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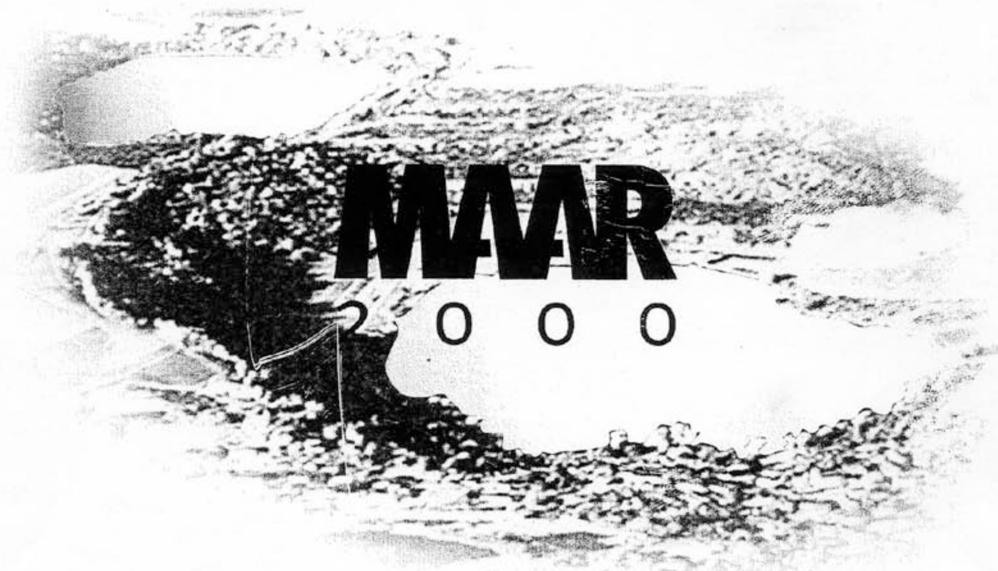

MAIN TOPICS

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- Formation of Maar Volcanoes
- Maar Lake Sediments
- Paleontology of Maar Lake Sediments
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Formation of partially submerged tuff ring during the 1996 sublacustrine surtseyan eruption in Karymskoye lake, Kamchatka, Russia

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The 1996 eruption was the third basaltic phreatomagmatic eruption of Holocene age in Academiya Nauk caldera, in which Karymskoye lake is located (Belousov et al., 1997). The repose period before the 1996 eruption comprised approximately 4800 ^{14}C years. The feeder dyke of the 1996 eruption intruded along a major NNE fault, as has occurred here during previous eruption of basic magma (Fig. 1).

Course of the 1996 eruption

The eruption in Karymskoye lake started 2.01.96 at approximately 13^{00} LT after a short seismic swarm (Fedotov, 1998; Belousov and Belousova, 2000). The only observation of the eruptive processes in the lake was made during an overflight at 15^{20}-16^{20} LT. By the time of the overflight, the ice cover of the lake had melted, and an eruption of Surtseyan type was in progress from a vent ~400 m off the northern shore. Initial water depth above the vent is estimated as ~50 m. Underwater explosions occurred every 4-12 min; in total about 6 explosions were observed with an average interval of 6 min. Cock's tail outbursts of water- gas-pyroclastic mixtures occurred to heights up to 1 km, with initial velocities of 110 m/s. The eruption slugs collapsed back into the lake producing base surges (run out up to 1.3 km; average velocity 12.5 m/s). The eruptive cloud rose to a convective height of 3 km. Tsunamis, generated by underwater explosions, periodically forced water from the lake into the canyon of Karymskaya river, forming pulsing lahars (Belousov et al., 2000).
The total duration of the eruption is estimated as 10 - 20 hours. Taking the average observed interval between the explosions as 6 min, we estimate that 100-200 explosions in all occurred in the lake.

