of the volcano and the transition to the critical phase.

A more cost – effective solution, in addition to providing a continuous flow of information, can be the installation of temperature monitoring sensors as close as possible to the magmatic chamber. Due to the activation of volcanic processes, the task of complex monitoring of changes in geophysical fields around the Elbrus is very relevant. First of all, it is important to control the dynamics of changes in the various precursors of the eruption, which are: reducing the depth of the hypocenters of microseismic events, deformation (in particular, swelling) of the Earth's surface in the area above the magmatic focus, the increase in the temperature of the subsoil near the volcano and the change in the gas-hydrogeochemical composition of fluids from fumaroles and thermal sources. A consistent decrease in the depth of the hypocenters indicates the rise of magma to the surface. In some cases, the rate of magma rise was able to accurately predict the time of eruption three months before the event, for example, Kilauea volcano, Hawaii, in 1959 (Rasp, 1982). However, the probability of accurate prediction of the beginning of the eruption from microseismic data is much higher for effusive eruptions of shield volcanoes of Hawaiian type.

Elbrus belongs to stratovolcanoes, which shove more insidious behavior, because their magma is more acidic in composition, and therefore is more viscous and slow-moving. The main source of energy of eruptions of stratovolcanoes is a durable accumulated pressure of volcanic gases, which are the most important factor causing volcanic eruptions (Rasp, 1981). Swelling of the surface due to the pressure of the accumulated gases may indicate the approach of an explosive eruption with the greatest risks to the population due to its suddenness and catastrophic consequences. Historical examples of such catastrophes as the destruction of Pompeii during the eruption of Vesuvius (79), the ruin of St. Pierre during the eruption of Mont Pele, Martinique (1902), the eruption of St. Helens, USA (1980), etc., pose the problem of the need to improve the accuracy of forecasts of time, nature and scale of natural disasters.

4. Objectives of subsurface monitoring

Especially valuable information can be given by the systems of underground monitoring of temperature, pressure and microseismicity, installed in sufficiently deep inclined wells, directed towards the magmatic focus. The sensors must meet the requirements of high accuracy and long-term stability of measurements in an aggressive environment (hydrogen sulfide, acid solutions, etc.). The measuring system should be placed along the entire wellbore in order to obtain a spatial dynamic picture of the thermal field, variations in reservoir pressure and groundwater level, localization of seismic events. Modern technologies make it possible to place a multiparameter measuring system in a well on a single geophysical cable. It is believed that the magma is heated in the upper volcanic chamber under the Elbrus to 1000-1100°C, so the geothermal gradient in an inclined well drilled in the direction of the magmatic focus can be 140-160 mK/m, and the temperature at the bottom of the well depth of 1800 m can reach 260-290°C even with the assumption of a purely conductive nature of heat transfer from the edge of the magmatic chamber to the surface. However, an additional convective heating of the volcanic construction is possible by penetration of hot volcanic gases from the magma hearth through the faults in volcanic rocks. In addition, with the increase of magmatic activity, the deep temperatures will also grow, so it is necessary to apply technological solutions designed for high temperatures.

The specified requirements are met by fiber-optic monitoring systems (FOS), widely used in the oil industry to monitor steam injection, high-temperature production, as well as geothermal wells. The capabilities of most modern downhole electronic sensors are limited to a temperature of 177°C (www.slb.ru), and they are more susceptible to aggressive environments and to damage due to mechanical shocks and vibration.

Drilling an exploration well in the hot rock area will allow to study both the thermal regime in the bowels of the volcano, and also the presence of groundwater, their chemical composition, the degree of fragmentation and permeability of rocks. All this is important not only to control the risks of the eruption, but as well to assess the prospects of environmentally friendly geothermal energy for the further development of the resort infrastructure.

The question arises, where and to what depth it is advisable to conduct drilling to solve the whole complex of tasks?

