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El'gygytgyn impact crater, Russia: Structure, tectonics, and morphology

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Abstract–The 3.6 Myr old El'gygytgyn impact crater is located in central Chukotka, northeastern Russia. The crater is a well-preserved impact structure with an inner basin about 15 km in diameter, surrounded by an uplifted rim about 18 km in diameter. The flat floor of the crater is in part occupied by Lake El'gygytgyn, 12 km in diameter, and surrounding terraces. The average profile of the rim is asymmetric, with a steep inner wall and a gentle outer flank. The rim height is about 180 m above the lake level and 140 m above the surrounding area. An outer ring feature, on average 14 m high, occurs at about 1.75 crater radii from the center of the structure.

El'gygytgyn crater is surrounded by a complex network of faults. The density of the faults decreases from the bottom of the rim to the rim crest and outside the crater to a distance of about 2.7 crater radii. Lake El'gygytgyn is surrounded by a number of lacustrine terraces. Only minor remnants are preserved of the highest terraces, 80 and 60 m above the present-day lake level. The widest of the terraces is 40 m above the current lake level and surrounds the lake on the west and northwest sides. The only outlet of the lake is the Enmivaam River, which cuts through the crater rim in the southeast. In terms of structure, El'gygytgyn is well preserved and displays some interesting, but not well understood, features (e.g., an outer ring), similar to those observed at a few other impact structures.

INTRODUCTION

El'gygytgyn impact crater is located in the central region of Chukotka, northeastern Russia, centered at 67°30′N and 172°34′E. The crater is situated in the Anadyr Highland of central Chukotka, which is characterized by a complex relief of low hills and mountains (Fig. 1). The structure was earlier thought to be either of volcanic or impact origin (see short history in Gurov et al. 2005). It was confirmed as an impact crater by Gurov et al. (1978, 1979) during their extensive field investigations, which led to the discovery of shock-metamorphosed rocks, impact glasses, and impact melt rocks.

Although the remnants of ejecta around the structure are completely eroded, El'gygytgyn crater is one of the better preserved impact structures on Earth (Dietz and McHone 1976; Layer 2000; Gurov and Koeberl 2004; Gebhardt et al. 2006). Its surface expression in space images has been described as "excellent" (Garvin and Grieve 1986; Grieve et al. 1988). According to the classification of impact structures by preservation (Grieve and Robertson 1979), El'gygytgyn crater represents the third level: ejecta removed, rim partly preserved.

The ages of impact glasses and melt rocks of El'gygytgyn crater were determined to be 3.50 ± 0.50 Myr by K-Ar dating (Gurov et al. 1979), and 3.45 ± 0.15 Myr (Komarov et al. 1983) and 4.52 ± 0.11 Myr (Storzer and Wagner 1979) by fission track dating. The most recent $^{40}Ar/^{39}Ar$ dating of impact glasses yielded 3.58 ± 0.04 Myr (Layer 2000), in agreement with earlier data. This is the currently accepted age of the structure.

El'gygytgyn crater was formed in a sequence of volcanic rocks and tuffs of predominantly siliceous composition. A classification of shock-metamorphosed siliceous volcanic rocks was proposed for shock pressures up to 55 GPa (Gurov and Gurova 1979, 1991; Gurov and Koeberl 2004; Gurov et al. 2005). The high-pressure quartz polymorphs stishovite and coesite were detected in quartz from strongly shocked rhyolites and rhyolitic tuffs (Gurov and Gurova 1991; Gurov and Koeberl 2004).

Investigations of impact melt rocks and impact glasses were carried out by Gurov and Gurova (1979, 1991), Feldman et al. (1981), Feldman (1990), Gurov and Koeberl (2004), Gurov et al. (2005), and a few others. The similarity in composition between impact melts and volcanic target rocks was shown by Gurov and Koeberl (2004). This particularly

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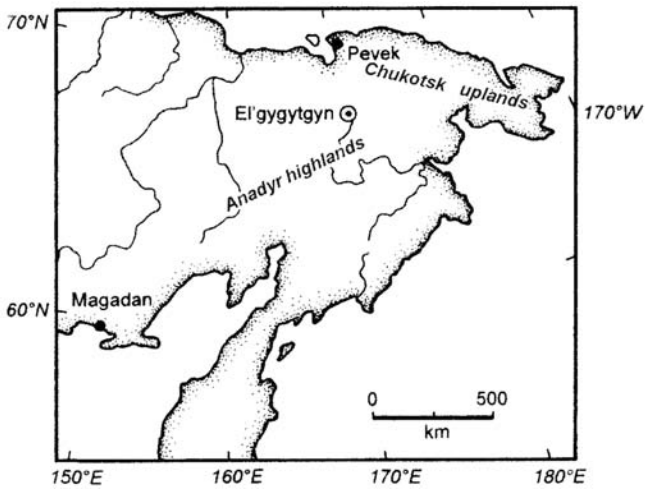


Fig. 1. Location of El'gygytgyn crater in central Chukotka, Russia.

holds for the upper layer of the rhyolitic ignimbrites, the uppermost member of the volcanic sequence in the area. Minor enrichments in chromium and a few siderophile elements in the impact melt suggest a stony meteorite composition of the El'gygytgyn projectile (e.g., Kapustkina et al. 1985; Gurov and Gurova 1991; Gurov and Koeberl 2004).

El'gygytgyn crater is surrounded by a complex fault system. Based on the occurrence of intensive faulting around the crater, a tectonic or other endogenic origin was postulated (Nekrasov 1963; Belyi 1982, 1998). Various aspects of the fault tectonics of El'gygytgyn were described by Gurov and Gurova (1983), who measured the fault network inside and around the structure.

Recently El'gygytgyn crater and, especially, its post-impact sedimentary record have been the subject of a joint investigation of the Alfred-Wegener Institute, Potsdam, Germany; the University of Massachusetts, Amherst, USA; and the Northeast Interdisciplinary Scientific Research Institute, Magadan, Russia. Particular attention was directed to the study of the crater morphology and its post-impact history (e.g., El'gygytgyn Lake Workshop 2004; Glushkova et al. 2004). Suggestions about a possible satellite crater ("Lagerny"), which adjoins El'gygytgyn at its southeastern rim, were published (Glushkova et al. 2001; Minyuk et al. 2003). Shallow cores into the lake sediments were drilled to gain paleoclimatic information (Brigham-Grette et al. 1998; Nowaczyk et al. 2002).

Scientific deep drilling of El'gygytgyn crater, with main funding provided by the International Continental Scientific Drilling Program (ICDP), is scheduled for 2008. The main goal of that project is to study the paleoclimatic history of the Arctic region since crater formation about 3.6 million years ago (El'gygytgyn Lake Workshop 2004), but drilling into the impact breccia on or near the central uplift of the structure is also planned. The study of shock metamorphism of the rocks of the central uplift is of special interest; in addition, such a drilling project will allow, for the first time, the study of in situ impactites (possibly melt-bearing breccias) within this crater.