Morphology of the 1996 tuff ring

As a result of the eruption, at the place of underwater explosions, a tuff ring emerged from the lake water. Northern parts of the tuff ring and most of its crater rim are subaerial, but the crater itself and the southern ring slopes are under water. The highest parts of the ring lie only several metres above the level of the lake. The crater is 650 m across and 60 m deep with inner slopes dipping up to 12°. The outer, southern slope of the tuff ring gently dips outward (up to 10°), but the northern slope, which overlaps the pre-eruptive shoreline, is horizontal or even inclined inward towards the crater. The northern, outer edge of the tuff ring is bounded by the steep wall of the Akademii Nauk caldera, where no deposition occurred (only strong erosion of poorly consolidated bedrock). Further northward from the crater, beyond the eroded caldera wall, deposition of tephra occurred, but the character of the deposit (which we refer as a distal base surge deposit) is different from the tuff ring deposit. The radius of the base of the tuff ring is about 0.8 km. Maximum height of the edifice is estimated at 40 -50 m.

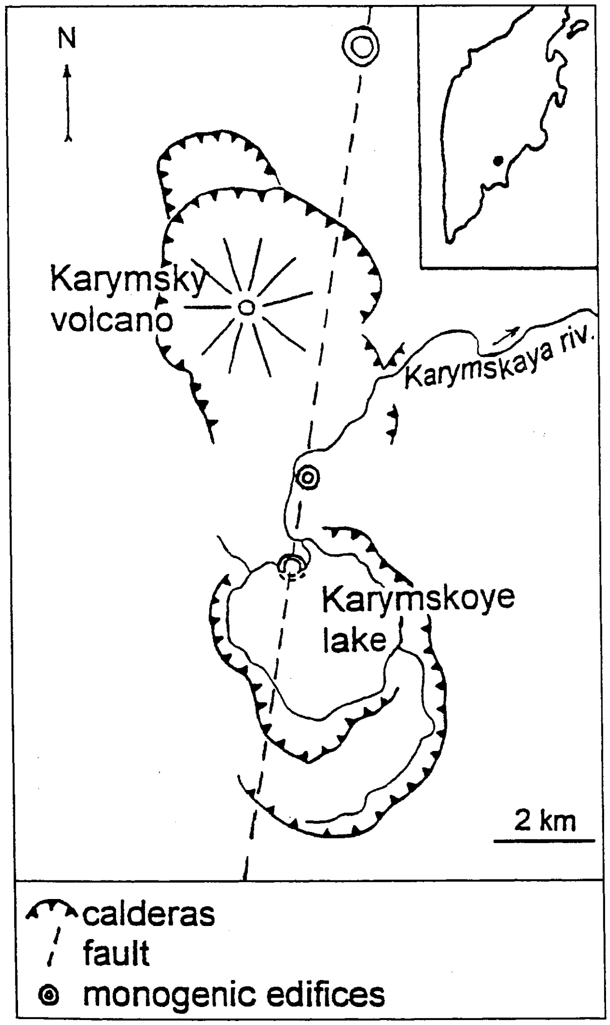

Fig. 1: Location of Karymskoye caldera lake and Karymsky volcano, with inset showing their location on Kamchatka peninsula. Figures are redrawn with changes after Belousov and Belousova, in press.

based on pre-eruptive bathymetry. Bottom of the crater of the edifice lies close to the pre-eruptive surface. The ratio of the height to the basal diameter of the ring is about 0.03. The volume of the edifice was roughly calculated as 0.047 km^3.

Stratigraphy of the 1996 deposits
Four types of ejecta were found: 1) proximal thick ash lapilli beds comprising the tuff ring, 2) distal base surge deposits, 3) deposits of distal co-surge fallout, 4) fields of bedrock blocks and juvenile bombs (ballistics) (Fig. 2)

Tuff ring deposits
In the proximal outcrops the exposed upper 4 m of the tuff ring is regularly medium- to thick-bedded (10-60 cm), dark-grey, fines poor, grain-supported, basaltic ash lapilli and lapilli ash.

The large lapilli are mostly irregular in shape and are angular to subrounded. No sag structures have been found under even the largest clasts. Dip of the beds is very gentle; in outcrop they appear subhorizontal. Bed boundaries are usually diffuse, and beds are planar and continuous. No erosional discordances have been found. The beds exhibit normal, reverse, or reverse-to-normal grading.