As noted, the well should be inclined towards the magmatic focus, up to 1800 m deep, drilled in compliance with all safety measures and considering the risks of abnormally high temperatures, pressures and hydrogen sulfide during the penetration of volcanic gas pockets and fault zones. It is necessary to take into account the inevitable natural difficulties – sharply dissected terrain, harsh climate and tenuous air at high altitude, high hardness of rocks and extremely high «environmental sensitivity» of the resort area. In the event that the well shows the prospects for the development of geothermal energy resources, a fairly extensive site for the construction of a GeoPP complex and a network of geothermal wells, protected from avalanches and mudflows, may be required.

As one of the possible options for the drilling site, the author recommends considering a relatively flat area near the Mir station (Fig. 2) cable car «Azau» (about 3400 m above sea level). There are likely to be other suitable sites for geothermal exploration drilling on the slope of Elbrus. The main conditions required here is the availability of the access way for drilling equipment and the safety of operations.

Fig. 2. View of the valley Azau from the station «Mir» cable car (photo: Mochalov, 2017). A flat area at an altitude of about 3400 m with an access road is a potentially convenient place for drilling exploration and/or observation geothermal well

5. Underground monitoring systems

Modern fiber-optic (FO) systems for underground monitoring have a number of undoubted advantages in comparison with near-surface thermal sensors and satellite IR imaging:

- Real temperature measurements can be carried out in maximum proximity to the object of study (magmatic chamber).
- Continuity of observations provides operational control in case of sudden changes in the thermal regime.
- The amount of incoming information in the monitoring process is easily optimized by recording data in standby mode.
- Automatic transmission of data in real time – through the satellite system SCADA in the center of data collection and analysis provides convenience and safety.
- There is a real opportunity to control changes in gas-hydrothermal activity on the faults connecting the magmatic chamber with the surface.
- Carrying out a complex of various geophysical measurements in the well with the help of sensors installed on a single geophysical (optical) cable provides high information content of the system and reliability of the forecast of eruptions.

The disadvantage is a fairly high cost of the project drilling and completion of the well with the FO monitoring system.

6. Technological solutions

Successful and repeatedly tested technological solutions for underground monitoring in extremely harsh conditions are developed, in particular, in the leading oil service companies-Schlumberger and Weatherford. Fiber-optic measuring system, in contrast to electronic sensors resistant to mechanical shock, vibration, corrosive chemicals and can withstand much higher temperature and pressure.

Schlumberger, which has been operating in Russia since 1991, has a Sensa™ fiber optic monitoring system that enables reliable and accurate wellbore temperature profile data to be received and transmitted in real time. The FO temperature profile monitoring system for steam injection wells is designed for operating temperatures up to 250°C; the system also has a built-in discrete pressure and temperature sensor. In oil production, temperature monitoring is most often used in such a method of extraction as steam assisted gravity drainage (SAGD). The dynamics of changes in the temperature profile along the horizontal section of the trunk is used to increase the efficiency of steam injection into the formation and helps to identify the places of breakthrough and inflow of fluids (water, steam, gas, oil) into the well.

Weatherford monitoring systems offer a wide variety of technical solutions for underground monitoring and include, in addition to temperature and pressure sensors, options such as downhole seismic receivers and flow meters. The optimal configuration is selected depending on the tasks to be solved in oil and gas production, steam injection and geothermal wells. An important advantage of these systems is that the sensors are mounted on a single cable. In the arsenal of the company there are systems designed for operating temperatures up to 300°C and aggressive environment, which is especially important for solving problems of volcanology. Sensors on the FO cable are divided into two groups – discrete, the principle of which is based on the use of Bragg gratings, and distributed temperature sensors (DTS), using the refraction of the beam in the MM light guide. Usually, combinations of sensors of different types are used due to the capabilities of a special three-core optical cable (Fig. 3).

Fiber Optic cable. FO cable has three cores: two single-mode (SM), designed only to work with sensors on Bragg gratings, and one multimode (MM), serving to measure the profile of the distributed temperature (DTS). The cable is protected from external chemical and mechanical influences. Up to 8 seismic receivers, or a system of 12 micro-temperature sensors, as well as various combinations of pressure-temperature (PT) gauges with other sensors can be installed on each SM core.

