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Kamchatkan Valley of the Geysers: Geodynamic Processes, Seismicity, Landsliding

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ABSTRACT

It is well-known that Kamchatka represents one of the most geodynamically active regions of the World. But along with it, its territory is characterized by wide variety of natural hazards; many of them initiate or significantly increase occurrence probability of the others. In particular, the earthquakes initiate tsunamis, accompany or forestall volcanic eruptions, activate slope instability processes such as collapses, landslides and avalanches.

The Valley of the Geysers area is one of the most hazardous on Kamchatka due to intensive development of landslide processes within its territory. The study of landslide generating factors is not less important than investigation of landslides themselves. In this study it is necessary to regard the whole complex of processes, controlling the slope instability development: its geological structure, relief, recent tectonic motions, seismic and volcanic activity of the region, climate and meteorological data, geological, geothermal and geocryology conditions, vegetation and soils, economical activity.

Weight of geodynamic factors in estimation of landslides and landfalls risk significantly increases in regions with high seismic and geodynamic activity, on Kamchatka particularly. The geodynamic risk factors for landslide, which occurred on June 3, 2007 in the Valley of the Geysers (fig. 1, 2) are presented in this paper:

- Rates of present-day regional neotectonic motions,
- Tectonics and main faults,
- Volcanic activity of Kikhpinych Volcano,
- Present-day local earth crust motions,
- Hydrothermal activity,
- Largest Earthquakes and regional seismicity.

1. INTRODUCTION

The Valley of the Geysers is one of the main points of interest in the World. Its territory having totally about four square kilometers embraces more than 200 thermal springs including about 90 springs of geyser type; 20 of them - are big geysers. The Kamchatka Valley of the Geysers is the only one geyser field in Asia. It is a picturesque deeply cut mountain river canyon located in out-of-the-way area remote from main infrastructure of the peninsula. Geological, hydrological and morphological (Fig. 3, 4) peculiarities of the Valley of the Geysers control both high geodynamic activity and increased landslide risk of this territory. The Valley of the Geysers belongs to Kronotskiy State Natural Biosphere Reserve; it is included in the UNESCO World Natural Heritage Complex Site "Volcanoes of Kamchatka". It represents biological and landscape diversity of the Kamchatka Peninsula.

The strategy of ecological tourism development in the Valley of the Geysers and other nature-conservative Kamchatka territories is being elaborated presently in frames of Joint Project of United Nations Development Program (UNDP) & Global Environment Facility (GEF) called "Conservation of Kamchatka Biological Diversity".

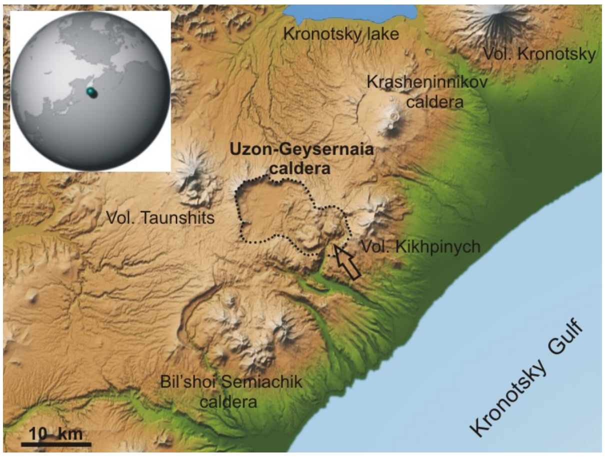

Figure 1: Uzon-Geysernaia and neighbor calderas in the Eastern volcanic front in Kamchatka peninsula. The Valley of the Geysers is located at the eastern margin of the caldera. Area of June 3, 2007 landslide is marked by arrow

2. NATURAL DISASTER ON JUNE 3, 2007 IN THE VALLEY OF THE GEYSERS

A natural disaster - big landslide with volume estimated from 8-15×10^6 m^3 to 20×10^6 m^3 - occurred on June 3, 2007 in the Valley of the Geysers (Leonov, 2007, Gordeev et al., 2007, Pinegina et al., 2008, Kugaenko, 2008), (fig. 1-3). Complicated multiphase character of failure characterized the landslide in the Valley of the Geysers. According to rocks displacement rate it was a rapid landslide and thus the most dangerous one. The flow rate reached 30-40 km/hour. The height of separation (cleavage) wall was up to 150 m and its length was about 800 m.

