THE GREAT TOLBACHIK FISSURE ERUPTION

geological and geophysical data 1975–1976

EDITORS-IN-CHIEF

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Chronology and features of the Southern Breakthrough of the Great Tolbachik Fissure Eruption 1975–1976

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Introduction

The Great Tolbachik Fissure Eruption (GTFE) occurred, as was reported earlier (Fedotov *et al.*, 1976), to the south of the Ploskiy Tolbachik volcano, within the Southern Tolbachik zone of cinder cones that was named thus and first described by B. I. Piyp. Morphologically speaking, this is a gently sloping lava shield resting up against the Ploskiy Tolbachik stratocone and falling away at an average angle of 3–4° to the west, south and south-east, towards a large meander in the River Tolbachik. The shield has an area of about 800 km² (Piyp, 1956). Within it are situated several dozen monogenic eruptive systems, mainly cinder cones in varying states of preservation, with less frequent lava domes. The volcanic systems are often combined into groups and chains, but also occur singly. They are considerably closer together in the axial band of the shield than on the flanks. The eruptions of 1975–76 were also confined to the axial band of the shield and were evidently typical in all their features of the Southern Tolbachik zone.* As a result of the eruption at the Northern Breakthrough (Fedotov *et al.*, 1976) a chain of three cinder cones formed on top of the already existing chain of cones from earlier eruptions, while at the Southern Breakthrough, 10 km south-south-west of the Northern Breakthrough, a single cone emerged. In both regions extensive lava fields formed, and cinder and ash covered an enormous area.

During the eruption the summit caldera of Ploskiy Tolbachik subsided. This must have begun early in August 1975. In September–October of that

* In addition to the present authors' observations, this description is based on data collected by V. A. Andreyev, V. A. Budnikov, A. L. Budnikov, Yu. V. Vande-Kirkov, V. A. Dvigalo, A. P. Ivanov, N. N. Litasov, I. A. Menyaylov, N. V. Ogorodov, V. S. Petrov, A. A. Razina and A. Ye. Shantser.

year a warm-water lake appeared in the pit, fed mainly by a glacier that had fallen into it. Evidently the subsidence practically stopped at the end of 1975. In August 1976 the level of the water in the lake remained approximately the same as in April, but after the eruption at the Southern Breakthrough had stopped it fell considerably: according to observations of 29 March 1977 the surface of the lake had contracted, exposing screes at the foot of the sheer walls of the caldera.

The eruption at the Southern Breakthrough, whose description is the object of this paper, had a number of distinguishing features. It was almost exclusively effusive, its lavas were liquid and it was closer to the Hawaiian type than any other eruption observed in the Kuril–Kamchatka arc in historical times. Unlike the Northern Breakthrough, at the Southern the lavas are of the subalkaline basalt type that is already known in the region of the Klyuchi group (Volynets *et al.*, 1976a, b), and in texture they are megaplagiophyric (Yermakov, 1971).

A short chronology of the activity of the Southern Breakthrough

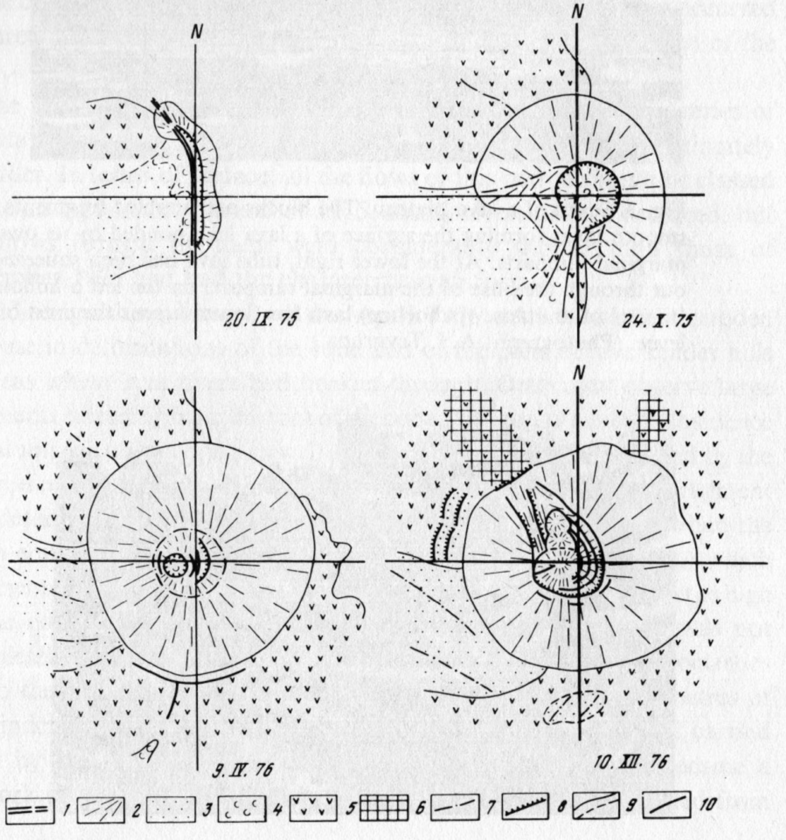
On 18 September 1975 a fissure of north–south strike opened, the northern end of which curved slightly north-north-westwards. Lava fountains appeared the entire length of the fissure, followed immediately by lava flows moving westwards and south-westwards in the direction of the general slope of the locality. The length of the fountaining part of the fissure grew at first from 200 m to 600 m, but subsequently decreased rapidly.