PT sensors on Bragg gratings. The principle of operation of the sensors on the Bragg gratings (FBG) is as follows. The light beam is directed through the light guide core. Part of the beam of light – only at the wavelength of the lattice-is reflected back. Applied strain changes the length of the FBG reflected wave. Surface equipment detects the wavelength shift due to the deformation of the sensor. The factory calibration allows to convert the wavelength measurement in terms of pressure and temperature values.

DTS (Distributed Temperature Sensing) technology. Multi-mode optical fiber is used for continuous monitoring of the temperature profile along the wellbore. In the DTS system, the fiber optic cable itself is a distributed temperature sensor. DTS measurements are based on the principle of Raman backscattering. The intensity of the measured signal depends on the energy state of the optical fiber. The temperature is calculated by the ratio of the peak intensities of the Stokes /anti-Stokes. The DTS system can be used to detect gas and water breakthrough, dynamics of thermal field change along the wellbore. The accuracy of the DTS temperature measurement is improved in combination with the use of point sensors as reference measuring devices.

Seismic monitoring – Clarion™ system. An example of a successful project is the monitoring of microseismic events, pressure and temperature in the T-24 well at the Tengiz field (Kazakhstan) (www.weatherford.com). Microseismic sensors were installed in an abandoned production well, which was transferred to the category of observation. At the customer's request, the monitoring system has to work for many years, so the Clarion™ long-life optical seismic system has been selected (Fig. 4). The operation of passive accelerometer sensors in the well is supported by the FO system; while there is absolutely no downhole electronics, which ensures high reliability of this sensor system. The design of the spit consists of eight seismic receivers installed at different

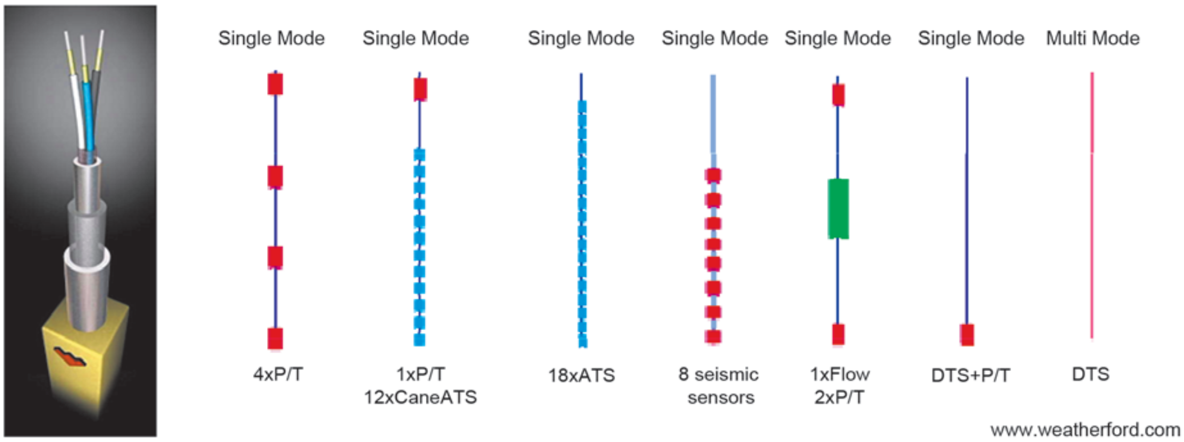

Fig. 3. Flexible sensor configuration in Weatherford fiber optic monitoring systems (www.weatherford.com)