Grain-size histograms of the deposits are commonly unimodal with the modes lying in the area of coarse ash (Fig. 3). A very low content of fines is typical of the deposits. In the uppermost parts of the sections, where the deposits become notably coarser, histograms usually have an additional lapilli mode. The deposits are moderately to poorly sorted (Figs. 4, 5). The material was deposited somewhere near the water/air interface. Probably deeper, unexposed layers of the tuff ring can differ to some extent due to deposition in a subaquatic environment.

Each bed of the tuff ring is believed to represent the deposit of a single explosion. Taking nominal deposit thickness to be 50 m, and average proximal bed thickness to be 25 cm, it can be estimated that 200 explosions occurred, averaging about $2x10^5$ m^3 of tephra per explosion. This coincides with the previous estimation (100-200 explosions), based on total duration of the eruption and average interval between explosions, and thus seems reasonable.

The deposit in the most distal outcrop is different from that described above. It has smaller median diameter and better sorting. The deposit is mostly ash with discontinuous trains of coarse lapilli. Unlike the proximal deposit, this deposit lacks well-developed parallel bedding. Instead it has low-angle, ill- defined layering with notable lateral grain-size variations. Laterally the deposit transforms into deposit of distal base surges.

The characteristics of the tuff ring deposit are not entirely consistent with any depositional process previously known to form tuff rings. We suggest that the studied tuff ring deposit was formed by multiple (periodic) flows of hyperconcentrated water-pyroclastic mixture, which moved radially from the crater (Smith, 1986). The absence of scour and channelling indicates that the flows were depositional and unconfined. It is likely that the flows had different concentration of solid particles; the more diluted flows left normally graded layers, whereas the most concentrated flows show reverse grading formed by basal shear and grain- dispersive forces. Origin of the flows is is attributed to very wet base surges of the eruption. We suggest that the flows existed as peculiar water-pyroclastic underflows in the basal parts of the surges. Probably flows of similar origin were witnessed during some explosions of Surtsey (Thorarinsson, 1964, p. 43): “explosions were often followed by greyish-white cloud avalanches which rolled over the crater rims and after the island had grown to some appreciable height, they sometime spread a few hundred metres out over the sea. Sometimes the explosion ejected so much sea water over the crater rims that *mud streams* ran all the way down to the beach.”

Surface layer of the tuff ring. The surface layer of the tuff ring quite different from the deposits that comprise the upper (studied) part of the tuff ring. The layer is approximately 1 m thick and strongly enriched by coarse lapilli and basaltic bombs up to 1 m across, which were ejected at the end of the eruption. The “Ballistics” section describes the bombs in greater detail.

