

**MEASUREMENTS OF MORPHOMETRIC PARAMETERS FROM
DIGITAL ELEVATION MODELS**

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ABSTRACT:

The present research examines the measured morphometric values of monogenetic cinder cones in the Tolbachik volcanic field (Kluchevskaya volcanic group, Kamchatka). The cones were measured from digital elevation models derived from satellite data (ASTER and SRTM) and from digitized topographic maps. The GPS measurements of 85 locations were performed in the field to provide geodetic reference for DEM processing as well as to assess the accuracy of the DEM. A methodology for morphometric measurements on a DEM is proposed. The morphometric parameters derived from a DEM include the main characteristics that control the rate of degradational evolution of the cone: height, width and slope. The measured morphometric values were compared and accuracy assessment was carried out.

Our study analyzes the morphometric values of four recent cinder cones formed during the last basaltic eruption in 1975-76, and of five older ones formed during the last 2000 years. We show that morphometric values obtained from a DEM are affected by the resolution change, and characteristics of the same cinder cone may vary in their values among DEMs of different resolutions. According to the results, the morphometry of the cinder cones can be well characterized by a DEM derived from remotely sensed data. The calculated morphometric parameters showed a correlation with the spatial resolution of the DEM and relative age of the cinder cones. All studied DEM (including coarse resolution SRTM) were found suitable for morphometric measurements under the constraint of spatial resolution.

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1. INTRODUCTION

Remotely sensed stereo imagery acquired from space-borne sensors provides the accurate DEMs and offer the potential of worldwide coverage (Kervyn et al., 2008). Digital elevation data gathered by remote sensing methods are widely used to study the dimension and shape of volcanic structures (Kervyn et al., 2007). Radar interferometry and optical digital photogrammetry are two leading methods used to derive DEMs from remotely sensed datasets. The spatial resolution of a DEM controls the precision and accuracy of height and slope estimates (Guth, 2006). Kervyn et al. (2008) assessed the effect of changing the DEM resolution on the quantitative characterization of volcanic structures using a simulated cinder cone with typical characteristics.

The objective of this study is to analyze calculated morphometric parameters, derived from different DEMs of recent cinder cones formed by an eruption that occurred in 1975-76, and of older cones formed during the last 2000 years in the Tolbachik volcanic field of Kluchevskaya volcanic group. These parameters include the main characteristics controlling the rate of degradational evolution of the cone: height, width, height-width ratio, and slope. The morphometric parameters were calculated from DEMs derived from satellite data (ASTER and SRTM), and digitized topographic maps. The accuracy of the studied DEMs was assessed by a field GPS survey, and the consistency of calculated morphometric parameters derived from different DEMs was verified. The effect of DEM resolution on measurements of morphometric values was evaluated. We also classified the resulting morphometric parameters of the cinder cones in the two age groups to analyze the potential of morphometry for relative dating.

2. STUDY DATA

2.1 Study area

The Tolbachik volcanic field located in the southwest part of the Kluchevskaya volcanic group is one of the youngest volcanic landforms on the Kamchatka peninsula (Fig. 1a). Our study was focused on four youthful cinder cones that formed during the Great Fissure Tolbachik Eruption (GFTE) of 1975-76 - the youngest episode of Tolbachik volcanic activity, and five older cones that formed during the last 2 Kyr (Fig. 1b, Table 1).

