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MOST RECENT FALL DEPOSITS OF KSUDACH VOLCANO, KAMCHATKA, RUSSIA

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Abstract. Three of four Plinian eruptions from Ksudach Volcano are among the four largest explosive eruptions in southern Kamchatka during the past 2000 years. The earliest of the eruptions was voluminous and was accompanied by an ignimbrite and the fifth and most recent caldera collapse event at Ksudach. The isopach pattern is consistent with a column height of 23 km. The three more recent and smaller eruptions were from the Shtyubel' Cone, within the fifth caldera. Using isopach and grain size isopleth patterns, column heights ranged from ≥ 10 to 22 km. Although the oldest eruption may have produced a large acidity peak in the Greenland ice, the three Shtyubel' events may not be related to major acid deposition. Thus it is possible that few if any of the uncorrelated acidity peaks of the past 2000 years in Greenland ice cores result from eruptions in southern Kamchatka.

Introduction

Ksudach volcano lies 150 km south-southwest of Petropavlovsk, Kamchatka, Russia (Figure 1), and consists of a shieldlike structure surmounted by a nested caldera formed during five collapse events since latest Pleistocene time [Melekestsev and Sulerzhitskii, 1990]. The fifth caldera formed 235-325 cal A.D. and encloses the recently active Shtyubel' Cone, which is built of interbedded lava flows and pyroclastic debris. All eruptions subsequent to the formation of the fifth caldera have originated from the Shtyubel' Cone, which began its activity approximately 1300 yr B.P. and was most recently active in 1907 [Hultèn, 1924].

Three of the four largest fall deposits from southern Kamchatka during the past 2000 years originated from Ksudach. The most voluminous tephra fall layer of this time (KS$_V$) accompanied the fifth caldera collapse event. Subsequent Plinian eruptions were from the Shtyubel' Cone (KSh$_1$, KSh$_2$, KSh$_3$). Deposition of the KSh$_3$ tephra was witnessed by the inhabitants of Petropavlovsk on the night of March 28, 1907 [Hultèn, 1924]. In this contribution, we discuss the dispersal patterns and ages, and infer column heights for these eruptions.

The Deposits

The recent deposits of Ksudach are described briefly in Melekestsev and Sulerzhitskii [1990]. Here, we concentrate on features of the fall beds pertinent to the current discussion.

KS$_V$. The 235-325 cal A.D. KS$_V$ tephra is a voluminous, widespread layer of dacitic tephra that was deposited northeast of the vent (Figure 1; Table 1). Petropavlovsk is on the dispersal axis for the KSh$_3$ and near the axis for the KS$_V$ tephra. At Petropavlovsk, the KS$_V$ tephra consists of a massive, 5-cm-thick bed of coarse dacitic-rhyolitic pumice ash. It is both thicker and coarser grained (mean grain size ~ 1ϕ versus ~ 2ϕ) than KSh$_3$, suggesting that it is the product of an eruption column higher than that which generated KSh$_3$, and that it may not be a coignimbrite deposit, even though the tephra is closely associated with an ignimbrite on the volcano.

Fall deposits of the Shtyubel' eruptions are characterized by reversed grading and zonation from scoria of basaltic andesite to dacitic pumice. The scoriaceous subunit comprises a variable fraction of the stratigraphic section for each deposit, ranging up to 50% of the section in KSh$_1$, 30% in KSh$_2$ and 43% in KSh$_3$, although in no case does it comprise a significant volume itself, because of its local dispersal. Within the upper, pumiceous subunit of each deposit, prominent lithics are andesite, peridotite, and dacite.