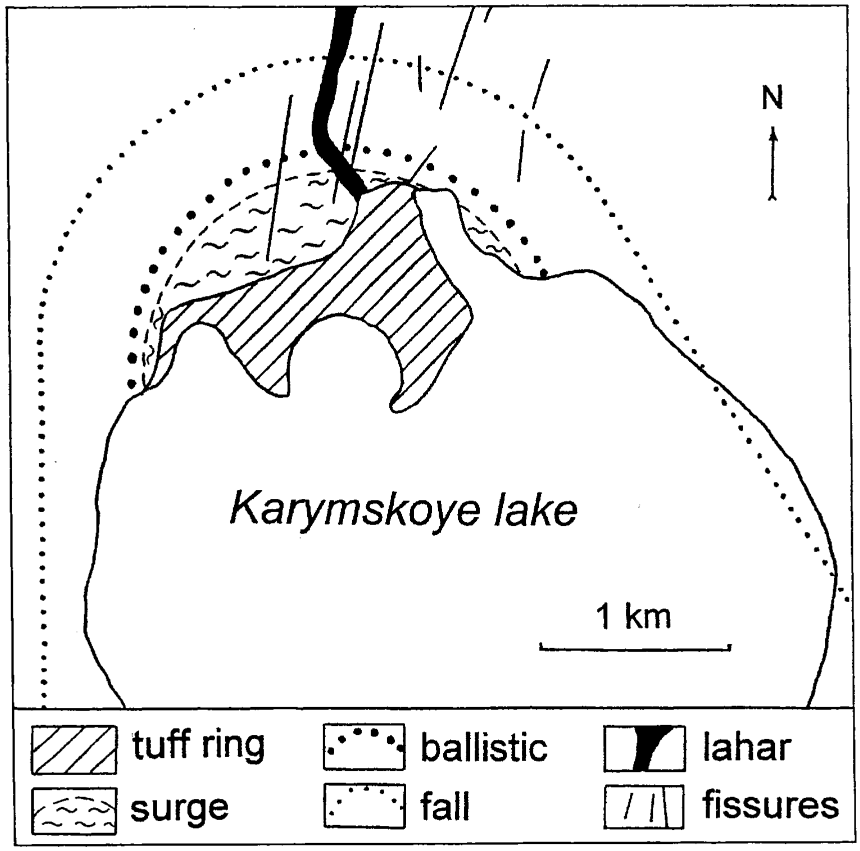

Fig. 2: Sketch map of deposits of the 1996 eruption. Deposits of tsunamis are not shown.

Surface of the tuff ring has large-scale ripples in several places. The ripples are very gentle, almost flat, dune-like patches of coarse lapilli and bombs. The dunes with wavelength 4-6 m are elongate in the direction parallel to the crater rim. The ripples were likely formed by tsunami waves caused by underwater volcanic explosions. The waves redistributed coarse-grained clasts on the surface of the ring.
The underwater surface of the tuff ring is mantled by a layer of pale-grey fine vitric ash (Md 6.7ϕ; sorting 1.5 ϕ) up to 30 cm thick. This layer represents the most fine-grained pyroclastic products of the eruption, and it is inferred that when the eruption ceased, this material, along with fines eroded from the shores by the tsunami waves, slowly settled in the lake to form the fine ash layer.

Distal deposits of base surges In the distal zone the surges generated by the eruption attacked the steep northern shore of the lake. They sandblasted bushes as far as 1-1.3 km from the vent (Fig. 2). As marked by damage to bushes, the surges climbed gradients of up to 40° on the caldera wall. The highest elevation reached by the surges is about 150 m above the level of the lake. Most of the damaged branches showed no signs of scorcing, but a few were slightly browned.

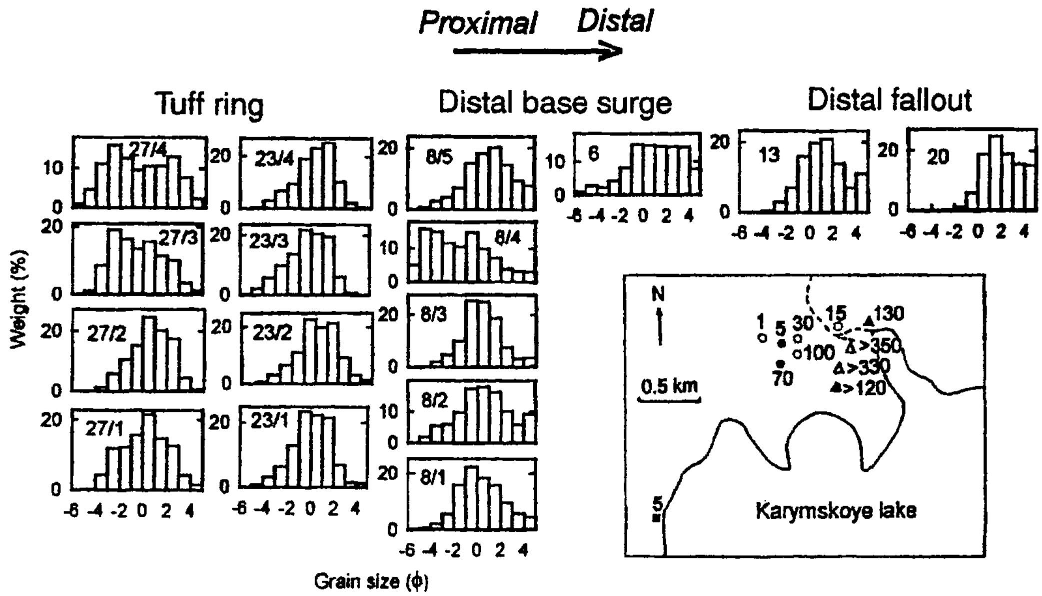

Fig. 3: Examples of grain-size histograms for the 1996 tuff ring, distal base surge and co-surge fallout deposits at different distances from the crater. Numbers on histograms: field number of site/number of layer (from bottom to top). Sketch map insert shows sampling sites: triangles - tuff ring, circles - distal base surge, square -co-surge fall. Filled symbols - sites for histograms shown on this figure. Distal fall is located on opposite shore of Karymskoye lake and is not shown. Numbers on the map show thickness of deposits in cm.

