Hypsobathymetric Models of Ksudach Caldera Complex (Kamchatka)

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Abstract. The Ksudach volcano is one of the most complicated and dynamic volcanic centres of the Russian Far East located on the south of Kamchatka peninsula. Modern cone of the volcano is composite construction with five different size and time calderas, two lakes and recent Shtubel’s cone. Studying of modern terrain dynamics on the volcano can be carried out with by comparison of two digital elevation (hypso- and bathy-) models for state of 80s in the 20 century (created on the data of aerial photographs and the bathymetric surveys) and for modern state (on the data of ArcticDEM and digital echosounding bathymetric survey with synchronized satellite fixation of the profiles). The elevation models like these (for Kamchatka’s volcanoes and for different it’s conditions) were created at the first time. Its comparison allowed us to recognize new underwater extrusion dome with extensive underwater gas-hydrothermal outlets. Besides this we got the possibilities for clear bordering of different-time calderas using fractures on the automatic traceable small river profiles. Comparison of high-resolution different-time DEMs for volcanic research is relatively new and perspective way for understanding volcanic life and development.

1. Introduction
The caldera complex of Ksudach in the South Kamchatka volcanic zone is one of the largest and most complicated volcanic centers of the peninsula, its history being distinctive and prolonged. The complex is located in the southern part of the Eastern volcanic belt of Kamchatka (figure 1). At present the Ksudach edifice is a gently sloping shield cone, essentially eroded, with an ellipsoid base 18×22 km in size, its long axis is northwest oriented. Its top is complicated with five nested calderas of the Pleistocene-Holocene age [1], with remains of volcanoes within calderas and a young Shtyubel cone (figure 1). The inner part of the caldera is ~8 × 10 km in size, with Klyuchevoye and Shtyubel lakes in its eastern part. The western part of the caldera is dominated by flat interfluves at 650-800 m above sea level dissected with valleys of 2nd to 4th order. The Shtyubel volcanic cone between the lakes is a regular truncated cone about 3 km in diameter, 650 m a.s.l., rising ~240 m above the lakes. The absolute height of the ridge – remnant of the parent construction surrounding the caldera complex – is about 900-1000 m over its entire length, except for a few summits in the north and south slightly above 1000 m [2].
Figure 1. Location of the Ksudach volcano and cone’s general topography.

The youngest – 5th – caldera of the complex enclosing the lakes resulted from an extremely large eruption of the volcano about 1725 cal yr BP [3, 4]. A new volcano – the Shtyubel cone – began to grow in its northern part about AD 350-390 [5], its explosive activities are dated to around AD 1000 and AD 1650 [6]. During the latest eruption in 1907 a new crater originated at the top of the cone and later joined the Shtyubel lake in the north.

The watershed area of the entire caldera complex amounts to ~64 km$^2$. It is drained by the Teplaya River flowing out of the Shtyubel Lake and belonging to the Pacific Ocean basin. Modern processes of relief forming include water and wind erosion, slow mass movements, such as creep, defluxion, and solifluction in wetter places; gravitational processes dominate on steep slopes [7]. The thermal water discharge is recorded on the lakes coasts. The thermal anomaly is recorded on the western coast of the Klyuchevoye lake (Goryachiy Beach), and also at the Paryashchiy Ledge scarp [8-10].

Observations on the dynamics of the volcanic relief are of considerable interest, but the inaccessibility of potential objects does not always allow these studies to be carried out in full, even with extensive use of aerial and satellite images. Ksudach caldera complex is one of the successful exceptions. For studying the dynamics of the transformation of the relief of this active caldera complex under the influence of modern endo- and exogenous processes, it was decided to use hypsobathymetric modeling.

2. Methods of hypsobathymetric modeling of caldera complex

Two composite hypsobathymetric models of the Ksudach complex were created. The first model was created according to terrain condition for the end of the 80s years in the 20th century on the base of aerial photographs of V.N. Dvigalo (unpublished) and the bathymetric surveys of KamchatNIRO [9]. The second model was created for stage of the middle of the second decade in the 21st century according to the results of ArcticDEM [11] and D. N. Kozlov's bathymetric surveys with a Lowrance 527 CDF-iGPS echo sounder with 1 m sampling resolution and synchronous satellite reference profile measurements (unpublished) (figure 2). Merging of the data sources with different resolutions can be done in two ways: 1) with coercing of more detailed data to coarse resolution or 2) with a mechanical increase in detail (but not accuracy) of more coarse data. The model of the modern underwater surface
has been cell size of the bathymetric data set as resolution of the ArcticDEM. The elevation model of the volcano on the state of thirty years ago has the resolution of the original data comparable. Method used for resampling is bilinear interpolation, traditionally applied for continuous data (include elevation spots). Because the hypsometric and bathymetric models for the end of the 80s were interpolated from contours, and methods of such interpolation have a few of limitations and problems - the final resolution of this model reached 13 m only. The resolution of the model of the modern terrain turned out to be 2 m.