KSh$_1$. The KSh$_1$ tephra (Table 1), is a massive bed of scoria and pumice that locally overlies nearly contemporaneous loose scoria and andesitic lava flow, and is in turn overlain by a pyroclastic flow near the vent. The tephra was dispersed primarily to the southwest of Ksudach (Figure 1) and attains a maximum thickness of 4 m at a distance of over 2 km from the vent. Thickness maxima that are displaced from the vent are relatively rare in fall deposits and indicate unusual eruption conditions. Within ~1 km of the present edge of Shtyubel' crater, the deposit shows an incipient eutaxitic texture and a high density resulting from welding, thus accounting for the greater thickness at more medial localities (Figure 2a). The modelling of Thomas and Sparks [1992] suggests that welding to distances of ~1 km is compatible with magmatic temperatures of ~1000 °C. Such a high temperature for the initial Shtyubel' deposit is compatible with eruption from a magma chamber that had perhaps been recently replenished with hotter, more mafic magma (the andesitic component?). Lithics are locally concentrated at the transition from scoria to pumice, compatible with a slight reorganization and erosion of the conduit as the lighter magma began to be withdrawn.

KSh$_2$. The KSh$_2$ eruption was the smallest of those considered herein. The KSh$_2$ tephra is well exposed along the shore of Shtyubel' Lake, and consists of approximately 50 cm of white dacitic tephra overlying 10 cm of darker andesitic scoria (Figure 2a). The proximal thickness and grain size data show a relatively symmetrical disposition about the vent, suggesting only a weak interaction with the wind for the lower eruption column. More distal tephra seems to have been dispersed progressively westward then northward (Figure 1), possibly within a sheared windfield.

KSh$_3$. The KSh$_3$ tephra is bilobate (Figures 1, 2). Dark andesitic pyroclasts occur in the upper, primarily dacitic section of the north tephra lobe but not the south tephra lobe,

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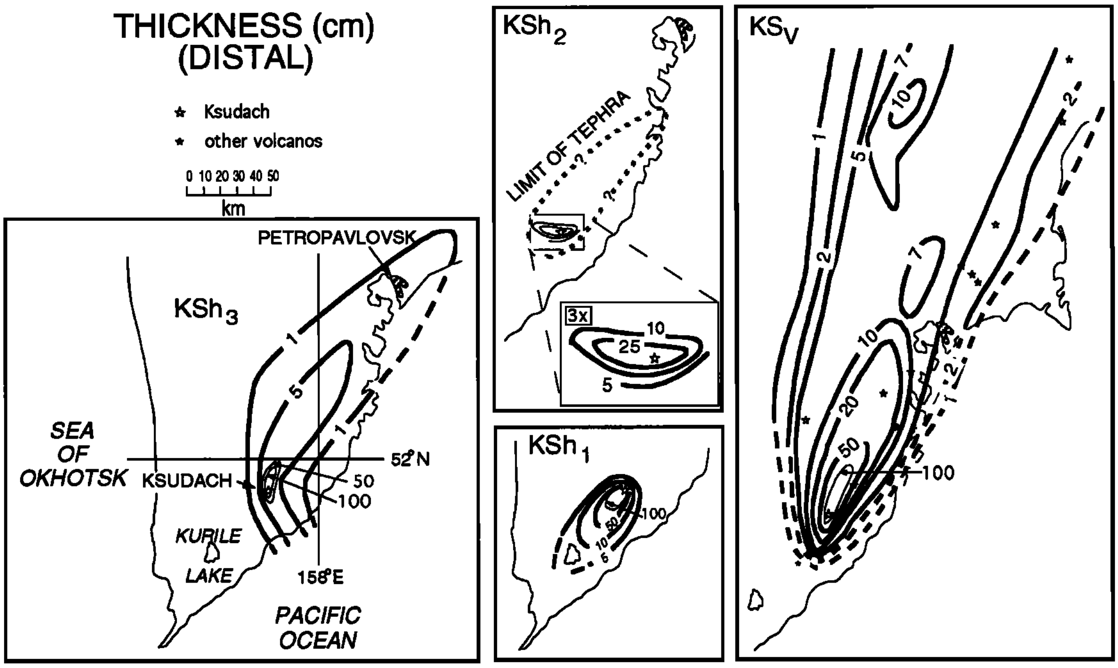

Fig. 1. Distal isopachs of the Ksudach fall deposits. The most widely dispersed Ksudach tephra is KS$_V$.

TABLE 1. Volumes, column heights and ages of most recent Ksudach fall deposits.