Hence we estimate the temperature of the surges to be less than 200°C. Pyroclastic deposits in the area of damaged bushes are notably different from the deposits of the tuff ring. Distal deposits of the surges are moderately sorted dark-grey basaltic lapilli ash with abundant fines (Figs. 3 - 5). The deposit comprises a sequence of 2-3 major, grain-supported parallel beds, each 10-35 cm thick, and several minor ones, each less than 1 cm thick. Bed boundaries are usually well defined. The beds are massive or with poorly developed planar or low-angle undulatory lamination. The lowermost layer of the deposits in places contains uncharred fragments of plants, but in upper sections these are rare. Grain-size of the deposit is commonly unimodal (between -1 ϕ and 2 ϕ), sometimes with an additional poorly developed fine grained mode (>4 ϕ). The maximum total thickness of the deposit is 1 m, but this very quickly decreases both on steep slopes and with distance from the crater. The area covered by the surge deposit onshore is 0.4 km^2 and its volume is about 10^3 m^3. Laterally the base surge deposits transform into deposits of distal co-surge fallout.
The surge effects and deposits show that the base surges were relatively weak, cold, and non-erosive in distal; area. Pyroclastic particles from the surges were deposited “grain-by-grain” with little or no traction before deposition.

Distal co-surge fallout. The fall deposit extends from the 1996 tuff ring to the SE (Fig. 2). The maximum thickness of the co-surge fall deposit onshore is 5 cm at the place where the base surge deposit transforms into the fall deposit. The transformation is marked by a disappearance

of both internal laminations, characteristic of the surge deposit, and damage to bushes. The thickness o the fallout deposit declines rapidly with distance: on the southern shore of the lake it is only 1cm thick. The approximate volume of the fall deposit is 0.001 km^3.
The fall deposit is massive, moderately sorted medium-coarse ash with a small admixture of fine ash and lapilli (Figs. 3 - 5). Close to the vent, grain-size characteristics of the deposit are similar to those of the most fine-grained surge deposits. Further from the source, the fall deposit becomes finer grained and better sorted.
The lateral transition of the surge deposit into the fallout, the similarity of grain-size distributions of the fall and the most fine-grained surges, and observations of the eruption all suggest that convectively buoyant clouds of decelerated surges were the main source of the fall deposit. The carrying capacity of such clouds was very low, which explains the small volume of the resulting co-surge fallout.

Ballistics
We estimate the volume of ballistic material to be less than 2 % of the total erupted volume. The most distal ballistics fell 1.3 km from the centre of the 1996 crater (about 1 km from the crater rim) (Fig. 2). We distinguish three types of ballistic material: bombs of juvenile basalt (dominant); blocks of hydrothermally altered breccia (abundant); and bombs of remelted old rhyolite (very few).
Bombs of juvenile basalt constitute ~90 % of all ballistics. They densely cover a significant part of the surface of the tuff ring and loosely scattered beyond its limits. In sections of the tuff ring, bombs are absent, suggesting that they were ejected only at the end of the eruption. The bombs have irregular, but approximately equidimensional shapes. Most have a scoriaceous outer layer several cm thick, whereas their interior is commonly poorly vesiculated, sometimes with inclusions of cm-sized xenoliths of country rocks. This peculiar structure, the presence of xenoliths of country rocks in the bombs, and deposition at the end of the eruption, suggest that the bombs represent solidified magma from the conduit wall, which was ripped off and enveloped by fresh magma. We propose to call this peculiar type of bombs as "scoria crust bombs".
The diameter of the basaltic bombs ranges from 10 to 60 cm, with a few up to 1 m. The largest bombs occur at intermediate distances from the vent. This distribution may not be original, because most bombs in the proximal area (on the surface of the tuff ring) are inferred to have been redistributed and broken by the tsunami waves. Thus the basaltic bombs may have originally decreased in size with distance from the vent.
Blocks of hydrothermally altered breccia constitute ~10 % of all ballistics. The diameter of these blocks typically ranges from 10 cm to 2 m, with a few up to 3 m. The largest blocks were ejected to a maximum distance of 1.3 km, where they produced impact craters up to 4 m wide and 2 m deep. The blocks probably represent a tectonic breccia of the NNE fault along which the feeding dyke of the eruption was intruded. Stratigraphic relationships with other deposits of the eruption, as well as the fact that the blocks show no signs of contact with basaltic melt, suggest that these blocks were ejected by the first, vent-clearing explosion(s) of the eruption
Several exotic bombs, up to 2 m across, of pumice-like remelted old rhyolite contained in and/or mixed with juvenile basalt also occur.