The purpose of the present paper is to summarize geological, structural, and morphological aspects of El'gygytgyn crater.

GEOLOGICAL BACKGROUND

El'gygytgyn impact crater is located within the Okhotsk-Chukotsky Volcanic Belt (OCVB) in northeastern Russia. This region occurs near the margin of the stationary Eurasian Plate, about 600 km north of the inactive Aleutian Basin of the American Plate, and 1400–1600 km north of the mobile Pacific Plate (Le Pichon et al. 1973). The crater area is within the outer zone of the OCVB, which was superimposed on the Mesozoic structures of the Verchoyano-Chukotsky Fold Belt during the middle Albian to middle Cenomanian (Kotlar et al. 1981).

The circular crater is located at the axial part and the southeastern slope of the Academician Obruchev Ridge, in the northeastern trend of this area. There is no evidence of glaciation in the crater area. According to Minyuk et al. (2003), the nearest center of the Quaternary mountain glaciation was located about 100 km to the west of the crater area.

El'gygytgyn crater has a rim-to-rim diameter of 18 km. The crater floor, about 15 km in diameter, is covered by Lake El'gygytgyn, which is 12 km in diameter and up to 170 m deep in its central part. A complex of lacustrine terraces surrounds the lake. The crater is surrounded by an uplifted rim with steep inner walls and gentle outer slopes (Fig. 2). From the study of Landsat images of the crater, Dietz and McHone (1976) suggested that it is a well-preserved structure and that ejecta should be present. However, despite the fresh appearance of the rim in satellite images (Dietz 1977; Garvin and Grieve 1987; Grieve et al. 1988), it is somewhat eroded and dissected by numerous creeks that drain into the lake.

The inner crater structure is still not well known; however, some information recently became available from geophysical investigations (e.g., Gebhardt et al. 2006). According to the seismic measurements, the thickness of the sedimentary fill near the crater center is about 360 to 420 m. The sediments are underlain by units with distinctly higher seismic velocities, interpreted as allochthonous breccia, 100 to 400 m thick (Gebhardt et al. 2006). The probable presence of a central uplift, about 2 km in diameter and centered relative to the crater rim (not with respect to the center of the lake), was suggested earlier from a NW-SE gravity profile across the crater area by Dabija and Feldman (1982); the presence and location of the central uplift have been confirmed by the seismic investigations of Gebhardt et al. (2006). The displacement of Lake El'gygytgyn towards the southeastern part of the crater rim is confirmed by more rapid sedimentary infilling of the western part of the structure.

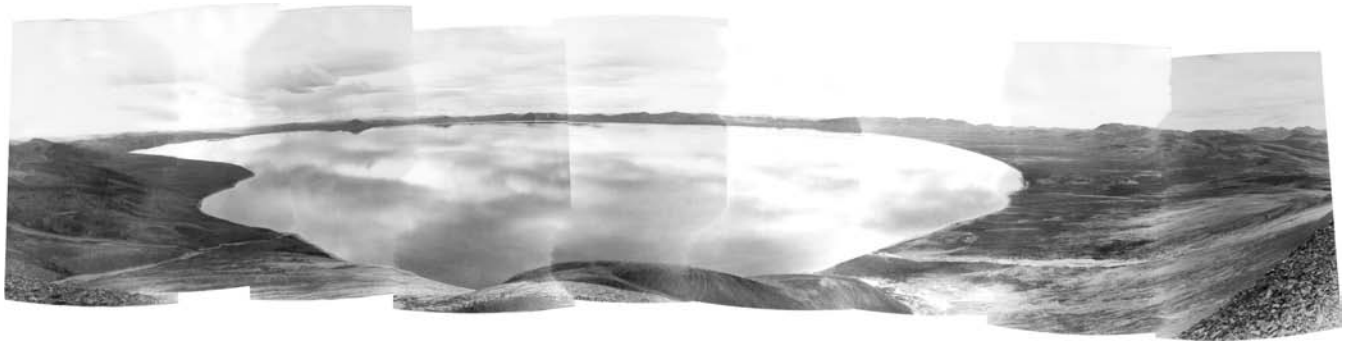


Fig. 2. Panoramic view (165° wide) of El'gygytgyn impact crater as seen from a 758 m high peak on the northeastern part of the crater rim. The crater basin is surrounded by an uplifted rim, which is dissected by valleys created by streams draining into the lake. The low watershed of the crater basin and the Otveverghyn River is visible to the lower right. The outlet of the Enmivaam River is in the far upper left. Detrital material (in the foreground) is comprised of unshocked volcanic rocks. The whole area is a mountainous tundra with a detrital stony surface and rare grassy vegetation.

If the thickness of sedimentary fill is about 400 m, the lake depth is 170 m, and the highest lacustrine terrace is 80 m above lake level, then the apparent crater depth is about 650 m. The true depth of the El'gygytgyn crater, after formation, is estimated to be about 900 m according to the relationship of Grieve and Robertson (1979):

$$P_t = 0.52D^{0.189} \quad (1)$$

where P_t and D are the true crater depth and the rim diameter, respectively. Thus, the thickness of allochthonous rocks in the crater should be 900 – 650 = 250 m. This estimate is in agreement with the results of the seismic studies that indicate an allochthonous unit 100 to 400 m thick (Gebhardt et al. 2006).

El'gygytgyn crater is surrounded by a complex system of faults (see below). The fault network of the crater is composed predominantly of minor faults, which did not produce any major displacements of target rock blocks (Gurov and Gurova 1983).

The target of the crater is composed of volcanic rocks of Late Cretaceous age (Feldman et al. 1981; Kotlar et al. 1981), as confirmed by K-Ar dates of 83.2 to 89.3 Myr for the target rocks (Belyi 1998; Layer 2000). The volcanic strata are composed of rhyolitic and dacitic lava, tuffs, and ignimbrites, and rarely of andesites and andesitic tuffs. In the crater region these deposits show a gentle dip of 6° to 10° to the E-SE. From outcrops in the crater area and surroundings, Gurov and Gurova (1991) (see also Gurov and Koeberl 2004) assembled a generalized pre-impact target stratigraphy. From the top downwards, the following are exposed (thicknesses in brackets): rhyolitic ignimbrites (250 m), rhyolitic tuffs and lavas (200 m), andesitic tuffs and lavas (70 m), rhyolitic and dacitic ash tuffs and welded tuffs (100 m). This sequence of volcanic rocks is found in the southwestern, western, northern, and northeastern sections of the crater area and thus covers about two thirds of the structure.