Giant mud-stone avalanche, formed by landslide, descended along Vodopadnyi Stream bed into Geisernaya River. A natural rock-fill dam with length about 300 m, height reaching 50-60 m and width up to 250 m in the widest place originated. A dam lake with length about 2 km appeared. The landslide by lucky chance did not cause human victims. Nevertheless helipads, bridges and economic buildings were crushed or partially destroyed. The debris avalanche stopped only in one meter from Visit Center Building of Kronotskiy Reserve.

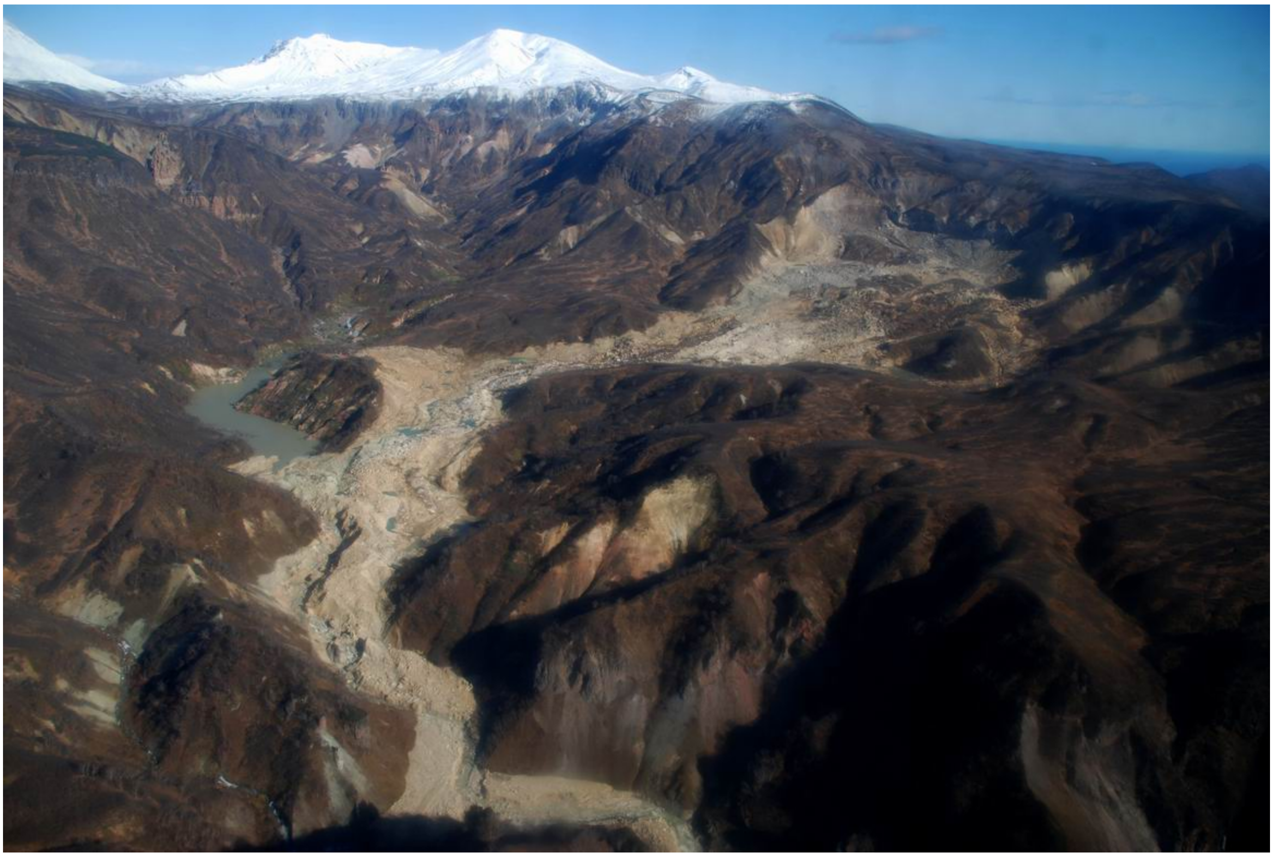

Figure 2: Panoramic photography of the eastern rim of Uzon-Geysernaia volcano-tectonic depression, the Valley of the Geysers and vicinity made from helicopter on October 14, 2008. In central part of photo – the landslide and the dammed lake. On the background: volcanic massive Kikhpinych

Figure 3. a, b: The separation (cleavage) wall of the landslide. The height of the subvertical wall is about 150 m. Photo by V. Saltykov. September 29, 2008

3. RISK AS PROBABILITY OF LOSSES

The central place in modern strategy of natural hazards control belongs to development of scientific methods for natural risks estimation.