On the second day of the eruption, 19 September, the cinder–agglutinate embankment that had arisen along the fissure (Fig. 1) already began to change into a horseshoe-shaped cone and a single vent to form. The cinder–agglutinate masses that were accumulating to the west of the fissure were dispersed in various directions by the lava flows for a distance of up to several hundred metres; as a result, to the west of the cone arose an area of lava–agglutinate hills several tens of metres thick. This area, bounded by clearly-expressed ledges, retained its morphological individuality throughout the eruption (Fig. 2). The formation of the horseshoe-shaped cone was complete by 30 September. Lava poured from its mouth (open to the south-west) at an average rate of 25 m^3/s until 7 November 1975.

Flows of cinders and blocks poured out of the horseshoe-shaped cone during the entire period of its activity.

On 8 November the cone closed up and thenceforth the discharge of lava occurred only through boccas that kept opening around the foot of the cone. From 8 November until 28 December 1975 they opened almost exclusively to the west of the cone, along the perimeter of the area of cinder–agglutinate hills. Each bocca gave rise to a lava river, which flowed continuously for as much as several weeks. It was at this time that the longest lava flows were formed, which remained in existence throughout the eruption. The lowest viscosities also occurred then (up to 1×10^4 poise). The cone was operating at a steady rate of 10–12 ejections a minute and with average height of up to 150–200 m.

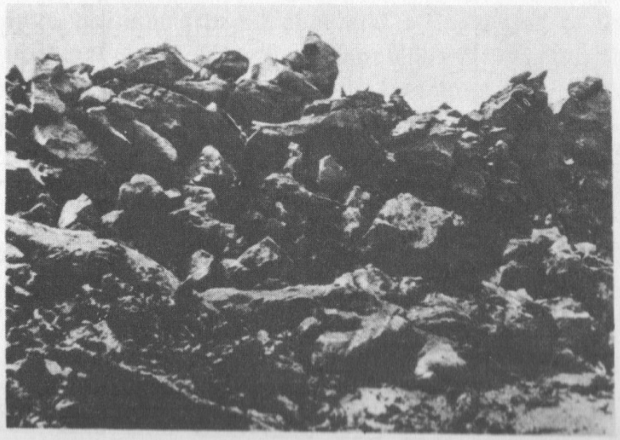
Fig. 1. Stages in the development of a cone.
1, fissure of the initial breakthrough; 2, build up of loose material; 3, continuous cover of cinders and agglutinates on fresh lavas; 4, liquid, glowing lavas; 5, dark lavas, including stationary and chilled lavas; 6, elevation caused by lava being expressed from under a cone; 7, axis of a crest; 8, edge of the scarp of an intra-crater terrace; 9, morphological or geological boundary; 10, fissure.



From 27 December 1975 until the beginning of April 1976, the discharge of lava occurred only to the south of the cone. Boccas opened mainly along the perimeter of the cinder–agglutinate hills and the lava plateaux adjoining the cone; these plateaux underwent extensive deformation (Fig. 3) in the

Fig. 2. Cinder cones and cinder–agglutinate hillocks. View from NNW in June 1976. (Photograph: A. I. Tsyurupa.)