Deposit	Vol. DRE (km^3)[a]	H_t (km)[b]	^{14}C age (yr B.P.)[c]	Calendric age (cal A.D.)[d]
KS$_V$	4-6 [10-15]	([e]), 23	= 1781 ± 32[f]	235 (256, 303, 317) 325
KSh$_1$	0.4 [1]	> 15, 15	≤ 1300 ± 60[g]	660 (690, 750, 760) 800
KSh$_2$	0.1-0.2 [0.4-0.5]	> 10, 11	= 300 ± 60 ≥ 297 ± 34[f]	1490 (1640) 1660 1527 (1643) 1652
KSh$_3$	0.6-0.8 [1.5-2]	> 10 (S lobe), 22 (N lobe)	--	March 28, 1907

[a] Dense rock equivalent (DRE) volumes are calculated for dense rock at 2500 kg/m^3, and deposits measured at 1100-1200 kg/m^3 (KSh$_1$) and 1000 kg/m^3 (others). Deposit volumes in brackets.

[b] Estimated with maximum clast method, estimated with thickness method.

[c] From Melekestsev and Sulerzhitskii [1990]. =, age of included organic material; ≤, age of underlying organic material; ≥, age of overlying organic material.

[d] Calendric ages from technique of Stuiver and Reimer [1993]. Ages shown are -1σ (age) +1σ.

[e] Poor exposure in proximal localities.

[f] Weighted average of multiple determinations.

[g] More recent data suggest that the age of KSh$_1$ is close to 1000-1100 yr B.P.

consistent with deposition of the north lobe predating deposition of the south lobe. The stratigraphic relationship between the dacitic fall units and the erosive (?) surge or blast flow units north of the vent is unknown, although the andesitic fall material occurs everywhere at the base of the section. A proximal traverse across the south lobe (Figure 2a) shows that it thickens from 5 cm to 3 m over a distance of several kilometers, probably as the result of high wind speeds. The north lobe is widely dispersed throughout eastern Siberia, cropping out on the Siberian coast from Okhotsk to Anadyr'. Hulten [1924] noted that the average pyroclast mass decreased more rapidly with distance for the Krakatau fall deposit than for the KSh$_3$ deposit, suggesting to him that the KSh$_3$ eruption was larger than the Krakatau eruption. It has since been learned, however, that the Krakatau deposit is of coignimbrite origin, and therefore dominated by pyroclasts <50 μm in diameter [Self and Rampino, 1981]. Comparisons between the two deposits based on clast size are therefore unreliable. The Krakatau deposit is probably considerably more voluminous (~8.5 km^3) [Self and Rampino, 1981].

Column Height

Column heights were estimated using two independent methods (Table 1). One technique was the maximum clast method of Carey and Sparks [1986]. The three principle axes