Natural risk is a quantitative characteristic, probabilistic assessment, characterizing probability of material damage and irretrievable losses caused by development of different dangerous processes. The procedure of risks estimation includes fulfilling of a number of successive operations, namely: identification of hazard, hazard forecasting, estimation of vulnerability, risk estimation. Application of risk conception converts danger into category of measured quantities. To calculate risk estimations in frames of some mathematic model it is necessary to fill it with objective data on specific territory.

Risk analysis for the object (region, territory, and infrastructure) begins with identification of natural hazards. To estimate the risk information on different factors which determine it should be used.

Risk factors are represented by conditions, which does not serve as immediate causes of unwanted results, but increase probability of their origin.

4. GEODYNAMIC FACTORS OF LANDSLIDING

Geodynamics is a science about deep forces and processes arising due to evolution of Earth as a planet and controlling movements of matter and energy inside the Earth. The geodynamic processes which influence on landslides origin include: present-day earth crust motions, seismicity, volcanism, hydrothermal and geothermal activity. The information on geodynamic processes in the Valley of the Geysers is not full due to absence of basic local observation systems (GPS and seismic networks).

5. RATES OF PRESENT-DAY REGIONAL NEOTECTONIC MOTIONS

The mobile belts with high rates and gradients of neotectonic motions are distinguished among mobile structures of continents and oceans. The Kurile-Kamchatka Island Arc is elongated on 2500 km from Hokkaido Island to Northern Kamchatka. The general features of this system are:

- shape of gentle convex (in direction to the ocean) arc;
- lengthwise, i.e. north-eastern, zonality of main structural elements;
- volcanic belt arranged in a complicated manner;
- narrow deep-water trench before the arc front,
- a belt of earthquake hypocenters concentration inclined under the arc, which can be traced deeply into the mantle (Wadati-Zavaritskiy-Benioff seismic focal zone).

Kamchatka Peninsula lies in the north-western part of convergent junction of Eurasian and Pacific plates (fig. 4). The line of lithosphere plates' contact is manifested in the bottom relief by narrow deep-water (up to 8 km) Kamchatka Trench. The Pacific Plate which moves here to the north-west with rate 8-9 cm/year goes under Kamchatka (nearly immovable continental margin of Eurasian Plate). According to GPS data Kamchatka also moves to the north-west but very slowly (with rate less than 1 cm/year). Thus the rate of lithosphere plates' relative convergence here is about 8 cm/year; it determines the subduction rate as well (Minster and Jordan, 1978, Levin et al., 2006).

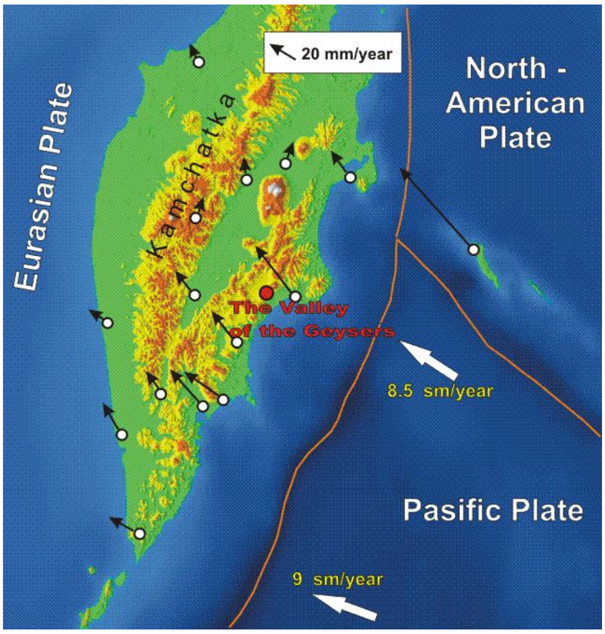

Figure 4: Present-day regional neotectonic motions

6. TECTONICS AND MAIN FAULTS

The Valley of the Geysers confines to eastern edge of vast complicatedly arranged Uzon-Geyzernaya volcano-tectonic depression elongated in WNW direction (Leonov et al., 1991), Fig. 1. Uzon-Geyzernaya volcano-tectonic depression represents a failure caldera bordered by ring fault - downdip block of general north-western strike. The fault is manifested by scarp in present-day relief. The visible amplitude of displacement along the fault - 300-400 m. The depth of upper edge of supposed magma source beneath the caldera and its diameter are estimated as 7-8 km and 10 km, correspondingly.