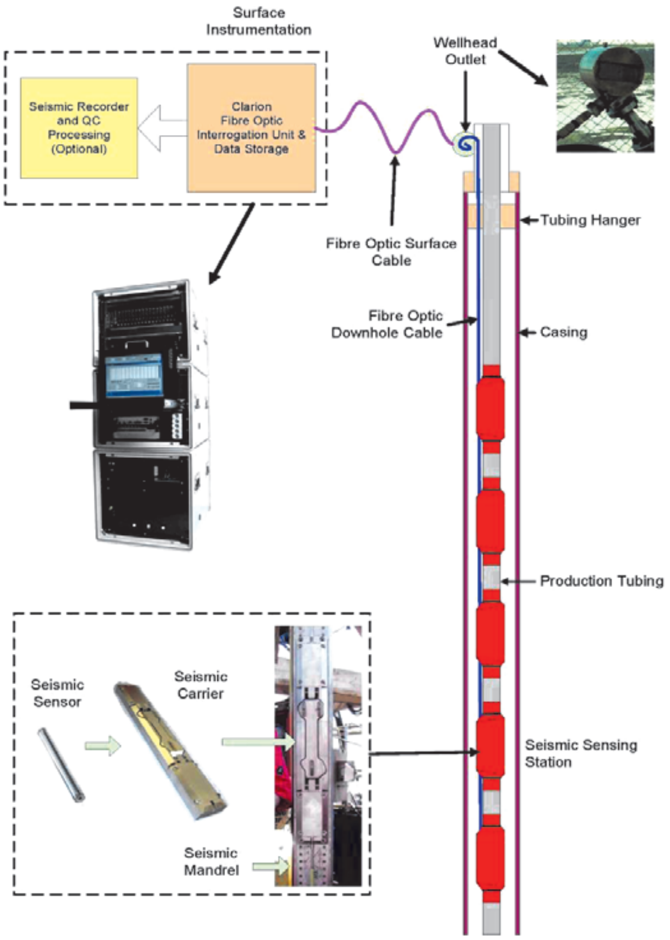

Fig. 4. Clarion™ Borehole Seismic Fiber Optic System. The installation process at the Tengiz field (www.weatherford.com)

depths, each of which includes three accelerometers in coordinates (XYZ). The total length of the sensors cable assembly was more than 500 m. Seismic receivers are mounted on specially designed mandrels as part of the completion layout. Fiber optic cable is fixed with clamps on each section of tubing – to the wellhead. After installation at a given depth, the sensors were deployed perpendicular to the casing string, closely connected to the geological formation through the cement ring. Deployed sensor holders are also designed to isolate seismic sensors from noise in the production tubing, increasing the signal-to-noise ratio. Since the output signal is a laser beam, there is no electrical interference in the downhole system. Physical orientation of sensors in the wellbore was carried out to minimize the error in the evaluation of localization of microseismic events. This was done using a special tool and a gyroscope inside the tubing. Orientation sets the absolute direction of the X and Y sensors relative to the magnetic North. Surface equipment, located at a distance of several hundred meters from the wellhead, were connected via optical cable and put into operation to record data in October 2006, to the present time, there is recorded data in continuous mode. By promoting the front of microseismic events it is possible to control the process of field development within a radius of 15 km. Similarly, on Elbrus it is possible to track the dynamics of magma movement to the surface and the moments of formation of faults in the Earth's crust.

LxData™ Technology. LxData™ technology with an operating temperature of up to 300°C, designed specifically for steam injection wells, is the most cost-effective solution with the use of underground monitoring systems (www.weatherford.com). It is designed for the installation of up to 40 temperature micro-sensors on one FO cable along wellbore, with a pressure sensor at the end of the cable (Fig. 5; Table. 1).

The arrangement of downhole sensors allows the use of configurations with 10, 20 or 40 temperature sensors and individual placement of sensors and the step between them (Fig. 6). The system provides accurate real-time temperature measurements, which makes it possible to monitor the intensity of hot volcanic gases release from faults and to forecast eruptions promptly. This does not require calibration of downhole and ground fiber optic lines, and the sensors can be reused if necessary. The LxData system is a cost-effective, alternative solution