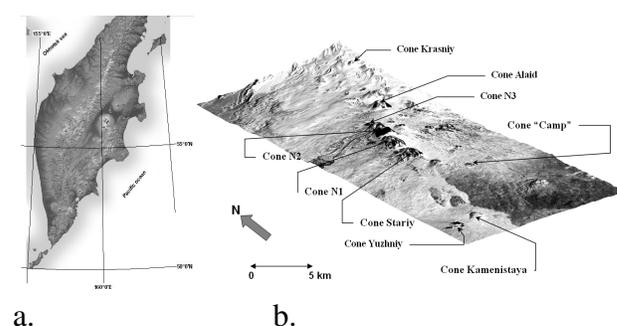


Figure 1. The study area.

a – Kamchatka peninsula; b - Perspective view of Tolbachik volcanic field with the nine cinder cones analyzed

	<i>Item</i>	<i>Code</i>	<i>Height (m)</i>	<i>Age (AD)</i>
Recent cones	Cone N1	CN1	295	1975
	Cone N2	CN2	273	1975
	Cone N3	CN3	108	1975
	Yuzhniy	YZN	105	1975-1976
Older cones	Krasniy	KRS	110	1740
	Alaid	ALD	220	1000-1100
	“Stariy”	STR	180	200-500
	“Camp”	CMP	75	0-500
	Kamenistaya	KMN	115	500-1000

Table 1. Descriptive characteristics of the cinder cones.

2.2 Field GPS measurements

During fieldwork in August 2007 on the Tolbachik volcanic field, GPS measurements were acquired on nine cinder cones located along the main sub-meridian fault. Acquisition of GPS measurements of planar coordinates and elevation were one of main objectives of the field survey. The elevation measurements were obtained as WGS84 ellipsoid heights. In total we have measured 85 ground control points (GCP) within the study area including 73 measurements of randomly oriented elevation profiles of the nine cinder cones.

2.3 ASTER

ASTER (launched in December 1999) is a medium-to-high spatial resolution, multispectral imaging system ranging from the visible to thermal infrared portion of the electromagnetic spectrum (EM). An ASTER scene, covering 61.5 x 63 km, comprises data from 14 spectral bands divided into three radiometers: VNIR, SWIR and TIR. The high resolution VNIR optical instrument (15 m spatial resolution) records spectral reflection from the ground surface from the visible to near infrared (0.52 - 0.86 μm) portion of the EM spectrum. VNIR has two near infrared bands with similar wavelengths: 3n (nadir looking) and 3b (backward looking) with an angle of 27.6°. The purpose of the addition of band 3b is to obtain stereoscopic images for generation and processing of DEM (Hirano et al., 2003).

In general, the accuracy of DEMs derived from ASTER data depends on the availability, spatial distribution and accuracy of ground control points as well as on image contrast (Kervyn, 2008). Due to persistent cloud cover over the study area most cloudless ASTER scene was selected for DEM generation (March 2004). Derivation

of a DEM from ASTER data began with image orthorectification. The nadir image VNIR3N (left stereo image) and backward looking VNIR3B (right stereo image) were orthorectified by means of rational polynomial coefficients (RPC) based on sensor geometry; information derived from each ASTER scene's metadata and product documentation. The availability of 40 ground control points precisely located in the field and on the ASTER stereo pair allowed good absolute orientation of generated DEM. A number of experimental DEMs were generated by varying a DEM spatial resolution and matching interval of two epipolar image templates (left and right images of stereo pair). Optimal results were obtained by matching interval (moving window size) of 3x3 pixels, with the highest possible level of detail and spatial resolution of 30 meters. Holes in the generated DEM were filled by automated interpolation, and then smoothed by 3X3 low-pass filter to reduce the effect of possible artifacts (blunders).

2.4 SRTM

NASA's SRTM provided digital elevation data for over 80% of the globe during the Endeavour mission (February 2000), using both a C- (5.6 cm wavelength) and X-band (3 cm) radar. Kervyn et al. (2008) showed that a spatial resolution of 90 meters limits the vertical accuracy of topographic features thus reducing the usefulness of SRTM data. Nevertheless, the SRTM3 is one of the best available topographic datasets for Kamchatka. Comparison of ASTER and SRTM DEM products in the complex physiographic landscape of Crete indicated close correlation for estimated elevation (Nikolakopoulos et al., 2006).