The Uzon-Geyzernaya volcano-tectonic depression area belongs to Eastern volcanic belt of Kamchatka. It is connected with crossing knot of major faults with north-eastern and latitudinal strikes. A network of faults, oriented in concentrically way around Uzon-Geyzernaya depression was also distinguished (Belousov et al., 1984, Masurenkov, 1991).

North-eastern disjunctive dislocations are mainly represented by normal faults with south-eastern low side. Length of separate faults varies from 100-200 m to 1 km and more. Amplitude of vertical displacements varies from several meters to 50 m. The network of north-eastern dislocations in the area reflects large zone of earth crust extension; it has width 20 km and stretches far away from area boundaries. It was named as Vulkanicheskiy Razdvig (Volcanic Gapping). This structure is regarded as deep magma- and fluid-conducting fault of gapping type.

Latitudinal disjunctive dislocations are most distinctly mapped in the central part of the area lying within a belt with width 5-6 km. The belt strike coincides with long axis of Uson-Geyizernaya depression. The length of separate dislocations reaches 4 km and more. Amplitude of vertical displacements varies from first meters to 50-70 m. Total amplitude of downdip along the normal faults system of inner depression block reaches 200 m. Latitudinal faults in the described area trace regional latitudinal Uzono-Valaginskiy fault, which is a deep shear.

Arcuate disjunctive dislocations are oriented concentrically relatively the center of volcanic-tectonic depression and have character of fractures or low-amplitude normal faults. A system of inclined circular dykes was also distinguished; they apparently inherit a system of arcuate fractures. Time of the arcuate disjunctive dislocations system origin in general corresponds to the epoch of caldera forming, i.e. to the second half of Middle Pleistocene.

Two main periods of increased tectonic activity were established. The first period relates to the Middle Pleistocene. The displacements along north-eastern and arcuate dislocations are observed at that time. The close connection between faults origination and magmatic activity is also noted. The second period of active tectonic motions in the area relates to the beginning of Late Pleistocene when the system of latitudinal fractures and normal faults originated and the system of arcuate dislocations partially renewed. The normal faulting led to subsidence of significant part of depression on depth more than 200 m.

It is not improbable that tectonic motions along these systems occurred in Holocene as well.

7. VOLCANIC ACTIVITY AND PRESENT-DAY LOCAL EARTH CRUST MOTIONS

The Kikhpinych Volcano rises above eastern flank of Uzon-Geyizrnaya depression (fig. 5). The Valley of Geysers conjugates to its south-western slope; its heat supply is connected with water flow uprising from area of volcanic massif magma source (Braitseva et al., 1991).

Figure 5: Volcavo Kikhpinych

The Kikhpinych Volcano includes several different-nature and different-age edifices. Its base is the Staryi Kikhpinych Volcano; it was formed before stage of caldera forming in the Eastern volcanic belt (Middle-Upper Pleistocene). The youngest cone was formed about 1400 years ago and is considered active until present time. Its last and the strongest explosive-effusive eruption occurred about 600 years ago. The origination of effusive dome about 400 years ago is connected with the final Kikhpinych eruption.

At present time active Kikhpinych Volcano is characterized by weak fumarole activity and very fresh lava flows. The forecast of future activity of the volcano is ambiguous. There is no information on present seismic activity of this volcano; observations were not conducted here.

The active character of recent earth crust motions in the Kikhpinych Volcano area is an unexpected result (Lundgren and Lu, 2006) Satellite interferometry data (InSAR) show that in 2000-2003 the rising on 15 cm was recorded here (fig 6, 11-c). The modeling fulfilled by authors of publication (Lundgren and Lu, 2006) connects the cause of motion with crust magma source (Belousov et al., 1984). Time irregularity of the rising process was noted: in 1999-2000 and in 2004 InSAR data did not reveal any geodynamic activity. The rising process was not accompanied by essential (on level of regional network registration) seismicity. Apparently weaker seismic events took place here.