Composition, vesicuiarity and morphology of juvenile clasts. More than 95 % of the ejected material is juvenile calc-alkaline basalt (52-

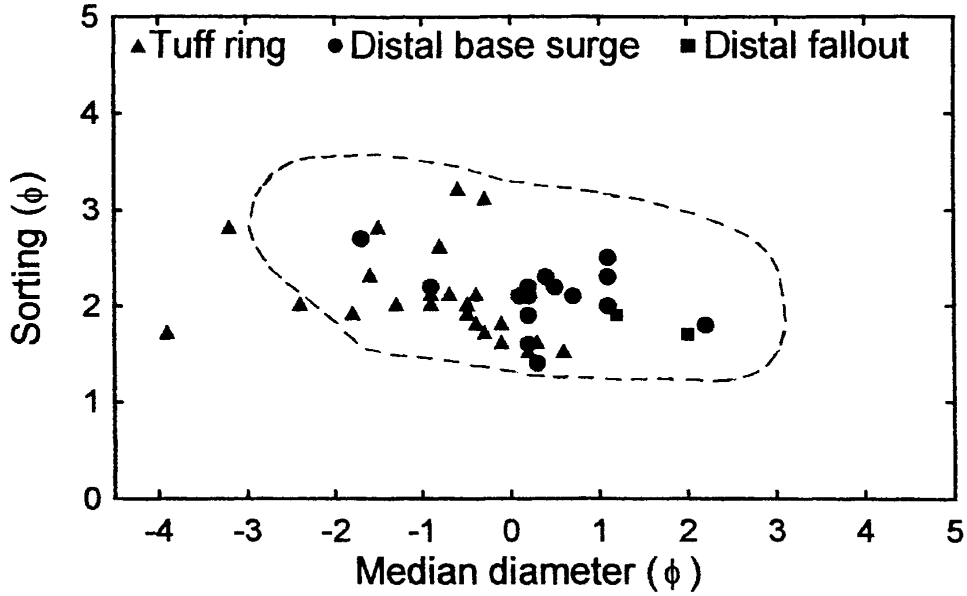

Fig. 4: Relationship between sorting and median diameter (Inman coefficients) for the deposits of the 1996 eruptions. Dashed line is "Surtseyan" field after Walker and Croasdale (1972).

53 % $Si0_2$). The deposits have vesicu- larity indices of 7 % - 63 % (mean 34 %). This range is appreciable larger than in most strombolian deposits (Houghton and Wilson, 1989), thus indicating fragmentation of a variably vesiculated magma rather than wholly "magmatic" fragmentation simply by bursting of bubbles.

SEM images of sand-sized particles of juvenile basalt display different clast shapes and degrees of vesiculation. The surfaces of poorly vesiculated clasts have peculiar chip-marks, and some are intersected by thin, curved cracks. The character of these surfaces shows that the vesiculated glass was brittle during fragmentation. Highly vesiculated particles have multiple, irregular vesicles of different sizes, which are separated by thin walls. The walls are frequently broken and the vesicles are interconnected. Overall shape of such particles is scoriaceous, determined mostly by processes of vesiculation of magma.

The above surface morphology of the 1996 juvenile particles is typical of products of phreatomagmatic basaltic eruptions, in which fragmentation of liquid magma occurs as a result of a complex interplay between vesiculation and water-magma interaction (Heiken and Wohletz, 1986).