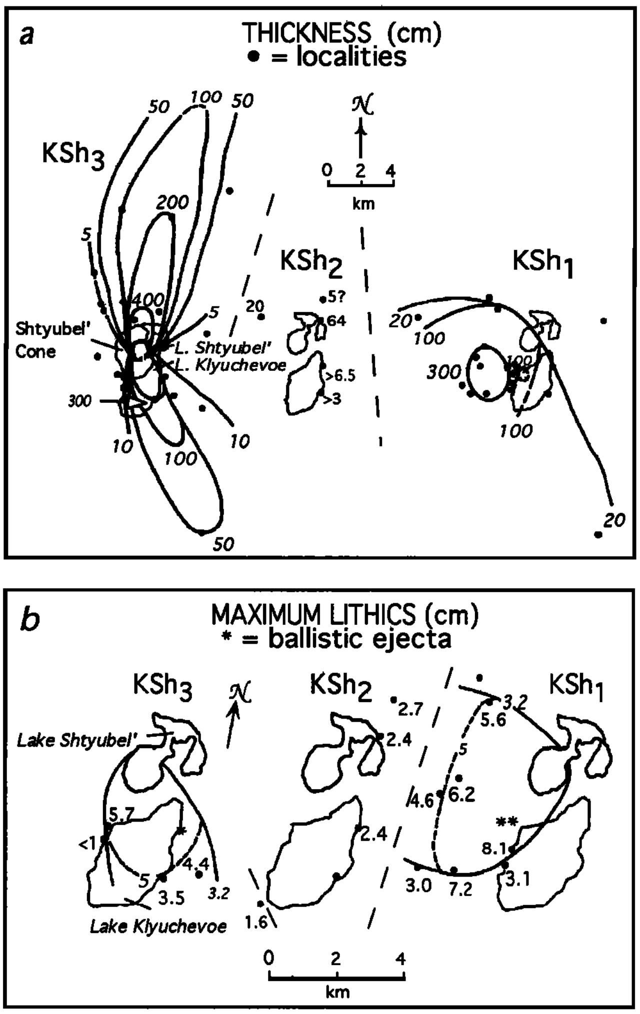

Fig. 2. Proximal isopach (a) and maximum lithic isopleth (b) maps for the Shtyubel' deposits. Clast sizes were recalculated to a constant density of 2500 kgm^{-3}.

of the five largest lithic clasts were measured in 1 m^2 outcrops of the deposits at proximal localities for the Shtyubel' tephras (Figure 2b). Where the deposits were thin and fine grained, a sufficiently large volume of material was inspected to ensure that representative large clasts had been found.

The second method used to calculate column height was derived from the use of thickness data, and is based on the sedimentation model described in Bursik et al. [1992] and Sparks et al. [1992]. Bursik et al. [1992] have shown that the mass of particles of a given size in a volcanic umbrella cloud decreases as an exponential function of time. Using their treatment, for any time, t, the mass of particles of a given grain size fraction falling from the base of an umbrella cloud per unit area, S (in kg/m^2) is given by:

$$S = S_o \exp\left(-\int_0^t \frac{v(H_b)}{h(t)}dt\right) \qquad (1)$$

where S_o is the boundary value of S (the value of S extrapolated to the vent), h is the cloud thickness and v is the terminal fall speed at the base of the umbrella cloud, H_b. Assuming steady flow and negligible entrainment of air into the umbrella cloud, dt can be approximated by $d(Ah)/Q$, in which A is the area to which the material in the cloud has spread and Q is the volumetric flux of material into the cloud from the column. Thus, equation (1) integrates to yield

$$S = S_o \exp\left(-\frac{vA}{Q} - \frac{vA}{Q}\ln\left(\frac{h}{h_o}\right)\right) \approx S_o e^{-vA/Q} \qquad (2)$$

where the approximation (far right-hand side) can be made if we consider only the interior of the umbrella cloud where cloud thickness remains near its initial value. Thus, the approximation probably will not hold when considering the deposition of extremely distal ash hundreds of kilometers from the vent. Assuming that the areas defined in equation (2) can be mapped to the earth's surface by following the average trajectories of pyroclasts from the umbrella cloud, then the equation also holds for the deposition of material on the surface. If S_{i0} is the sedimentation of particles of the ith size fraction extrapolated to the vent, and v_i their fall velocity then

$$Th \approx \frac{1}{\rho}\sum_{i=1}^{N} S_{i0} e^{-v_i A/Q} \qquad (3)$$

in which Th is deposit thickness, and ρ is deposit density. Assuming a volumetric flux and an initial grain size distribution (S_{i0}), equation (3) can be applied to predict the variation in deposit thickness as a function of area. Finally, using the relationship $Q \approx 747 H_t^{5.3}$ [Bursik et al., 1992], a column height, H_t (in km), can be calculated for the plume of which the deposit is the product. Sensitivity studies done with a variety of S_{i0} and Q suggested that the model is much more sensitive to the choice of Q for reasonable grain size distributions from which the S_{i0} are taken. For the column heights shown in Table 1, the ratios between the S_{i0} were held constant at values that yielded the best overall fit to the data for every deposit. Four grain size fractions were used with mean clast densities of 1000 kg/m^3, and dimensions of 10^{-1}, 10^{-2}, 10^{-3} and 10^{-4} m. The fraction of clasts within each size class was compatible with an initial size distribution (in ϕ units for $\mu \pm 1\sigma$) of -1.6 ± 2.7, similar to the total grain size distribution of Plinian fall deposits [Woods and Bursik, 1991].