The southeastern and eastern parts of the crater target are composed predominantly of dacitic and andesitic lava and tuff. A generalized stratigraphy of this area could not be compiled because of limited exposure. The northwestern-southeastern gravity profile across the crater area revealed a regional gradient of about 20 mGal underneath the lake, indicating more dense rocks in the southeastern part of the structure (Dabija and Feldman 1982). This gradient may correspond to the boundary between the two different target types in the crater area.

The ejecta layer was completely eroded around El'gygytgyn crater. Thus, the shock metamorphosed volcanic rocks and impact melt rocks are not preserved in their initial locations, but have been redeposited in lacustrine sediments and alluvial stream deposits around the crater (Gurov and Gurova 1979, 1991; Gurov and Koeberl 2004). Impact rocks at El'gygytgyn include glasses, impact melt rocks, and breccias, as well as shock metamorphosed volcanic rocks and tuffs of predominantly siliceous composition. Shocked andesites and andesitic tuffs with maskelynite inclusions are rare within material that makes up the lacustrine terraces in the eastern part of the crater. The ICDP deep drilling, anticipated for 2008 (see above), should finally provide information about crater-fill breccia and melt rocks for comparison with the currently known redeposited surficial ejecta.

Along the inner slopes of the crater rim, several levels of lacustrine terraces are present. These terraces reflect ancient high stands of the lake. The highest lacustrine terraces were formed before the Enmivaam River cut the crater rim. The study of these terraces started long before the confirmation of the impact origin of the structure. A terrace 40 m above the lake level was first described by Obruchev (1938) during his short visit to the crater in 1935. Nekrasov investigated the terraces in the El'gygytgyn depression and discovered lacustrine sediment deposits 80 and 40 m above the lake level (Nekrasov 1963). Further studies of the lacustrine terraces were carried out by Gurov et al. (1978, 1979), because they represented the main source of impact rocks in the crater at the present erosional stage (Gurov and Koeberl 2004).

The Enmivaam River cuts the rim of El'gygytgyn crater and is the only drainage that at present determines the water level in the lake. There are lacustrine terraces along the river as well. Descriptions of the Enmivaam River terraces were first given by Nekrasov (1963), and later by Glushkova et al. (2004). We investigated the terraces of the Enmivaam River from where it flows out of Lake El'gygytgyn to the Leonovsky rapid, 150 km downstream.

METHODS

The main data used in this paper were collected by E. Gurov and E. Gurova from 1977 to 1980 during field investigations at the crater and its vicinity, covering an area of about 400 km^2. The structure of the rim, bedding of the rocks, and their compositions were studied. One of the primary goals of the field work was related to the search for and study of impactites. The structure and composition of the volcanic rocks were investigated to better understand the types and locations of the target rocks from which the impactites formed.

The present-day morphology of the crater region is complex. Twenty four radial profiles were taken across the crater, spaced 15° apart, from the bottom of the inner crater walls across the rim and further outward to the distance of two crater radii, using 1:100,000 scale topographic maps. An average rim profile was compiled using the individual profiles, to obtain the general trend and avoid local irregularities (Gurov and Yamnichenko 1995).

The complete removal of the ejecta by erosion around the crater, and the absence of any significant vegetation, allowed us to investigate the distribution of the faults in the entire crater area using remote sensing. Although the larger faults are visible on satellite images, only aerial photographs show the complete fault network around the crater. Aerial photographs of the crater area at a scale of 1:30,000, together with field observations, were used to compile a schematic fault map within and around the El'gygytgyn structure to a distance of four crater radii. All faults noted on aerial photographs were transferred onto a topographic map to document the complete fault distribution. The mapping identified long faults, which are probably pre-impact lineaments. Many faults were visited during field work. On the surface the faults are present as trenches up to several meters wide. The fault directions were measured in the field within an area extending to 1.5–2.0 crater radii. Only in a few cases was it possible to determine the displacement of rocks by the faults.

The density of faults versus the distance from the structure center was measured along latitudinal and longitudinal profiles across the crater center. The fault density was determined as a number of faults per km^2. The measurements were made within rectangular areas of 10 km^2 (6.7 × 1.5 km) across each 0.5 crater radius from one to four crater radii. The long sides of the rectangles in each profile were oriented parallel to the crater rim. Faults equal to or greater than 0.5 km length were plotted (Gurov and Gurova 1983).

Particular attention was devoted to the study of lacustrine terraces, as these are the only source of impact rocks in the crater at its current erosional stage. The aerial photographs of the crater area were used to produce a schematic map of the lacustrine terraces. The structure of the terraces and the composition of their deposits were studied in the field.

RESULTS

Crater Rim

El'gygytgyn crater is surrounded by an uplifted rim that shows indications of erosional modification and degradation (Fig. 2). The rim and its slopes are dissected by numerous streams that flow into Lake El'gygytgyn, and which also form the drainage system around the crater. The crater rim is distinctly expressed in the northern and western parts of the structure, where it forms a divide of the river basins of the Polar and Pacific Oceans. The external rim slopes are visible at the northern, western, and southern parts of the structure within an arc of about 300°. In contrast, they are weakly expressed at the eastern and southeastern parts of the structure. Here, the inner walls of the rim are up to 150 m high, sometimes forming rocky exposures of weakly disturbed volcanic rocks, but the rim crest and its outer slopes are not clearly visible. We could not confirm the existence of the proposed Lagerny satellite crater structure (Gushkova et al. 2001; Minyuk et al. 2003).

The Enmivaam River cuts the rim in the southeastern part of the crater, forming a valley about two kilometers wide. The altitude of the water table at Lake El'gygytgyn is 489.5 m, whereas peaks in the crater rim are about 800–900 m, and the highest mountain located on the northwestern part of the rim is 941 m above sea level. The rim of El'gygytgyn crater is dissected by numerous depressions that correspond to faults of predominantly radial orientation. Short creeks dissect the inner walls of the crater. Their lengths range from 3 to 6 km in the western part of the crater and decrease to 1–2 km in the southern and eastern parts. The transverse profiles of the creeks show a V-shape. In the upper parts of the crater rim, the creeks have incised up to about 100 m into the inner crater walls (Fig. 3); on lacustrine terraces these depths are reduced to just a few meters.

In its northeastern part, the rim is of lower elevation at the divide between the lake basin and the upper part of the Otveverghyn River. The elevation of the divide is 50–70 m above the lake level. Remnants of a flat surface covered with pebble deposits occur in the upper reaches of the Otveverghyn River; this is an area in which impact rocks (e.g., impact glass fragments) are preserved outside the crater basin.



Fig. 3. V-shaped valley in the southern part of the crater rim. The valley is 80 to 120 m deep at the deepest parts. The slopes and floor of the valley are composed of volcanic rock debris and do not contain any impact-derived material.