The study (Lundgren and Lu, 2006) shows that analysis of RADARSAT-1 SAR data for Uzon caldera yields observations of positive displacements during the 2000 to 2003 time period, with no significant deformation in each of the years before and after. Authors model the deformation source as a heterogeneous, interconnected set of cracks with an over-pressure of 1.6 MPa, along a plane dipping 19º toward the NW, approximately 4 km below the caldera surface, which has a mean elevation of approximately 1 km. The close proximity of this source with geologic estimates of the graben structure and solidifying magma chamber does not distinguish between either the magma chamber itself or an overlying hydrothermal origin as the source of the deformation. The heterogeneity of the source structure and its apparent connection to deformation around adjacent Kikhpinych volcano suggests a hydrothermal system linked to the underlying magma system. The variability of the deformation during the 1999 to 2004 time period shows that further observations are required to better constrain the source mechanism and its temporal behavior.

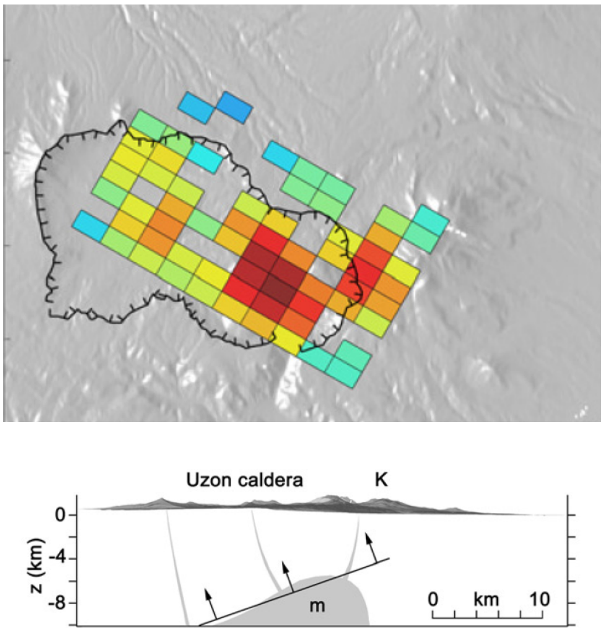

Figure 6: Map views of the modeled solutions (Lundgren and Lu, 2006). Distributed crack solution, for a constant over pressure of 1.6 MPa at an up-dip half-space depth of 4 km. Side view of the solution in Figure 4b with the approximate magma chamber (m) and fault and conduit structures given by (Belousov et al., 1984). K - Kikhpinych volcano

The eastern caldera slope rise should be related to one of the determinative factors, which accelerated the process of landslide development during last decade. Possibly this process is connected with hidden increase of volcanic activity: with Kikhpinych Volcano or surface magma source of Uzon-Geizernaya volcanic-tectonic depression.

8. HYDROTHERMAL ACTIVITY

Present-day hydrothermal activity is observed in Geyizrnaya River valley and in its upper reaches near south-western foot of the Kikhpinych Volcano. Geysers and other forms of hydrothermal activity represent surface manifestations of big hydrothermal field – Geyizernaya (fig.9, 10). The supposed feeding area of this hydrothermal system is the Kikhpinych volcanic massif (Leonov et al., 1991).

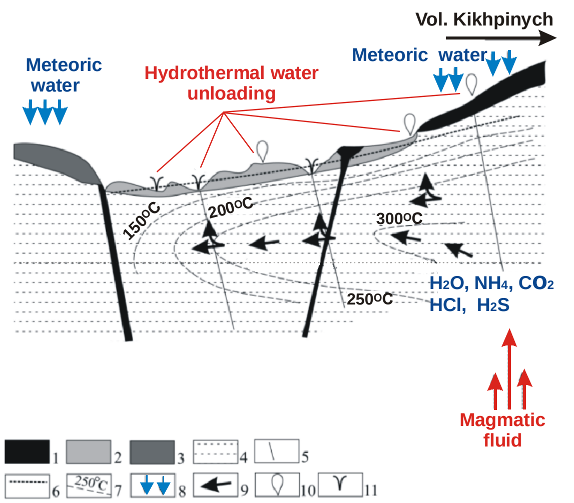

Figure 7: Schematic model of Geyizernaya Hydrothermal system (Sugrobov et al., 2004). 1-3 – relatively waterproof rocks: 1 – andesite lava and dikes, 2 – tuffs, 3 – lavas, tuffs, ignimbrites. 4 – slides of tuffs and crumbling lava – relatively water-permeable deposits. 5 – faults. 6 – piezometric level of underground thermal water. 7 – isotherms. 8 – meteoric water. 9 – direction of thermal water flow. 10 – steam-outs. 11 – geysers, boiling and hot springs

Hydrothermal model of Geyizernaya system represents a upwelling water flow from magma source area of Kikhpinych volcanic massif; it is formed by local infiltration waters and waters of regional groundwater runoff which acquire temperature about 250 ºC at certain levels. On the way to the surface they cool adiabatically with loss of vapor and mix with cool groundwater; thus lateral hydrotherm flow with temperature about 180 ºC originates. Its main unloading occurs in undercurrent of Geyizrnaya River. Total unloading of thermal waters consists 250-300 l/sec.