Interpretation of the 1996 eruption processes

Initial explosion(s)

The pre-eruption seismic swarm was associated with intrusion of a basaltic dyke along the fault zone, which is, marked by hydrothermally altered breccia. A wave of elevated pore pressure propagated through the country rock ahead of the intruding dyke (Elsworth and Voight, 1992).

As the dyke approached the ground surface, opening of an eruption fissure initially allowed rapid decompression of the country rocks in which pore sure was elevated. This caused decompression-fragmentation of the country rock along the fissure. The resulting fragments have been transported upward by a gas stream emanating from the fissure, which probably originated from both boiling of decompressed hydrothermal fluids and upward migration of magmatic volatiles from the degassing, ascending dyke. The combination of the above events led to the first phreatic, vent-clearing explosion(s) of the eruption; no fresh magma was involved. Fragments of country rock probably were carried out from relatively deep levels of the fissure, having been accelerated to large velocities; the largest fragments were ejected the largest distances (e. g. Self et al., 1980).
The phreatic explosion penetrated ca. 50 m of water and a 1m of thick ice sheet on the surface of the lake. The removal of rock fragments by this explosion widened the fissure, making a channel through which the following eruption of basaltic magma occurred.

Main stage of the eruption. The character of the basaltic eruption was directly linked to the fact that the gas-charged magma, with an average discharge ~ 10^6 kg/s had found its way to the ground surface under Karymskoye lake. The main part of the 1996 eruption consisted of a series of approximately 100-200 Surtseyan explosions. Although the magnitude of the explosions varied, they probably had similar mechanism and we will consider here a model for only one explosion “cycle”, or burst.

Fragmentation of magma. Between explosions, the crater of the tuff ring was filled with water, and the conduit throat was clogged by a mixture of water and pyroclasts left from the previous explosion burst. Basaltic magma lay deeper in the conduit where there were no significant water/melt interactions; if such interactions had occurred, fragments of country rocks would be abundant in the deposit (Fisher and Schmincke, 1984), which is not the case.
During each explosion, the process of magma fragmentation can be imagined in two stages. The first is mostly magmatic: rapid growth and ascent of bubbles pushing out a portion of vesiculated and partially fragmented magma in the upper part of the vent; this resembles the early stage of Strombolian outburst. The second stage is mostly hydrovolcanic. It occurs when the products of the first stage are injecting into the water-pyroclastic mixture filling the vent and crater. Contact with water led to additional fragmentation of magma. As a result, the shape of the pyroclastic particles displays features of magmatic fragmentation overprinted by features of hydrovolcanic fragmentation.

Ejection and deposition. At the start of an eruption burst, explosive expansion of gas-pyroclastic mixture exiting the vent pushed out and bulged the water and water-pyroclastic slurry clogging the crater upward. After several seconds a gas-pyroclastic mixture penetrated the upper part of the bulge and ejected the mixture into the atmosphere as a cock’s tail explosion. Ejection of pyroclasts through the layer of water led to their intermixing. The resulting explosion fountain was relatively cool, had a high content of water and steam, and was too heavy to rise buoyantly and form a sustained eruptive plume. Thus it began to descend down towards the lake surface as an overloaded vertical eruption column collapsing under gravity. The descending mixture formed a very wet base surge in which droplets of water, as well as pyroclasts, were a major component. We propose to call the flowing mixture a base surge but wish to add the modifier "water-rich" in order to distinguish it from a more dry, conventional gas-pyroclastic base surges. Water-rich base surge can be considered to be the end member of wet base surges. While the surge propagated radially from the crater, it has become density stratified due to gravitational settling of pyroclasts and droplets of water (Fisher, 1990). We suggest that this process led to formation of a distinct underflow at the base of the surge. In this underflow water was the continuous phase in which pyroclastic particles and gas bubbles were suspended. Thus, the upper gas-pyroclastic surge was a transport system, which contributed material to the lower water-pyroclastic underflow, which was the depositional system. Deposition from the underflow was similar to deposition from hyperconcentrated flood flow (Smith, 1986).