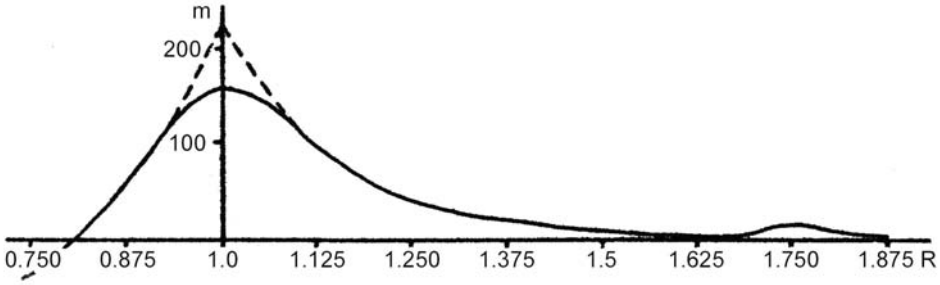


Fig. 4. Averaged morphological profile of the El'gygytgyn crater rim, plotted relative to rim radii (R). The rim has a steep inner wall (left), rounded crest, and a more gentle outer slope (right). A low outer ring structure, about 1/10 of the main rim height, occurs at 1.75 crater radii from the crater center. The inferred initial profile of the rim crest is shown with a dashed line.

The rim of El'gygytgyn crater consists of volcanic rocks and tuffs of predominantly siliceous composition. The rocks of the rim do not contain any evidence of shock metamorphism. Only intensive fracturing and formation of megabreccia occur in some original exposures at the base of the rim in the northeastern part of the structure.

The surface morphology of the crater region is very complex. The combined morphological profile of the present-day crater rim is asymmetric, with steep inner walls and gentle outer slopes (Fig. 4). The average height of the rim crest is 142 m above the lake level. The inner walls of the rim dip towards the center of the structure and disappear underneath high lacustrine terraces at a distance of about 0.75 crater radii from the center. The outer slopes of the rim gradually approach the level of the surrounding area at a distance of about 13 to 14 km, or 1.6 crater radii, from the center of the structure. The height of the rim flanks between 1.625 and 1.125 crater radii show an exponential behavior following the empirical equation:

$$h_r = h_R(R/r)^8 \quad (2)$$

where h_r is the height of the rim at the distance r from the crater center, h_R is the initial height of the rim crest and R is the crater radius. The initial height of the original rim crest was 230 m, according to this relationship. This equation is very close to the empirical equation derived for lunar crater rims with ejecta (Settle and Head 1977), which is characterized by a power index from 3 to 6 according to the variation in distribution and thickness of ejecta layers.

A weakly expressed outer rim, on average 14 m heigh (cf. Gurov and Yamnichenko 1995), is visible in the composite profile of the El'gygytgyn crater rim at a distance of about 1.75 crater radii (Fig. 4). The outer rim is separated from the

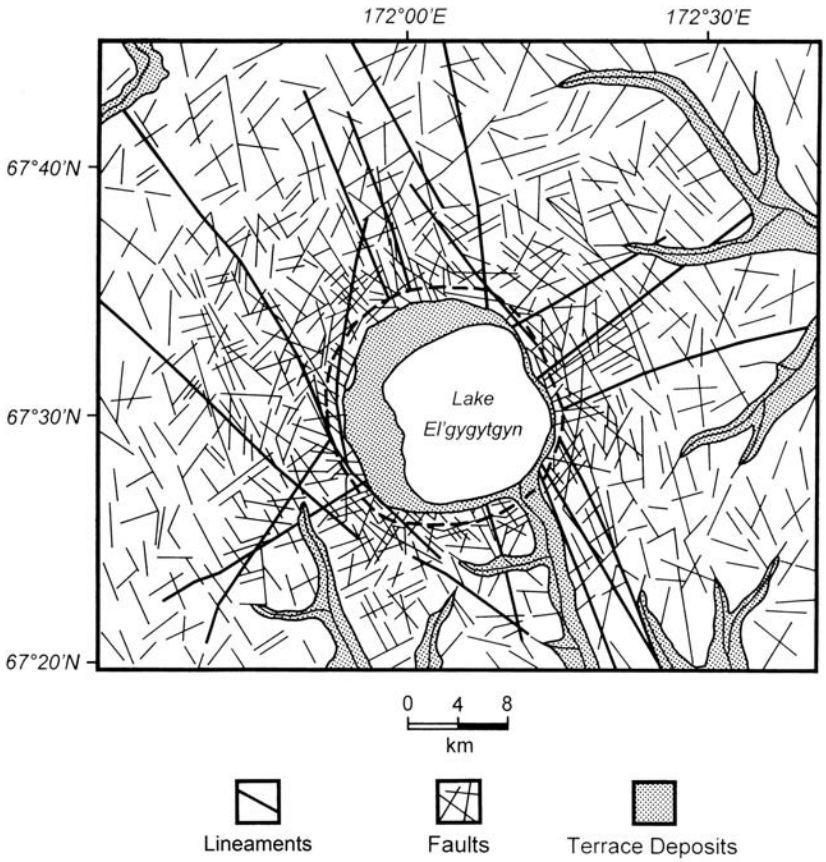


Fig. 5. Faults in the vicinity of El'gygytgyn crater. The main long regional pre-impact lineaments are oriented predominantly NW-SE and NE-SW. The short and irregular faults, which are thought to be related to the impact event, form a complex network around the crater. Arcuate faults that are concentric to the rim are rare in the crater area. The density of the fault system gradually decreases outwards from the crater center.

base of the main rim by a gentle depression at about 1.6–1.7 crater radii from the center; this depression is marked by segments of some streams and river valleys that flow concentric to the crater rim in this section.

Faults

Complex fault systems surround El'gygytgyn crater (Fig. 5). Two main types of faults occur in the crater area: 1) Main extensional lineaments up to a few tens of kilometers in length cross the crater area, mostly with NW-SE and NE-SW orientations. Some lineaments are visible not only on aerial photographs, but also on Landsat images as straight or slightly broken lines. At least some of these long lineaments are regional pre-impact structures. 2) Irregularly oriented short faults (Fig. 5), which vary in length from several hundred meters to 5 km. Straight radial faults predominate around the crater, while arcuate ones rarely occur in the crater area. One of the few arcuate faults is used by the upper flow of the largest stream in the western area of the crater, where it separates the rim into two concentric ranges.