Fig. 3. Scarp of a lava plateau. The blocks are tumbled fragments of smooth lavas forming the surface of a lava lake ponded by its own marginal ramparts. At the lower right, tube lava has been squeezed out through the base of the marginal rampart; on the left a hollow 'finger' of undulose (pahoehoe) lava has flowed across the crest of the levée. (Photograph: A. I. Tsyurupa.)



form of bulging and pulling apart at depth. Each bocca functioned for not more than several days, although any three or four might be working at once. Here hardly any continuous lava rivers were observed as in the preceding period, and the distribution of the lava sheets was more even. The average discharge of lava up to 9 April grew less and less, and the boccas functioned more and more erratically; brief spurts occurred followed by intervals of almost a week when hardly any lava was observed to flow. The activity of the crater fell steadily: the number of ejections per minute declined from 10–15 to 1, and the average height from 150–200 m to 5–10 m. The viscosity of the lavas throughout remained low, within 10^4–10^5 poise, and their surface was of pahoehoe type.

On 6 April there was a sudden increase in explosive activity, and on 9 April in effusive activity as well. Ejection frequency increased to 20 per minute, while the average height increased to 200–300 m. The discharge of lava, which on the first day attained 80 m^3/s, grew gradually weaker in the course of a month, but remained above 20 m^3/s. Discharge occurred in three main zones: to the east, south-south-east and north-west of the cone.

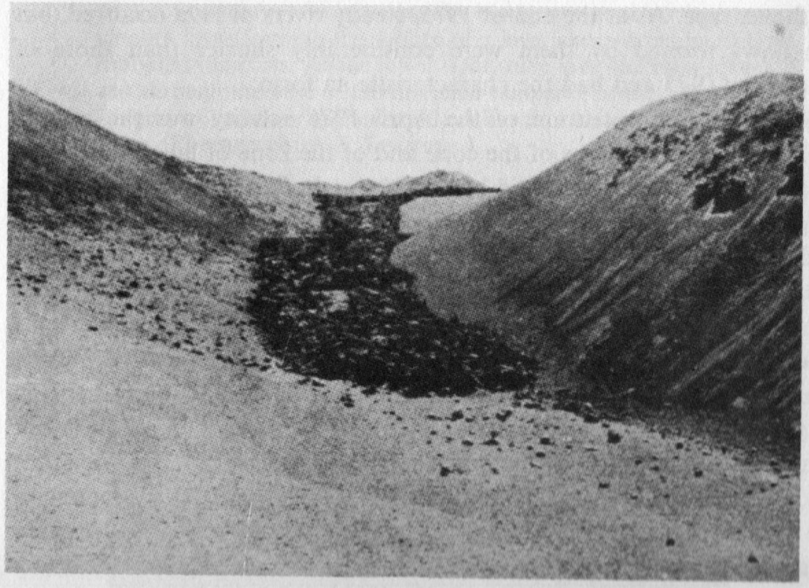
The activisation of the eruption was also accompanied by a series of qualitative changes. The viscosity of the lavas jumped by approximately an order. In terms of surface, all the flows of this period should be classed as the aa type. As at the end of 1975, steady rivers of lava occurred, but the flows formed by them were considerably shorter than those of December 1975 and had the characteristic aa form.

A distinguishing feature of the April 1976 activity was the sudden increase in deformations of the cone and of the zone of lava–cinder hills in areas where lava rivers had broken through. One could observe large fragments emerging from the foot of the cone, with simultaneous subsidence and slumping of its slopes, as well as internal collapse accompanied by the ejection of large masses of black ash from the crater. The largest fragment was detached from the southern part of the cone on 19 April, when the south-south-western lava river burst through. This fragment, which represented a whole segment of the structure and was initially almost as high as the cone itself, travelled about 100 m. However, the cone was not completely destroyed, and after a month intensive ejections of pyroclastics led to the 'wound' on the cone healing. Thousands of square metres of the cinder–agglutinate hills and lava plateaux were torn off and carried away by the lava, whilst the surface of the hills themselves became a network of wide and deep fissures. Moreover, the hill zone shifted from the cone as a whole (Fig. 4). Subsequently, although the general nature of the eruption remained the same, the discharge of lava and the intensity of deformation continued to diminish. The functioning of the cone was unaffected.