For Kamchatka, SRTM3 data are available as DEMs with a 3 arc-second (~90 meters) spatial resolution. The SRTM (orthometric

heights) used in this study was projected using the WGS84 horizontal datum to UTM projection (UTM 57N). A nearest neighborhood resampling method was used to preserve 90 meters pixel size.

2.5 Topographic maps

The survey of erupted material from four cinder cones started already during the GFTE, and detailed fallout cinder maps were presented by Budnikov et al. (1983) at a scale of 1:25,000 with contour interval of 5 meters. The entire Tolbachik volcanic field was topographically surveyed at a scale of 1:25,000 in 1976-80. The availability of these data allowed preparation of a detailed cartographically derived (map-based) DEM by digitization of fallout cinder maps and topographic maps. A map-based DEM was compiled from the fallout cinder isopachs maps and the topographic maps of Tolbachik volcanic field at a scale of 1:25,000. The DEM was generated from 5 meter contour lines and spot heights. The contours and the spot heights were digitized manually, and an elevation assigned to each digitized feature. Triangular irregular networks (TINs) were created from the digitized data and transformed into raster image of resultant DEM at a resolution of 10 m, with the help of Spatial Analyst tool (ArcGIS 9.2).

3. MORPHOMETRIC PARAMETERS

Cone height (h), cone width (W), h/W ratio and slope angle calculated from existing topographic maps are the main morphometric parameters used for determining the rate of cone degradation as a function of its exposure to erosion (Wood, 1980a, b). The standard definition of these parameters is based on the measurements from topographic maps. In Hooper and Sheridan (1998) cone width is calculated as

the average of the maximum and minimum basal diameters for each cone; cone height is defined as the difference between average basal elevation and maximum crater rim or summit elevation. The h/W ratio reflects the erosive process on the cone and decreases with age as material is removed from the crest to the cone base (Inbar and Risso, 2001). Hooper and Sheridan (1998) presented a progressive decrease of h/W ratio and slope with increasing age of the cone.

The definition of standard morphometric parameters derived from DEMs is different from that on topographic maps. The DEMs allow definition of morphometric parameters as variables of continuous topographic surface. Here, we acquired DEMs from different remotely sensed sources and used the detailed hill-shaded image in combination with derivative slope image to delineate the outlines of each cinder cone. Then, the standard morphometric parameters have been calculated using fitted-to-ellipse resulting outlines by means of ad-hoc developed IDL program.

3.1 Cone slope

We used slope models in combination with the respective DEMs to calculate the morphometric parameters of the cinder cones. The slope values were calculated in degrees by ENVI 4.6 topographic modeling procedure for every pixel in the DEM. In our study the basal outline ($e2$) of the cinder cone was defined according to the lowest elevation isoline ($e1$) with an average of slope pixels more than 5° (Fig. 2a). The basal elevation was estimated as the average elevation value of all DEM pixels located along the basal outline. Then we calculated the slope of the cinder cone as the average of pixel slope values situated along the steepest profile (S) with the greatest elevation difference (cone height, h)

between the highest cone point and the basal outline on the shortest horizontal distance L (Fig. 2b).

3.2 Cone height and width

The lowest basal isoline was fitted to ellipse shape (Fig. 2a) and the cone width (W) was calculated as the average of the maximum (D_{max}) and minimum (D_{min}) axes of this ellipse (Fig. 2b). Based on cone width and the above calculations of height we straightforwardly calculated the h/W ratio accordingly to Wood (1980a).