A rose diagram of fault orientations was compiled from 325 measurements of individual fault directions on aerial photographs, supported by measurements of fault orientations during the field investigations (Fig. 6). Three maxima are visible in the diagram: the most abundant at 150–155°, the second at 125–130°, and a third (bimodal) at 50–60°. We suggest that the unequal distribution of fault orientations is a consequence of the pre-impact faults in the area, some of which were rejuvenated during the impact (see, e.g., Casella 1976). The main maximum at 150–155° corresponds to a regional fault system, which later was used by the Enmivaam River to create its valley. The peak at 50–60° is connected with the complex fault system that crosses the crater and separates the southeastern part of the structure composed of dacites and andesites from its larger northwestern part composed of more siliceous volcanic rocks (Gurov and Gurova 1979; Gurov and Koeberl 2004).

Vertical or steeply dipping faults predominate, and more gently dipping faults rarely occur at the inner walls of the crater—for example, where a fault dips against a rhyolite block (about 250 × 150 m laterally and 40 m thick) that occurs

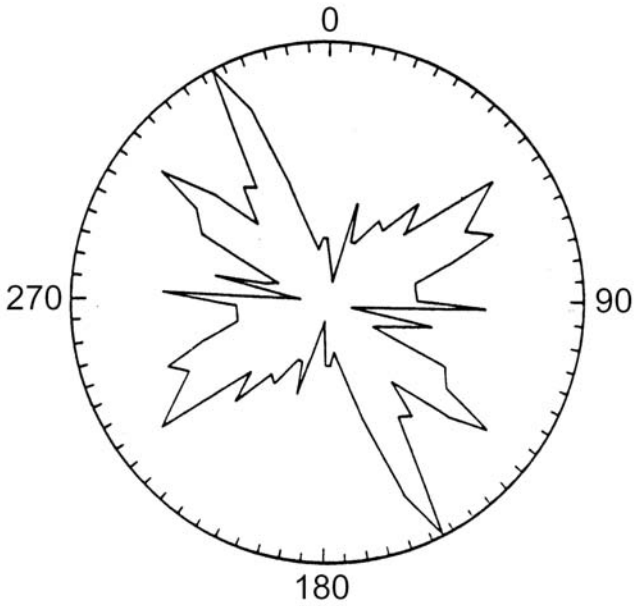


Fig. 6. Rose diagram showing the measured fault orientations around the El'gygytgyn impact crater (325 measurements). Three main maxima are at 150–155°, 125–130°, and 50–60°. We suggest that the unequal distribution of fault orientations is the result of reactivation of pre-impact faults during the impact event.

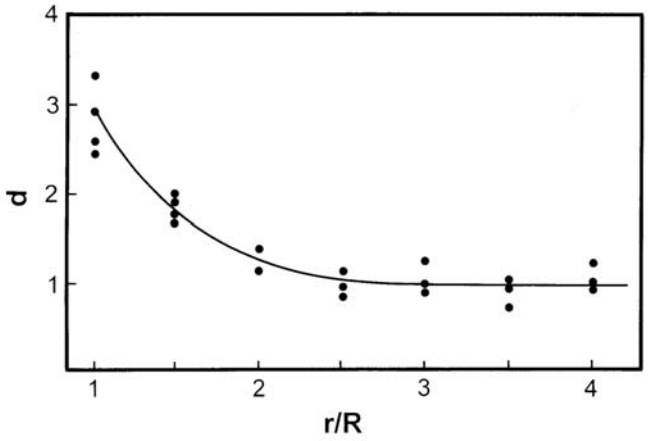


Fig. 7. Relation between fault density d around the El'gygytgyn crater and distance from the rim, where d is number of faults per km^2, R is the crater radius, and r is distance from the center in crater radii. At a distance of about 2.7 radii the density curve reaches the regional level of fault density.

on the surface of ignimbrites on the slope of a 758 m high peak in the northeastern part of the crater. Faults are exposed as trenches up to 3 m deep and to 10 m wide on the surface. The fault zones are composed of unconsolidated detrital material cemented by loose, fine-grained matrix. Rare fragments of weakly brecciated rocks in the fault zones do not contain any evidence of shock metamorphism or hydrothermal alteration. The radial faults were used by the drainage system of the crater basin, forming saddle-shaped depressions at the crater rim and some additional watersheds.

Exposures of target rocks are rare in the crater, so it is difficult to estimate the amplitudes of relative fault displacements of neighboring blocks. The lack in variability of rock types forming the southwestern, western, northwestern, and northern parts of the crater is evidence that there are no significant displacements or overturning of blocks by faults. In rare cases is it possible to estimate the displacement amplitude of neighboring blocks by faults. For example, a 100 m vertical downward displacement of the dacitic tuff layer by two parallel vertical faults was determined in the northern part of the crater rim near the peaks with elevations of 913 m and 844 m height. In some cases dislocations of blocks of volcanic rocks of up to tens of meters in size have been noted in outcrops of the eastern lake shore.

Nevertheless, the bedding in some outcrops at the crater rim shows a complex geological structure, especially at the base of the crater walls. A gradual transition from faulted target rocks of the rim to megabreccia of the rim inner slopes occurs in the northern-northeastern part of the crater. The target rocks at the axial part of the rim are cut by the fault systems and form parallel and subparallel rectangular blocks about 400–700 m long and 150–200 m wide, of which most preserve their initial orientation. On the slopes of the rim only irregular blocks of target rocks occur. Their size varies from tens of meters to 300 m. The compositions of these blocks, which mostly do not show internal brecciation, vary arbitrarily from rhyolites and their tuffs to andesites as well as other volcanic rocks. Blocks of dense and coherent rocks are partly buried within detrital material cemented by weakly consolidated matrix. The surface of the megabreccia zone has a fairly smooth relief, but some blocks protrude by up to several meters above the surrounding area. No shatter cones or microscopic shock metamorphic effects have been observed in the rocks of the megabreccia zone.

The nearest exposure of target rocks to the crater center is located about 8.2 km from the center, at the eastern bank of the lake. Here, dacitic tuffs form cliffs up to 40 m high. The rocks are intensively fractured, but not brecciated. A shock metamorphic overprint has not been observed in the rocks.

The schematic fault map at El'gygytgyn was used to derive their spatial density as a function of distance from the crater center. The density of faults is strongly dependent on the distance from the crater center. Fault density is highest at the inner slopes of the crater rim and gradually decreases outwards from there (Fig. 7). The density of faults at the rim crest is up to 2.9 faults per km^2 and exponentially drops down to 1.1 faults per km^2 at a distance of about 2.7 crater radii, without any further change noticeable at greater distances from the crater center. This means that, at this distance, the fault density reaches the regional background value (cf. Gurov and Gurova 1982). The fault density around El'gygytgyn follows the relationship:

$$d_r = D_R(r/R)^{-2.7} + D_0 \quad (3)$$

where d_r is the density of faults at the distance r from the crater center, D_R is the fault density at the crater rim, R is crater radius and D_0 is the regional pre-impact density of faults.