On 9 July a sudden increase occurred in the discharge of lava, similar to that of 9 April. At the same time, intensive deformation of the plateau around the cone occurred, parts of it were torn off and wrenched aside, and some areas were pushed up or subsided. The main events, as in April, occurred to the south of the cone, although a lava bocca to the west was also operating.

However, unlike its April counterpart the July activity was not accompanied by noticeable changes in the properties of the lava and the flow types. The activity of the cone remained at approximately the same level, but its nature changed slightly: whereas until 9 July bombs were ejected mainly in a fan, the ejecta were now more precisely directed and arrowlike,

Fig. 4. Sickle-shaped depression between the foot of the cone and the rear of the cinder-agglutinate hillocks. The depression was formed when these hillocks slid along the lava substrate. In the background are the summits of the largest of these separated parts of a cone, formed on 19 April 1976. Photographed at the beginning of June. (Photograph: A. I. Tsyurupa.)



and the discharge of black ash intensified. These changes indicated a considerable lowering of the lava level in the conduit, accompanied by collapse of its walls.

Subsequently the discharge of lava fell fairly quickly to an average level, and stable activity with a slight tendency to slackening continued until the beginning of November. Until 27 August the lava discharges took place mainly in the west and south-west. After that date the most important discharges occurred to the north of the cone, where practically all the effusive activity was concentrated after 18 October.

From 8 November 1976 onwards, up to three eccentric but similar conduits at a time began to form periodically in the northern segment of the cone. They produced mainly ash, but sometimes also ejected bombs. The lavas were discharged, as before, mainly through the northern boccas.

In the concluding phase, from the beginning of October until 10 December 1976, the activity of the Southern Breakthrough showed some special features. The increase and decrease in activity, as determined by the lava discharges and the frequency and height of the ejections of pyroclastic material, were clearly cyclical in character, with a periodicity that gradually decreased from 14 to 8 days. Moreover, each successive maximum of lava discharge was usually lower than the preceding ones, which implied a steady slackening in volcanic activity. The only exception was the last few days of the breakthrough's activity, when the visible lavas increased to twice the size of any others observed since October 1976.

Another peculiarity of the concluding phase was the fact that the orientation of the discharging sector of the cone (335° NW, based on the position of the boccas and eccentric conduits, orientation of the subsidences) was the same as that of the northern end of the original fissure. The possibility cannot be excluded that movements were continuing along this fault.

Characteristics of explosive activity

During the eruption, explosive activity was concentrated in the crater of the cone and took the form of a sequence of explosions whose characteristics are given in Fig. 5. Plot (*a*) shows the average height of ejections above the rim in a twenty-four hour period, and plot (*b*) shows the average frequency of the ejections. Some bombs were projected considerably further than the average height, attaining 400 m.

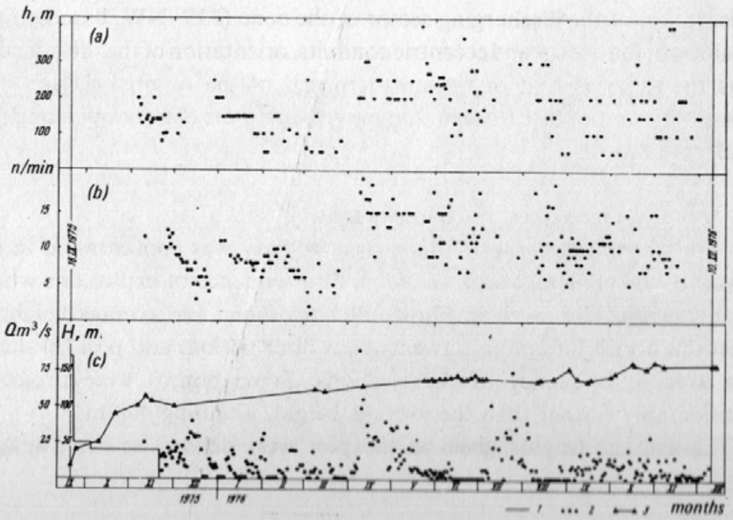
The average heights given in the plot were defined as the averaged maximum heights for several dozen ejections. In the majority of cases measurements were carried out on continuous series of ejections by comparing their height with that of the cone using a scale projected onto the object. The error might be as much as 10–15%. Some of the measurements were carried out using a seconds theodolite from a base 2300 m away, but because of the narrow field of vision and the loss of time in taking the reading, in these cases the averaging was done on random samples.