Both surges and the underflows moved subaerially along the surface of the tuff ring. Where the surges began to climb the caldera wall, the water-pyroclastic underflow decelerated first and began to flow back downslope (topographic blocking of Fisher, 1990), eroding the steep slope of the caldera and depositing backwash material near the base of the wall (not described here). Due to topographic blocking, the densest and wettest lower part of the surge was separated from the upper, relatively dry part of the base surge, which propagated further, leaving distal base- surge deposits. The surge propagated until it lost most of its pyroclastic load, became lighter than the surrounding air, and then lifted buoyantly.

The above situation occurred only near the end of the eruption, when the upper part of the tuff ring had emerged from the lake. Prior to emergence of the ring, collapse of the eruptive column created surges that moved along the water surface. The behavior of the water-pyroclastic underflow in this situation is unclear. The density of the surge underflow is expected to have been higher than that of water, so it probably sank down and then propagated subaqueously along the surface of the tuff ring as a sediment-gravity flow (White, 1996).

After each explosion, a part of the pyroclastic material fell back down into the crater and was temporary stored there until the next explosion remobilized it. Some part of the material may have experienced several expulsions and collapses before its final ejection out of the crater. Such recycling resulted in rounding of pyroclasts. Additional rounding may have occurred during transportation of clasts by turbulent surges.

Near the end of the eruption we infer that magma ascent rate declined and the feeder dyke began to freeze. The walls of the dyke were covered by a thick layer of partially solidified melt, and a waning stream of fresh magma detached clots of this semisolid material (sometimes enclosing fragments of country rock) and transported them upward. Most of the erupting magma near the end of the eruption may have represented such clots covered only by a thin layer of freshly arrived melt. The final explosions of the eruption ejected more and more of these clots, which led to an abrupt increase in the abundance of coarse-grained material in the uppermost layers of the tuff ring, and to the deposition of peculiar scoria crust bombs. The basaltic bombs decrease in size and abundance with distance from the crater and their source during the final explosions was probably shallow (e. g. Self et al. 1980).

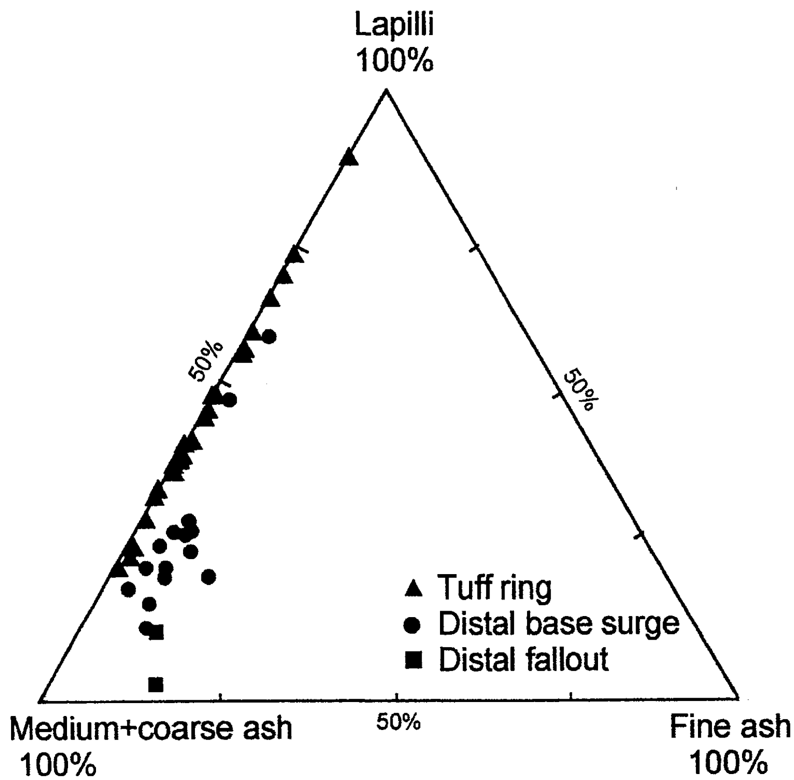

Fig. 5: Percentage of lapilli (>2 mm), medium + coarse ash (0.063 - 2 mm) and fine ash (<0.063 mm) in the pyroclastic deposits of the 1996 eruptions.

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