There are few data about the distribution of faults around terrestrial craters. A similar relative extent of faults was determined for the Deep Bay impact structure, Canada, where the regional values were reached at 2.8 crater radii from the center (Innes 1964). Similar relative fault extent values were obtained by Baldwin (1978), who presented data for 29 lunar impact structures and the lengths of their surrounding faults, but a much wider variation of "border values" was found in his work (Fig. 8).

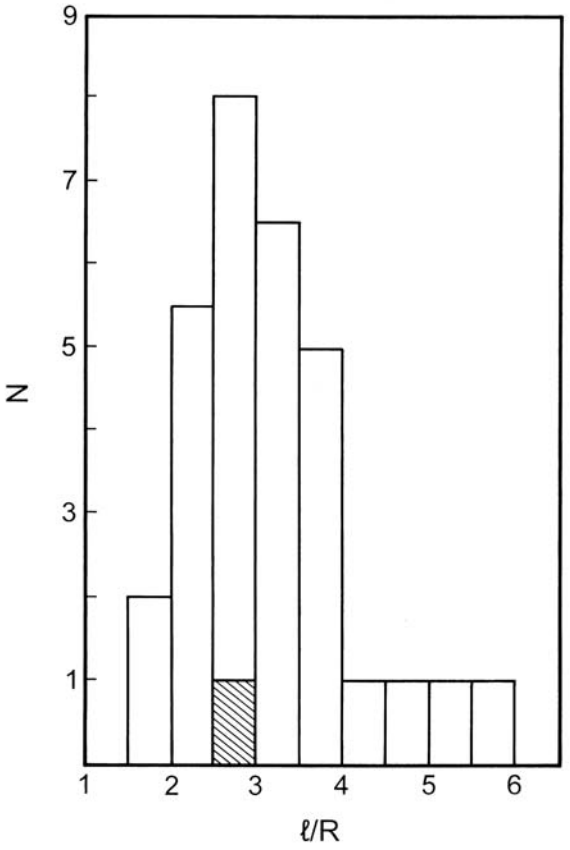


Fig. 8. Relative length of faults around the El'gygytgyn crater (hatched) compared to data for 29 lunar impact craters. Diameters of lunar impact craters and the lengths of surrounding faults are from Baldwin (1978). N is the number of craters, R is the crater radius, and l is the length of the faults.

Lacustrine Terraces

The center of El'gygytgyn crater is occupied by a relatively flat floor about 15 km in diameter, which is mostly filled by Lake El'gygytgyn, about 12 km in diameter, and surrounding terraces. The lake is displaced from the center of the depression towards the east by about 2–3 km. Thus, the lake is surrounded by wide terraces in the western part of the basin, while in the eastern part of the structure the lake shore is very close to the base of the rim (Figs. 9a and 9b).

The lacustrine terraces record previous high stands of the lake. Because of the current erosional status of the rim, with lower-lying breaches, it is likely that the higher terraces were deposited during the early history of the crater lake, whereas the lower ones formed more recently, although no direct dating of the terraces has yet been done and the exact development of the lake's high and low stands will be the subject of the ICDP drilling project. Studies and mapping of the lacustrine terraces received great attention during the field work in 1977–1980, because their deposits represent the only source of impact rocks in the crater at the recent erosional level (Gurov et al. 1978; Gurov and Koeberl 2004).

The highest lacustrine terrace is 80 m above the current lake level and is deeply eroded. Its occurrence and location were first noted on aerial photographs and confirmed by field studies. Terraces of this level are best preserved in the western and southwestern parts of the crater basin, and some isolated occurrences were noted in the southeastern and northeastern areas of the crater (Fig. 9b). These terraces are cut by numerous creeks and are preserved at the creek watersheds. Each terrace fragment is of crescent shape, convex to the crater center. The arcuate terrace contact with the crater slope is evidence of its deposition after the formation of the initial drainage system in the crater basin. The widths of the lacustrine terrace remnants range from 100 to 500 m, and the terrace surfaces are always inclined towards the center of the basin. The terrace cusp is not clearly developed due to intense erosion. Solifluction processes within the crater (Minyuk et al. 2003) caused the inclination of the terrace surface and its partial destruction.

The composition of the lacustrine terrace deposits was studied using material from their surfaces, which often are exposed in the form of polygonal soils, a regular structure produced by permafrost. The 80 m terrace consists of volcanic and impact rock debris. The source of these terrace deposits was not only disturbed rocks of the original rim, but also impact ejecta, comprising impact melt rocks and breccias, impact glasses, and shock-metamorphosed rocks.

Impact melt rocks and impact melt breccias are dark gray or black vesicular rocks with numerous xenoliths of glasses and volcanic rocks, and rare quartz and lechatelierite grains. In thin section, impact melt rocks display fresh glass with gas bubbles and transparent lechatelierite inclusions. Glassy bombs preserve initial aerodynamically shaped forms of drops, dumbbells, cylinders, etc., and consist of fresh shiny glass. Strongly to moderately shocked lavas are dark gray porous rocks of low density, and preserve porphyric structures. Strongly shocked volcanic rocks show, in thin section, vesicular glassy matrix and clasts of quartz and