Using both the maximum clast method, and the 'thickness' method (equation 3; Figure 3), we have estimated the heights of the eruption columns that deposited the Ksudach fall beds (Table 1). Where the two methods could both be used, the results are in agreement, although calculations from the maximum clast technique are minima because of the use of only proximal grain size data. The calculated column heights suggest that the eruption columns which generated the layers were all sufficiently high to inject aerosol into the stratosphere (Table 1), and that most can be considered Plinian, although the KSh$_2$ and the KSh$_3$-south lobe columns were probably subplinian [Sparks et al., 1992].

Ksudach Tephras and the Greenland Ice Cores

Major ash-forming eruptions of Kamchatka should be well-represented in the Greenland ice cores because of the zonal atmospheric circulation which tends to contain ash generated from high-latitude volcanos within the circumpolar

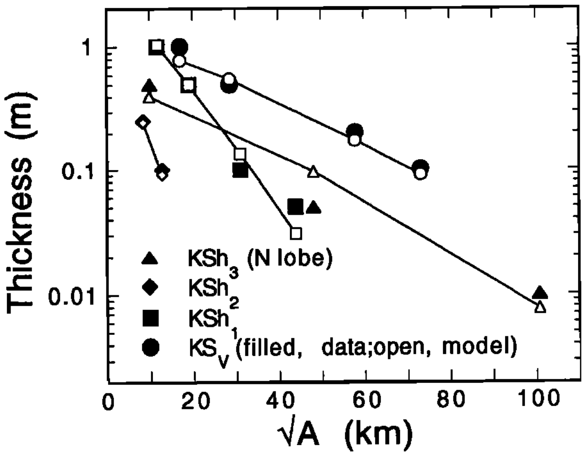

Fig. 3. Model and observed thickness variations for the Ksudach tephras are used to calculate the column heights shown in Table 1.

regions. A comparison of volcanism as recorded by acidity peaks in the Crête ice core, Greenland [Hammer et al., 1980] and the volcanism at Ksudach suggests that all but the KS$_V$ acidity peak should be modest in amplitude. The KSh$_3$ eruption caused only a moderate peak in acidity, but is otherwise known to have had a significant zonal atmospheric impact [Hulten', 1924; Lamb, 1970]. Similarly, the eruption of Bezymianny in 1956, which was only slightly smaller [Kirianov and Rozhkov, 1990], apparently left no discernible signal in the core. It is unlikely that the large, enigmatic atmospheric perturbation observed in A.D. 1601-2 [Lamb, 1970] and represented in the Crête core is the result of the 1490-1660 cal A.D. KSh$_2$ eruption, because of its low volume and column height. Hence it is unlikely that this peak is the result of any eruption in southern Kamchatka. One of the moderate acidity peaks shortly after the interval 660-800 cal A.D. may be the result of the KSh$_1$ eruption, which was similar in size to the KSh$_3$ eruption. The KS$_V$ tephra is similar in volume to the Plinian deposit of the 1912 eruption of Katmai/Novarupta (17 km^3) [Fierstein and Hildreth, 1992]. Calculated column heights are also in the same range (17-26 km for Novarupta). Hence, the KS$_V$ eruption may have had a similar major impact on zonal climate [Lamb, 1970], and should be well-represented in ice cores tapping the appropriate depth ranges, which the Crête core does not do.

The above interpretation is based on the assumption that eruption volume determines atmospheric impact and acid deposition. Rampino and Self [1984] have found that the abundance of sulfur-bearing compounds in an erupting magma is a factor of equal importance in determining acid deposition. Rampino and Self note that iron-rich, basaltic and andesitic magmas have a greater capacity to carry sulfur than do more felsic magmas. Because of their having a major mafic component, it is possible therefore, that the KSh$_1$ and KSh$_2$ eruptions could have resulted in ice core acidity peaks anomolously large relative to the volumes of the eruptions.

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