![Figure 2. Modern terrain of the Ksudach volcano and location of four topographic cross-sections.](image)

The datum planes of the bathymetric models were different, and the water levels of the Klyuchevoye and Shtyubel's lakes were taken as zero heights for each on the DEMs. Negative depth values from the bathymetric models were added to the surface levels of the lakes (from DEM), and a symbiotic hypsobathimetric models were obtained. A unknown systematic error (not giving in to an accurate estimate) is added by the fact that the topographic plan of V.N. Dvigalo was created in the conditional system of planned coordinates, when the true northern direction is rotated by about 40 degrees, and when the altitude shift is greater than about 20 (± 18.8) meters (numerical values was calculated).

The angles of rotation of the map were estimated as follows: the shorelines of the lakes, which had not significant changed its shape for a thirty-year period, taken from the plan of V.N. Dvigalo, are rotated around its geometric center until the degree of mismatch of contours with modern state did not become minimal. In this way, the required angle of rotation was estimated as 40 degrees. The planned shift, which in similar conditions is usually calculated manually, using several characteristic points, was determined a little differently - by an automatic method.

At first, approximate values of the shift were calculated - between the center of the height model constructed according to the Dvigalo's topographic plan and the common center of two lake's shorelines. Then the model of heights was iteratively cut along the contour of the lakes, and the
standard deviation of the «water surface» heights was calculated. In the case of partial convergence of the lakes shorelines with the shoreline edge on the DEM, the mean-square deviation cannot be small (due to the accounting of the slopes of calderas not covered by water by the contour of the lake). And only in the case of optimal alignment the mean-square indicator tends to zero. We have shifted the DEM first with a step of 100 m, then (after finding approximately the optimal shift) with a step of 5 m. Thus, the «exact» shift (at the model resolution of 13 m) was determined. The least developed task is the estimation of correct altitude shift for areas with active landform's dynamics. In the first approximation, this may be an iterative shift in height of one of the models (conditionally called «erroneous») with respect to the other (conditionally called «reference»).

If in the time between two terrain surveys of a volcanic cone there were no cardinal land shape transformation, the height shift that minimizes the sum of the height's deviations squares in the two models can be considered optimal. Otherwise, this simple and usually reliable approach may fail. Sometimes it is better to minimize not the sum of errors (or their squares) over the entire area, but only the sum of errors on relatively geomorphologically stable sites. The first approach allowed to determine that the height shift is most likely about 20 m.

3. Discussion and conclusion
The results of geomorphological and repeated bathymetric surveys were conducted with a break of 25 years permitted to understand the dynamic of relief of the active geological and geomorphological object - the Ksudach caldera complex. In the Shtyubel lake there is an instrumentally fixed underwater extrusion dome with extensive underwater gas-hydrothermal outlets. The morphological expression of extrusion in the relief of the bottom of the lake apparently occurred after the exploratory works of 1991, while the analysis of modern gas-hydrothermal activity in the Ksudach caldera shows the relative stability of the post-volcanic processes manifested as gas-hydrothermal outcrops both within the lake basins and on their shores.

We have obtained two different-time models also. A relatively large variance of the heights deviations on the two models, taking into account the correction for the vertical shift (± 18.8 m), does not allow quantitative comparisons. However, a qualitative interpretation of the most pronounced local changes in geomorphology remains possible. It allows to discuss the current trends in the volcanic structure of the Ksudach complex. Among the most striking trends is the appearance of a new underwater volcanic cone in the southern part of the Shtyubel lake (figure 3).

![Figure 3](image_url)  
**Figure 3.** Comparison of cross-sections (black - terrain of the 80s, grey - modern terrain). Arrow marks biggest modern uplift.

For the first time these hypsobathymetric models made it possible to estimate the structure of the Ksudach caldera complex as a whole, taking into account the morphology of the submerged relief of lake basins. They also made it possible to identify areas of development of surfaces with different slopes, which is important for determining the zones of development of different types of geomorphic processes. In addition we got a possibility for hydrological analysis of terrain structure, for example, using of longitudinal small river profiles for marking different-time calderas constructions. The
fractures on longitudinal sections (one or more) can show the calderas boundaries better that we can't saw on the DEM of topographic map.

4. References

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