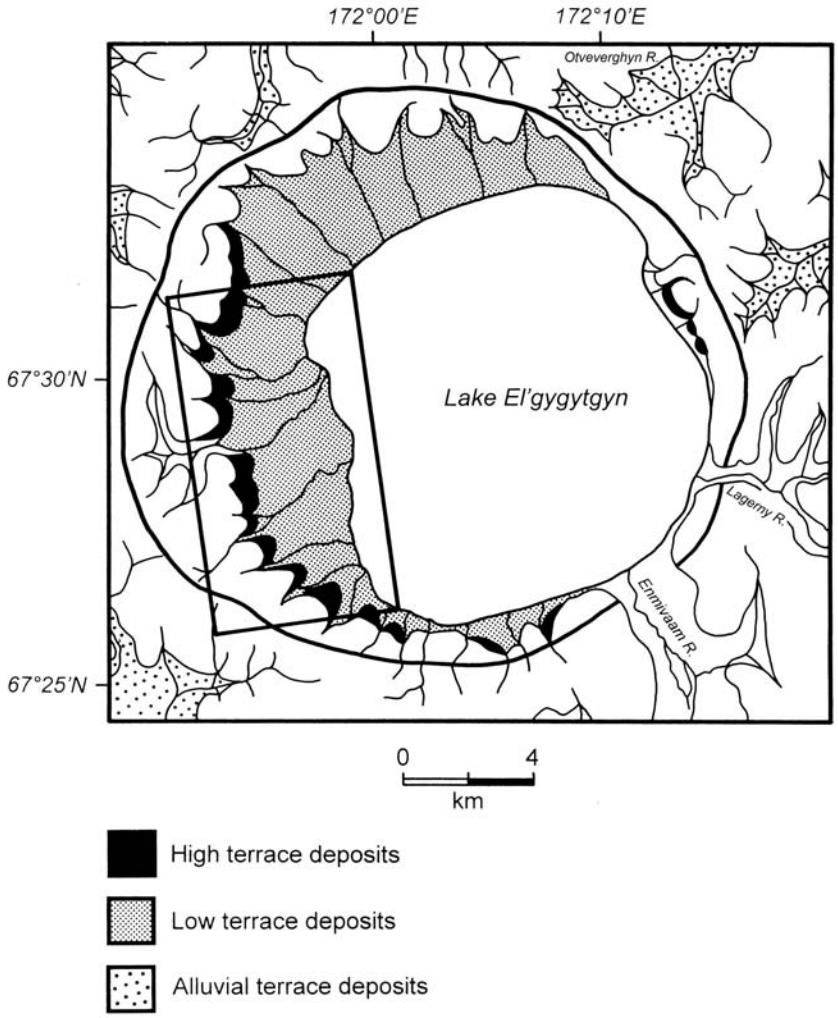


Fig. 9. a) Lacustrine terraces of Lake El'gygytgyn. The predominant occurrence of the "high terraces" (80 m above current lake level) is in the western parts of the crater basin. Only remnants of the 80 and 60 m high terraces are preserved at the foot of the crater wall. The 40 m high terrace also has its maximum extent in the western part of the crater basin. "Low terraces" are those that are 60 m and 40 m above current lake level. Terraces 10 m and lower are not shown in this figure.

feldspars, many of which are converted into diaplectic glasses. The classification of weakly shocked lavas and tuffs and their distinction from unshocked target rocks is only possible using thin sections.

The surficial distribution of rock types on a terrace at the foot of a 723.6 m high peak in the southern part of the crater, which was obtained by counting 1.6 square meters of surface, yielded: 20% (by area) of impact glasses and impact melt rocks, 67% strongly shocked volcanic rocks and tuff, and 13% unshocked and weakly shocked rocks. For comparison, the composition of deposits of the high alluvial terrace of the Chenuv'yiveem River at the outer southwestern slope of the rim is: 40% impact glasses, 23% strongly shocked volcanic rocks and tuffs, and 37% weakly shocked and unshocked rocks.

Nekrasov (1963) described the diatom flora of two soil samples from the surface of the 80 m high lacustrine terrace in the northwestern and northern parts of the crater. The most abundant species is *Stephanodiscus dubius v. ovalis* Seczkina, which was the main inhabitant of the lake (Nekrasov 1963).

Terraces about 60 m above the current lake level are preserved in the southwestern and western parts of the crater basin (Fig. 9a, b). Their remnants are visible in aerial photographs and are usually located just at the bases of the 80 m high terraces. The widths of individual remnants of the 60 m terrace are up to 0.5 km and their lengths reach 2 km. In the northeastern part of the crater rim, at the divide of Lake El'gygytgyn with the Otveverghyn River (upper right in Fig. 9a) and in the upper reaches of that river, flat surfaces about 50–70 m above the lake level are preserved. Partly rounded rock debris and, rarely, pebbles of volcanic rocks and impact glasses occur on the surface of the divide.

Another lacustrine terrace about 40 m above the present-day lake level occupies a considerable part of the crater floor.

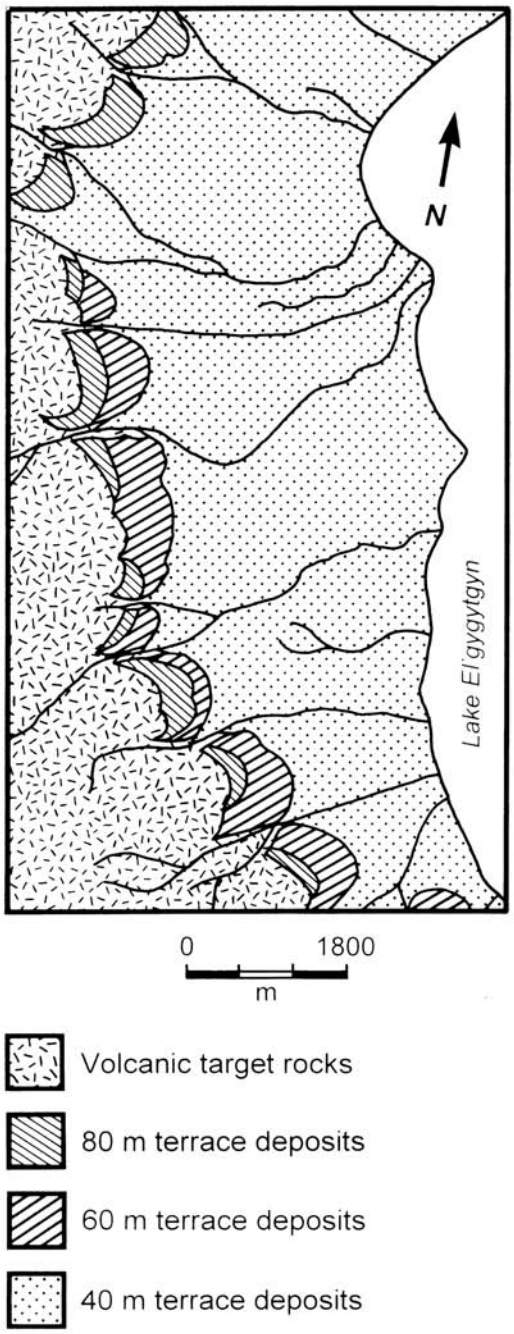


Fig. 9. *Continued.* Lacustrine terraces of Lake El'gygytgyn. b) A close-up of the distribution of the 80, 60, and 40 m high terraces in the western part of the crater rim. Valleys of radial creeks cut the high terraces into isolated crescent-like remnants preserved at the divides between the creeks.

The whole terrace in the crater is arcuate around the lake, and convex in the western direction. Its width is 0.5–1.0 km in the southern and northern parts of the crater area and gradually widens to 3.5 km in its western and northwestern parts. Volcanic rocks and tuffs predominate in the terrace deposits, but an admixture of impact rocks is always present.

Remnants of the local flora were described by Nekrasov (1963) from a shallow well drilled on the surface of a terrace in the southern part of the crater. Pollen of *Picea*, *Betula*, and *Pinus pumila* were found in the upper 25 cm of the core, consisting of loam. It is interesting to note that today the closest pine forests occur several hundred kilometers to the south of the crater area. Samples from the same well, at a depth of 1.5–2.6 m, also contain *Stephanodiscus dubius v. ovalis* Seczkina.