The results of landslide investigation show that heated rocks were involved in failure; earlier they composed the mountain massif. One of the main reasons of landslide is weakening of semi-rock pumice soils due to their steaming during hidden unloading of hydrothermal system. (Pinegina et al., 2008)

Figure 8: Geysers and other forms of hydrothermal activity represent surface manifestations of Geysernaia hydrothermal system. Photo by I.Shpilenok

9. SEISMICITY

The beginning of World instrumental seismology relates to the end of XIX century. Detailed seismologic observations on Kamchatka were organized in 1961-1962. The available instrumental data on Kamchatka seismicity form the information base for identification of seismic factor danger in development of slope failure process in the Valley of the Geysers.

Long-term estimation of seismic danger on territory is fulfilled on base of general seismic zoning data (Ulomov et al., 1999). In accordance with probabilistic seismic zoning map the Valley of the Geysers belong to the zone, where intensity of oscillations caused by big earthquakes may reach 9 units.

Seismic effect may be considered as two independent factors having an influence on landslide forming and development processes:

1. Each separate earthquake. Time of influence may be from several seconds to several tens of minutes. During this time seismic oscillations contribute to mechanic destruction of the slope. Along with direct effect of seismic accelerations on the value of destructive forces the soil oscillations may cause decrease of its strength along surface with resistance to slip. Dynamic shear strength of some materials is much less than static one. If there is a water-saturated layer separating landslide body from main massif, cyclic deformation may cause local effect of soil dilution. So trigger effect is possible: earthquake directly initiates landsliding on slopes, which exist in conditions close to instability.

2. Regional seismic process. It exerts influence on development of slope instability during whole time of landslide forming: from several years to several decades. This process has destructive effects on the slope: it activates origination and growth of fractures, changes fracture-pore space configuration and thus promote gradual penetration of cool and geothermal waters into rock massif. Big enough earthquakes may cause intensive earth's crust deformations in zones of present-day faults. In such a way seismic impact act as initial element of "domino effect" causing further chain of destructive events ("domino effect" means that some insignificant change entails linear series of other changes).

During last century the Valley of the Geysers three times suffered quakes with intensity 7-8 units (1923, 1927 and 1959) and three times - with 6 units (1952, 1971, 1997) according to macroseismic intensity scale MSK-64. The quakes were connected with the greatest within period of instrumental observations regional earthquakes with M=7.5-9, Table 1.

Table 1. Intensity of Ground Motions During Last Century in the Valley of the Geysers Caused by Largest Kamchatka Earthquakes.

Date yyyy mm dd and magnitude	Intensity of ground motions	Distance to earthquake source, km
1923 02 23 Mw=8.5 (8.7?)	8	180
1927 12 28 Mw=7.5	7-8	100
1952 11 04 Mw=9.0	6	200
1959 05 04 Mw=8.0	8	110
1959 06 18 Mw=7.0	4-5 ? 7-8 ?	60
1971 11 24 Mw=7.5	6	190
05.12.1997 Mw=7.8	6	130

Shallow-focus seismic activity of low energy level is typical for Uzon-Geyizernaya depression area, Fig. 11. Regional network has recorded several surface earthquakes from this area during period of detailed seismologic observations. Their parameters and time distribution is shown in Table 2 and on Fig. 12. Irregularity of events distribution in time attracts one's attention; it points on time-varying character of the process. Earthquake with K=9.3 occurred after 30-year period of "silence" (1968-1998); it was felt in the Valley of the Geysers as "very high-frequency one" (according to the report of eyewitnesses). A series of events apparently connected with local geodynamic stirring up begins with this quake. Due to restricted technical abilities of the regional network only biggest earthquakes are registered, but existence of local earthquakes in this area was demonstrated even on level of its sensibility; some of these earthquakes could be felt.

The occurrence of local earthquakes in the Valley of the Geysers area was confirmed by short-term instrumental observations of temporal seismic station conducted here in the end of 2007. An example of local earthquake record is presented on Fig. 13.