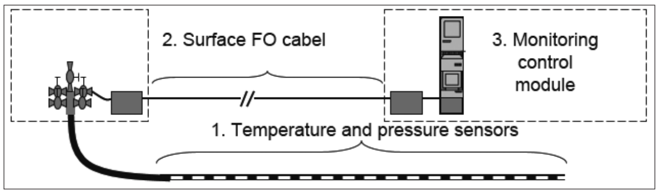

Fig. 5. Layout of downhole sensors and the surface part of the monitoring system

Parameter	Value
Operating Performance	
Temperature Measurement Range	-40° to 300°C
Temperature Accuracy	+/- 0.5°C
Temperature Resolution	+/-0.01°C
Update Rate	1s/channel
Typical Operating Lifetime	>10 Years
System Configuration	
Number of Channels/ Cabinet	Up to 32
Number of Sensing Points/Sensor Cable	40 +
Maximum Sensor Cable Length	1800 m
Nominal Sensor Spacing	20 m
Maximum Surface Cable Run	5000 m
Surface Instrument Module	
Cabinet Housing Type	NEMA Enclosure
Surface Power Requirements	500W (Integrated UPS w/Battery Backup)
Data Transfer Protocol	MODBUS over TCP
Surface Cable Operating Temperature	-50°C to 85°C
Environmental Conditions	
Maximum Non-Operating Temperature (sensing cable)	300°C
Maximum Pressure (sensing cable)	500 to 8500 kPa
Cabinet Storage Temperature	-20°C to 50°C

Table 1. Specifications of the LxDATA™ monitoring system (www.weatherford.com)

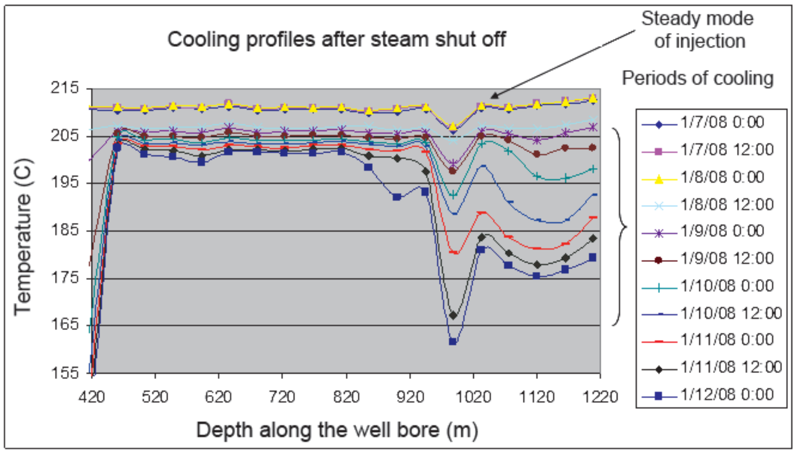

Fig. 6. An example of thermal monitoring with the LxDATA™ system. The dynamics of temperature variation along the well bore for five days after stopping the injection of steam shows the zone of inflow of formation fluid in the range of 960-1000 m

for high temperature monitoring. Instead of an expensive three-core cable, it uses an optical fiber placed together with temperature micro-sensors in a capillary tube ¼” of corrosion-resistant alloy Inconel 718/625. At the end of the capillary is placed a pressure micro-sensor with an operating pressure of 8.5 MPa (Fig. 7). To implement the descent of the sensor system in the directional well used flexible tubing (coiled tubing) (Fig. 8). The monitoring system is controlled from the surface of the room where the ground equipment for reading and storing data is installed (Fig. 9). From the wellhead (through the cable input) to the control centre, transmission of signals is via the ground-based optical cable. Operational control is carried out in real time, through the graphical user interface and playback system. The data is stored in the memory of the device, where it is stored for three months with a sequential update of the record. Remote configuration and software updates as well as access to data via web applications are possible.

At the wellhead, it is advisable to install an automatic monitoring system with geochemical sensors of the concentration of acidic volcanic gases (H_2S, CO_2, SO_2, HCl, HF). These components, along with water vapor, represent at least 95% of the gas volume of volcanic and geothermal systems and serve as indicators of volcanic activity. For example, monitoring of the amount of SO_2 emanations in the Caldera of Kilauea volcano, conducted by researchers since 1979, showed that in the periods immediately preceding the eruptions, there was a significant increase in the intensity of removal of sulfur dioxide (Sutton, Ellias, 2014). Thus, a month before the eruption in March 2008, the amount of SO_2 carried out doubled.