A terrace about 2–6 m above the water level surrounds the entire lake. It is composed of pebbles and partly rounded detrital material of target rocks derived from the crater rim and its inner slopes, including rhyolitic and dacitic ignimbrites, lavas, and tuffs, and rarely andesites and andesitic tuffs. Some rare pebbles of impact melt rocks, impact glasses, and shock metamorphosed rocks occur predominantly in the western parts of the terrace. The deposits within the higher lacustrine terraces are the source of the impact rocks in the recent, low terrace.

Some stone tools were found on the surface of the low terrace in the southeastern part of the basin. The tools include darts, arrowheads, and scrapers (Fig. 10), which were made from obsidian, silicified rock, jasper, chalcedony, and some other rock types that do not occur in the crater, but which were brought in from other regions. For example, the nearest known occurrence of obsidian is situated at the low flow of the Anadyr River, about 600 km from El'gygytgyn crater. One sample (Fig. 10, no. 1) represents the unsuccessful attempt to product the tip of a dart from black impact glass. The sample weight is 40.5 g and its dimensions are 52 × 35 × 29 mm. Perhaps this material was unsuitable for processing due to the internal stress within the originally superheated and quenched impact melt. Nekrasov (1958) was the first to mention stone tools in the El'gygytgyn crater basin. According to Okladnikov (cited by Nekrasov 1958), the tools are of Neolithic age.

SUMMARY AND CONCLUSIONS

Despite some erosional degradation of the crater rim and removal of impact ejecta from the surface, the 3.6 Myr El'gygytgyn crater is one of best preserved impact craters of this age on Earth. Its location in a mountainous region of the high Arctic, and the absence of any significant vegetation, are favorable conditions for study of its structure and morphology. Most of the flat crater floor, about 15 km in diameter, is occupied by Lake El'gygytgyn and its lacustrine terraces. The crater is surrounded by a rim 18 km in diameter that reaches elevations of about 100–200 m above the floor of the basin.

The original rim is well expressed over a sector of about 220°, or almost two thirds of its full circumference, in the southern, western, and northern parts of the structure, but is not well preserved in the southeastern sector. We could not confirm the existence of the proposed (Glushkova et al. 2001;



Fig. 10. Stone tools from the 6 m high terrace at the mouth of the Lagerny River in the southeastern part of the El'gygytgyn crater. The tools were found together with tool fragments and small chips of used rock. Materials of the tools: 1: impact glass; 2–5: silicified rock; 6, 8: jasper; 7: obsidian; 9: chalcedony.

Minyuk et al. 2003), 6 km in diameter Lagerny "satellite crater."

The averaged morphological profile of the crater rim shows an asymmetry, with steep inner walls and more gentle outer flanks. The calculated mean height of the rim above the surrounding plains is 142 m. The height of the original rim flank shows an exponential slope close to the empirical equation of Settle and Head (1977) for lunar craters. However, the original rim height of El'gygytgyn crater was calculated to be 230 m, in contrast to an expected rim height of 747 m for an 18 km diameter lunar crater, following the empirical equation of Pike (1977).

The averaged profile also shows the presence of a low, concentric outer rim at a distance of about 1.7 crater radii from the crater center. The height of this feature is up to 14 m, or about one tenth of the height of the main rim. Similar concentric features were described around some relatively recent terrestrial impact craters of more than 10 km in diameter, including Ries (Johnson et al. 1964), Bosumtwi (Wagner et al. 2002), and BP (Koeberl et al. 2005). Several explanations were proposed for the origin of these outer ring features (Wagner et al. 2002; Koeberl et al. 2005), but their formation mechanism—and if they are primary or secondary features—is not yet understood. More such features need to be studied to be able to generalize their characteristics and to try and reproduce them by numerical modeling.

El'gygytgyn crater is surrounded by a complex system of faults. The highest density of faults occurs at the base of the crater inner walls, where a transition from faulted rocks to megabreccias sometimes was observed. Low-amplitude, steeply dipping faults predominate in the crater target, and did not cause considerable displacements of neighboring blocks. The lack of variation in the rock types forming the southwester, western, northwestern, and northern areas of the crater target indicates that there are no significant fault-related displacements and overturning of blocks. The areal fault density decreases outwards from the crater center to a distance of about 2.7 crater radii, where it seems to reach the regional background value. A similar relative extent of faults was determined earlier for the Deep Bay impact structure (Innes 1964) and for some lunar craters with a wide range of crater radii (Baldwin 1978).

A variety of lacustrine terraces, which record past lake level high stands, surrounds Lake El'gygytgyn. Lake El'gygytgyn is off-center from the depression towards the eastern part of the crater rim. Thus, the terraces are asymmetrically arranged relative to the lake, having their maximum extent in the western and southwestern areas of the crater. El'gygytgyn crater was formed at the central part and on the southeastern slopes of Academician Obruchev Ridge. Thus, the heights of the surrounding areas of the northwestern and western parts of the crater are about 150–250 m higher in comparison with southeastern parts at the foot of the ridge. Gebhardt et al. (2006) noted that "erosion seems to be much higher in the northwestern part of the crater, causing large areas to be filled with coarse sediments, and consequently the

lake is not located in the center of crater." Another reason for the crater asymmetry is a possible more recent tilting of the crater area.

Lacustrine terraces that are about 80 and 60 m above the current lake level are preserved within the inner slopes of the crater rim. The higher terraces are deeply eroded and cut by numerous creeks flowing into the lake. Terrace remnants occur mainly in the western and southwestern parts of the crater, whereas only a few isolated patches are preserved in its southern and northeastern areas. The high terrace deposits are composed of angular detrital material cemented by sandy, fine-grained loam and sand. Detrital deposits consist of impact rocks and unshocked target rocks.

Diatoms within the lacustrine deposits were described by Nekrasov (1963) on the surface of the highest terrace. Taking into account the recent depth of Lake El'gygytgyn (up to 170 m in the center), a thickness of post-impact sediments of 360–420 m (Gebhardt et al. 2006), and an elevation of lacustrine terraces of up to 80 m above the current lake level, the initial crater depth can be estimated to have been about 650 m. The height of the 60 m terrace is equal to the height of a flat surface at the watershed of the crater basin and the Otveverghyn River valley. Thus, it is concluded that the earliest drainage of the lake occurred into the Otveverghyn Basin. Lacustrine terrace about 40 m high surrounds almost the entire lake, but its maximum width is in the southwestern and western sector of the crater basin. A more recent terrace, located 2–6 m above water level, is found all along the lake shore. The future ICDP drilling project will recover the first impact breccias and melt rocks from near the central uplift of El'gygytgyn, providing the first opportunity to conduct a shock barometry study in shocked volcanic rocks.

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