The average frequency was determined by counting every case when new pieces of incandescent material appeared above the rim of the crater over a particular interval of time.

All the measurements were carried out daily after dark, the weather and thick ash-showers permitting.

Apart from the frequency and height of the ejections, the explosions also differed in terms of the form of material ejected and the sound effects. All degrees of intensity and sharpness of sound were observed, from the bubbling 'blow-out' effect to an unusually piercing, powerful blast painful to the ears. These piercing reports were accompanied by the ejection in a symmetrical fan of a relatively small number of very large bright bombs. Until the fresh activity in April these occurred three to four times every

Fig. 5. Characteristics of eruption. (*a*) Average discharge calculated from volume of lava field. (*b*) Results of daily measurement of lava discharge through boccas (m^3/s). (*c*) Height of the cone.



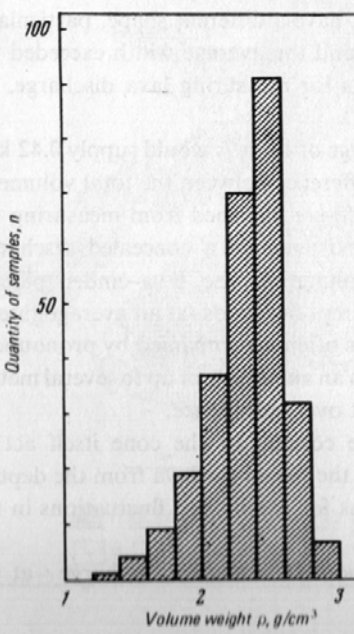
twenty-four hours, but after 6 April no less than once or twice an hour. The commonest of them were loud, but not very piercing explosions with an abundant ejection of small fragments of lava in the form of an absolutely vertical fountain.

Characteristics of the effusive activity

The lavas had the following physical properties. The temperature, measured at the sources of the lava rivers, fluctuated between 1050 and 1070 °C. Temperature was measured using a chrome–aluminium thermocouple with a cold weld, placed in melting ice with the thermal-e.m.f. registered on a PP-1 potentiometer. For the qualitative control of the upper limit of the temperature, samples of pure copper (melting point 1083 °C) were inserted into the lava. In no case was the copper observed to melt.

The effective viscosity of the flowing lava was calculated according to the formula for a plane layer: $\eta = (\zeta g h^2 \sin \alpha)/2v$, where ζ = density; η = effective viscosity; h = depth of flow; α = angle of incline (in fact it was the angle of incline of the flow's surface that was observed, the latter being taken as parallel to its base); v = maximum velocity on the surface of the flow and g = free fall acceleration.

Fig. 6. Volume weight of massive samples of lava.



An alignment was chosen for these measurements which would give the most favourable conditions for applying the above formula.

It was established that the value η at the sources of the lava flows near the cone fluctuated between 10^4 and 10^5 poise. The secondary breakthroughs 2–3 km from the cone gave flows of viscosity 10^6–10^7 poise. A calculation of the density from massive samples of lava gave an asymmetrical distribution with a considerable scatter (Fig. 6).

From the second half of November 1975 onwards, in addition to estimates of the average discharge of lava calculated from the increase in area of the lava field using aerial photographs, daily measurements were made of the visible lava discharge (see Fig. 5, plot (*b*)). The visible discharge (R) was calculated according to the formula $R = hdv$, where d = width of flow; v = average velocity of flow; h = depth of flow.

For this purpose the average velocity of flow on the surface of the lava was used, as this was close to the average velocity of the entire lava flow, assuming the latter behaves essentially as a Bingham liquid. This assumption is based on the properties of the lava and is confirmed by a number of observations carried out by us at the Southern Breakthrough and by Hulme (1974) on the basalt flows of Etna. It was also assumed that the bed of the lava river was rectangular in section, as has been generally confirmed from observations of lava tubes left empty once feeding had ceased. In some cases the tube might have a different shape, particularly where there were overhanging sides and the average width exceeded the visible width. In selecting alignments for measuring lava discharge, we attempted to avoid such locations.