According to available data the process of landslide and slope instability development lasted for a long time - during several decades and even centuries and longer.

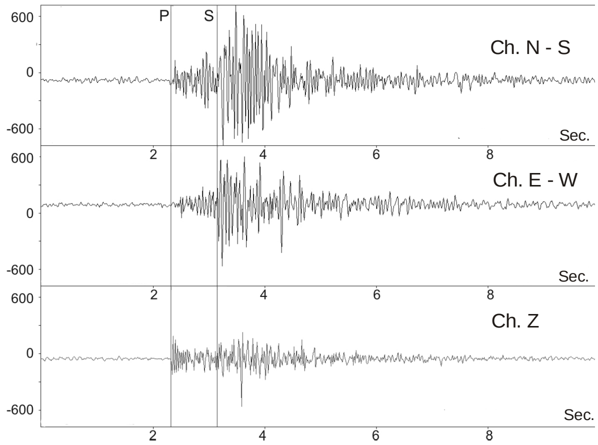

Figure 10: Seismic record of small local tectonic earthquake in the Valley of the Geysers. Ts-p<1 sec. M=0.3

There are some data on felt earthquakes from Valley of the Geysers area recorded during last days before the landslide. One communication is directly from Valley of the Geysers. Two others came from close to it places, from members of Kronotsliy Reserve staff, being there at that time. Small (I=2-3) seismic events on May 30 - June 1, 2007 were reported. It is possible that these small earthquakes exerted influence on final stage of June 03, 2007 geological catastrophe preparation.

In particular, the tectonic fracture along which the dislocation of block of landslide-forming rocks occurred can be seen on airphoto images of 1973 (Pinegina et al., 2008). Investigation fulfilled in 1974 showed that fracture looked fresh, contained small subsidence craters; it justifies recent motion activity and fracture opening. This fracture activity could be connected with seismic impact of earthquake in 1971 (Mw=7.5, I=6). But its origination could occur much earlier, for instance, at the moments of more intensive massif shaking (1923, 1927, 1959, I=7-8).

In calculation of landslide risk (as natural catastrophe) each seismic impact increases its probability because it influences on hidden mechanisms of watering in base of landslide body. It is also known that hydrothermal systems are very sensitive to seismic impact (Manga and Brodsky, 2006). It may be supposed that inner configuration of the Valley of the Geysers hydrothermal field is also sensitive to seismic effect. Let us generalize long-term influence of seismic process on development of the Valley of the Geysers landslide in respect of main collapse reason - massif weakening due to hydrothermal activity. Seismicity may be regarded in context of multi-step "domino effect" acting by scheme: *earthquake → seismic influence on landslide body, cyclic deformation → modification of fracture-pore space configuration → modification of hydrothermal field configuration → hydrothermal massif steaming → weakening of cohesion in some landslide base layer → slope collapse, landslide.*