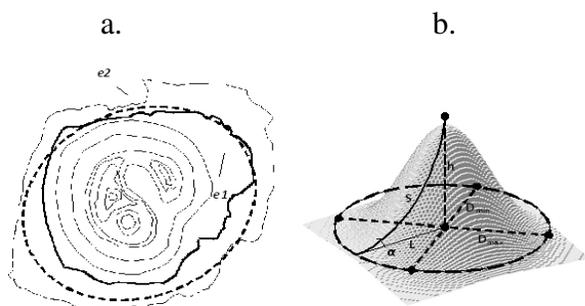


Figure 2. Morphometric measurements

(a) Example of basal line definition where $e1$ is lowest elevation isoline with average of corresponding slope pixels more than 5° and $e2$ is fitted-to-ellipse basal outline; (b) Definition of basic morphometric parameters over idealized cinder cone where D_{max} and D_{min} are major and minor diameters of the cone base; α is slope angle; h is cone height; S is profile with biggest elevation difference between cone's highest point and the basal isoline on the shortest horizontal distance (L).

4. RESULTS

In this study, the overall statistics of ASTER DEM and SRTM in relation to a reference map-based DEM was calculated. The elevation in 256 control points randomly selected pixels of map-based DEM was

compared with the elevation of the respective DEMs. The elevation in these pixels was compared to the elevation of the pixel with the nearest planimetric coordinates in the DEMs. The overall accuracy of each DEM was assessed by root mean square error (RMSE). The RMSE was calculated as the squared root of the average of the set of squared elevation differences between control points and corresponding DEM locations. The RMSE was calculated directly from the DEMs by means of ad-hoc developed IDL program. The summary of DEMs overall accuracy is presented in Table 2.

Source	Elevation range, m	Mean elevation, m	Std. Dev., m	RMSE, m
ASTER	413 – 1694	1015.6	345.2	21.2
SRTM	399 – 1644	993.1	339.8	32.8

Table 2. DEM statistics and elevation errors

Morphometric parameters of cone height, slope and basal width were calculated from the DEMs derived from remotely sensed data and from the cartographically derived (map-based) DEM (Table 3).

Table 3. Morphometric parameters measured from DEMs of different sources.

Item	ASTER			SRTM			MAP		
	h, m	W, m	Slope, degrees	h, m	W, m	Slope, degrees	h, m	W, m	Slope, degrees
CN1	290	1250	26.8	275	1300	25.4	300	1150	32.4
CN2	275	1100	26.2	260	1200	24.6	280	1050	30.9
CN3	110	524	26.1	100	556	22.1	110	478	29.9
YZN	95	452	25	90	529	21.6	105	477	31.4
KRS	172	853	24.5	159	813	20.6	180	890	28.9
ALD	210	1175	24.3	205	1364	20.9	220	1120	27.9
STR	165	1179	22.5	140	1100	19.8	180	1060	26.9
CMP	75	555	21.1	70	550	19.6	75	540	25.4
KMN	110	688	19.5	100	850	17.7	115	640	24.9

Spatial resolution of DEM directly affects the accuracy of elevation estimates. As pixel

size of DEM increases, a single elevation value represents larger terrain unit by averaging values within the pixel. The comparison of relative coarse-resolution DEMs (SRTM) with high-resolution DEMs (ASTER and map-based) shows underestimation of smaller height values and overestimation of larger width values. This also affects the slope values, which tend to decrease in all studied cones as DEM resolution is coarser.