Fig. 9. Hardware rack of the control center (a) and control panel (b) of 19”size (www.weatherford.com)

7. Cost-effective monitoring options

There are options that do not require drilling, but provide valuable operational information about volcanic activity. First of all, we are talking about the monitoring of the thermal state and gas-hydrogeochemical composition of fluids in the fumarole fields in the saddle and the Eastern part of the slope, in the zone of Hot Narzans, and, if possible, in the crater of the volcano. In other words, where there are already or are likely to be signs of increased heat

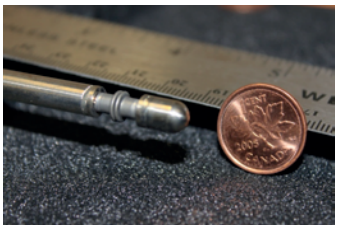

Fig. 7. Pressure sensor at the end of the capillary line (www.weatherford.com)

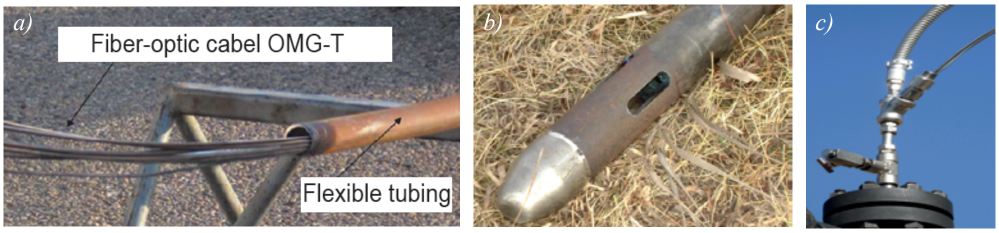

Fig. 8. Flexible tubing (a, b) with a diameter of 1.25” for the installation of T-P sensors in the well; (c) Cable entry at the wellhead (www.weatherford.com)

and mass transfer from the magma chamber due to the migration of hot gases through faults. It is advisable to install infrared thermal imagers on fumarole fields in order to continuously monitor the temperature of the soil surface in the areas of the greatest fumarole activity. Satellite data transmission can provide a rapid response in the event of an eruption. The installation of sensors to monitor the temperature and concentration of volcanic gases in the craters of the volcano makes sense only in the case of signs of geothermal activity and the possibility of open access to the crater. Currently, the craters are under the thickness of ice and snow, although on the Eastern wall of the Lateral crater (Fig. 10) participants in the tourist routes marked weak fumaroles. In addition to temperature sensors near fumaroles, it is advisable to install geochemical sensors of volcanic gas concentration.

Fig. 10. Side crater, on the east wall of which weak fumaroles are marked (photo from the Internet)

Summary

Geothermal monitoring is an effective tool for forecasting volcanic eruptions, as well as assessing the geothermal energy potential of volcanic areas.

The method of "thermal interference testing" as a supplement or alternative to hydrodynamic interference testing can be quite successful in assessing the spatial heterogeneity of the filtration characteristics in the underground circulation system in geothermal and gas fields, carried out in order to improve the efficiency of development. It is recommended to conduct such a trial at the North Mutnovsky geothermal field.

In order to monitor volcanic activity and assess the prospects for the development of geothermal energy in the region, it would be advisable to drill on the slope of the Elbrus volcano an observation well up to 1800 m deep, directed towards the magmatic chamber. As possible locations for the drill sites should consider the area in the vicinity of the Mir station of the ropeway Azau.

To improve the reliability of the forecast of sudden volcanic eruptions, it is recommended to use modern fiber-optic telemetry systems of underground monitoring, including array of temperature, pressure and microseismic events sensors.

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