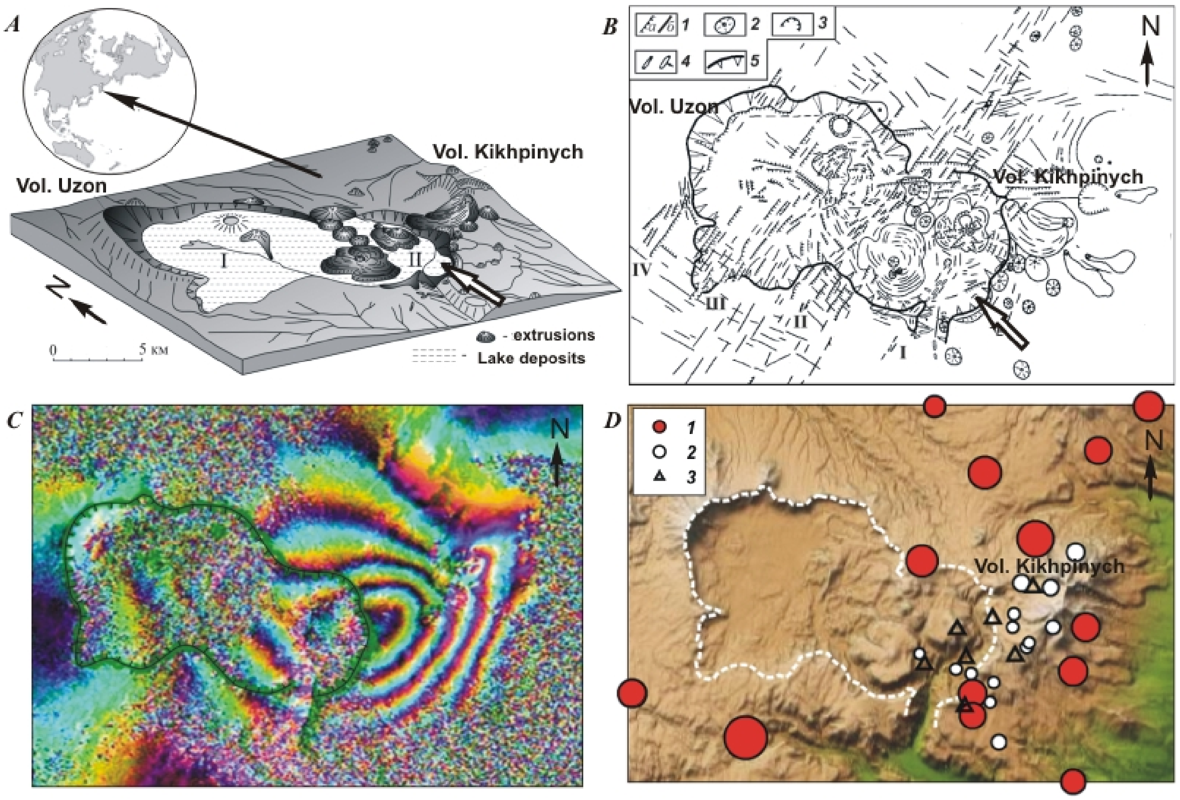

Figure 11: Comparison of geological, geophysical and seismological information about area of Uzon-Geysernaia volcano-tectonic depression

A – Block-diagram of Uzon-Geysernaia volcano-tectonic depression and vicinity. Place of June 3, 2007 landslide is marked by arrow.

B - Structure chart of Uzon-Geysernaia volcano-tectonic depression. 1 – faults and fissures , 2 - cinder cones and extrusive domes. 3 – craters. 4 – dikes. 5 - erosional scarps, limiting Uzon-Geysernaia depression. I-IV – groups of NE faults. Place of June 3, 2007 landslide is marked by arrow.

C – SAR interferograms, each color cycle represents 2.8 cm of surface displacement. It was found that from 2000 to 2003 Uzon caldera inflated with an amplitude of nearly 15 cm in the satellite line-of-sight (Lundgren and Lu, 2006). The geometry of the solution (fig.6) is similar to the upper boundary of the geologically inferred magma chamber. Extension of the surface deformation and source to adjacent Kikhpinych volcano, without an eruption, suggests that the deformation is more likely of hydrothermal origin, possibly driven by recharge of the magma chamber.

D – Seismicity in the area of Uzon-Geysernaia volcano-tectonic depression. 1 – by data of regional seismic network (1962-2008, H<20 km, M=1.5÷3.5). 2 – local shallow earthquakes, detected during field observations in 2007 and 2008 (M=-0.5÷1). 3 – field seismic stations.

CONCLUSION

The above presented information is not only of purely scientific interest and relates not only to landslide on June 3, 2007. All listed above geodynamic processes represent the factors which increase risk for other landslide bodies in the Valley of the Geysers as well (their presence and development are supposed, (Pinegina et al., 2008)). Thus geodynamic processes are one of the main risk factors of the continuing development of slope instability in the Valley of the Geysers.

Summarizing data about tectonic, raising of east slope of depression, landsliding and weak seismicity, we can suppose that all these phenomena are connected with each other and the deep processes under volcano Kikhpinuch are the reason of all these events (fig.11). Seismicity and intensive ground motions (as a result of activation of magma chamber or hydrothermal system) effect and destruct the caldera slop by activation of fissures and by change of pore-fracture configuration.

Local seismic-GPS network in the Valley of the Geysers area must be organized in addition to regional observation system which is aimed on local seismic monitoring and investigation of modern local earth's crust motions. Local microseismicity may be considered as informative factor in aspect of rock massif destruction by landslide forming (slope failure).

The Valley of the Geysers is considered as an object of UNESCO World Natural Heritage and ecological tourism. In this respect the estimation of landslide danger of territory taking into account all risk factors should be performed in frames of UNDP/GEF Project. One of the expected results of these works should be the instructions and recommendations for tourist industry management in conditions of landslide risk and on special nature-conservative territories. Traditional landslide protective measures are inapplicable in the Valley of the Geysers, because it is a part of Reserve and special nature-conservative object.

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