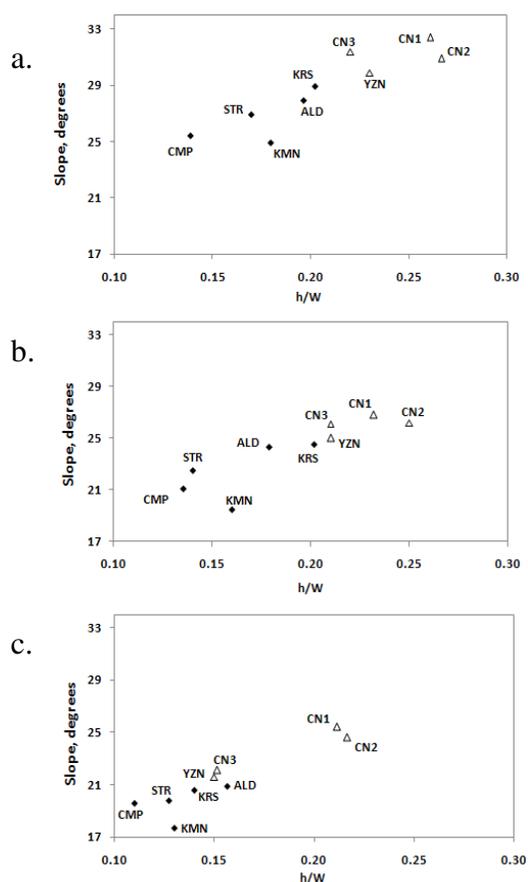


Figure 3. The comparison of cone slope values against h/W ratio. (a) Map-based DEM; (b) ASTER DEM and (d) SRTM DEM. Note that the same scale of the scatter-plots helps to compare the relationship between morphometric values measured from different DEMs.

Height and basal width values were used to calculate h/W ratio and were compared with

slope values. The graphic comparison of the slope and h/W values shows consistency in distribution of these parameters in all the DEMs and demonstrates a continuous shift towards smaller values of slope and h/W ratio with decrease of DEM resolution (Fig. 3a-c).

The map-based DEM has demonstrated an average h/W value of the recent cones as 0.24 ± 0.02 and average slope as $31.1^\circ \pm 1.1^\circ$; in older cones the estimated average h/W was 0.18 ± 0.03 and average slope as $26.9^\circ \pm 1.7^\circ$. This trend is further supported by similar pattern of distribution of h/W and slope values in all elevation models (Fig. 3a-d).

4. DISCUSSION

This paper assessed the accuracy of DEMs derived from different data sources in the Tolbachik volcanic field in Central Kamchatka. The presented are morphometric measurements of cinder cones from the DEMs of different resolutions. We found that decrease of DEM resolution affected the morphometric parameters of the cinder cones. The morphometric parameters of cone slope, height and width were measured from the remotely sensed DEMs and compared with a cartographically derived DEM (Table 3). The smoother representation of the surface by coarser-resolution DEMs is caused by interpolation of increasingly widely spaced data points in the vicinity of breaks in slope (Wright et al., 2006; Kervyn et al. 2008). This effect was observed in our study as well; of all the elevation models we studied, the SRTM DEM showed the greatest underestimation of elevation values and overestimation of cone width, compared to cartographically derived DEM. Similarly, the ASTER DEM and cartographically derived DEM have demonstrated the comparably close morphometric parameters (Table 3).

Decrease of DEM resolution shifts the slope and h/W ratio estimates towards lower values (Fig. 3). The decrease of elevation values in coarse-resolution DEM make it inherently less able to represent smaller elevation variations found within the terrain. The recent cones have provided highest slope and h/W values in all the studied DEMs. The cartographically derived DEM had the highest spatial resolution and provided numerically higher morphometric values of slope and h/W ratio; the lowest values were obtained from the SRTM DEM. A coarser DEM provides lesser morphometric values but generally preserves the trend in distribution of cinder cones' morphometric parameters (regarding to their age) as do high resolution DEMs. Thus the coarse resolution DEM affects the morphometric parameters of the cinder cones in the similar way as erosion by reducing h/W and slope values.

5. CONCLUSION

From our results, the morphometry of the cinder cones can be well characterized with DEMs derived from remotely sensed data. The morphometric values derived even from a coarse-resolution DEM can still be used for cinder cone classification and relative dating, under the constraint of spatial resolution. We emphasize that, especially on smaller cinder cones, the decrease of DEM resolution affects the calculation of morphometric parameters and consequently the relative age. Thus, the relative age should be obtained by comparing morphometric parameters of the cinder cones from DEMs of same resolution. The use of high resolution DEM for calculation of morphometric parameters may contribute to geomorphological modeling and estimation of relative age of cinder cones. Future research of cinder cones in complex terrain might be of interest to examine the

possible affect on calculated morphometric parameters.

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