Lava rivers with an average discharge of 11 m^3/s would supply 0.42 km^3 over the time of the eruption. The difference between the total volume of the lava field (6.5–7.0 km^3) and the figure obtained from measuring the discharges evidently points to the existence of a concealed discharge.

Throughout the eruption the volume of the lava–cinder plateau adjoining the cone grew as it slowly crept outwards (at an average rate of 1 cm/h). This outward movement was often accompanied by pronounced differentiated vertical movements with an amplitude of up to several metres a week and a predominance of uplift over subsidence.

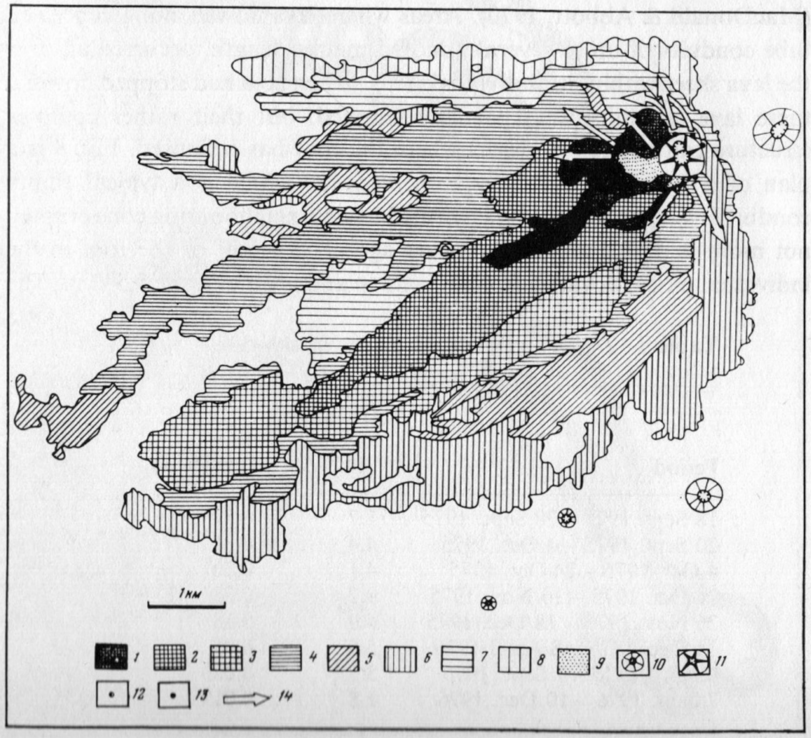
The lava–cinder plateaux and the conduit of the cone itself act as accumulation-reservoirs which check the rise of the lava from the depths, and this is one of the possible reasons for the sudden fluctuations in the visible discharge.

However, the three distinct high points in the lava discharge – at the

beginning of the eruption, and in April and July 1976 (see Fig. 5, plot (*c*)), were evidently caused by a change in the way lava was entering the conduit. The April peak is particularly interesting, as the change in the discharge was accompanied by a change in the properties of the lava and the activity of the crater.

The escaping lava formed a cover whose pattern of growth is shown in Fig. 7, whilst the rates of increase in area are given in Table 1. Whereas

Fig. 7. Diagrammatic map of areal growth of lava field.
1, by 20 Sept. 75; 2, by 4 Oct. 75; 3, by 22 Oct. 75; 4, by 26 Nov. 75; 5, by 18 Dec. 75; 6, by 9 April 76; 7, by 7 Sept. 76; 8, by the end of the eruption (survey of 22 Dec. 76); 9, lavas hidden by a continuous cinder–agglutinate cover; 10, cinder cones from old eruptions; 11, cone of the 1975–76 eruptions; 12, secondary bocca, fed from the beginning from horizontal lava conduits; 13, primary bocca, the result of a new breakthrough on the cone; 14, direction of the main systems of lava ducts with supply direct from the cone area. The outlines of the successive growth steps of the lava field were obtained by aerial photography; the survey and preliminary deciphering were carried out by N. A. Gusev and V. A. Dvigalo. (Compiled by A. I. Tsyurupa.)



at the beginning of the eruption it was almost exclusively an increase in area that occurred, in the last few months no more than 10–15% of the newly-appearing lava was expended in increasing the area.

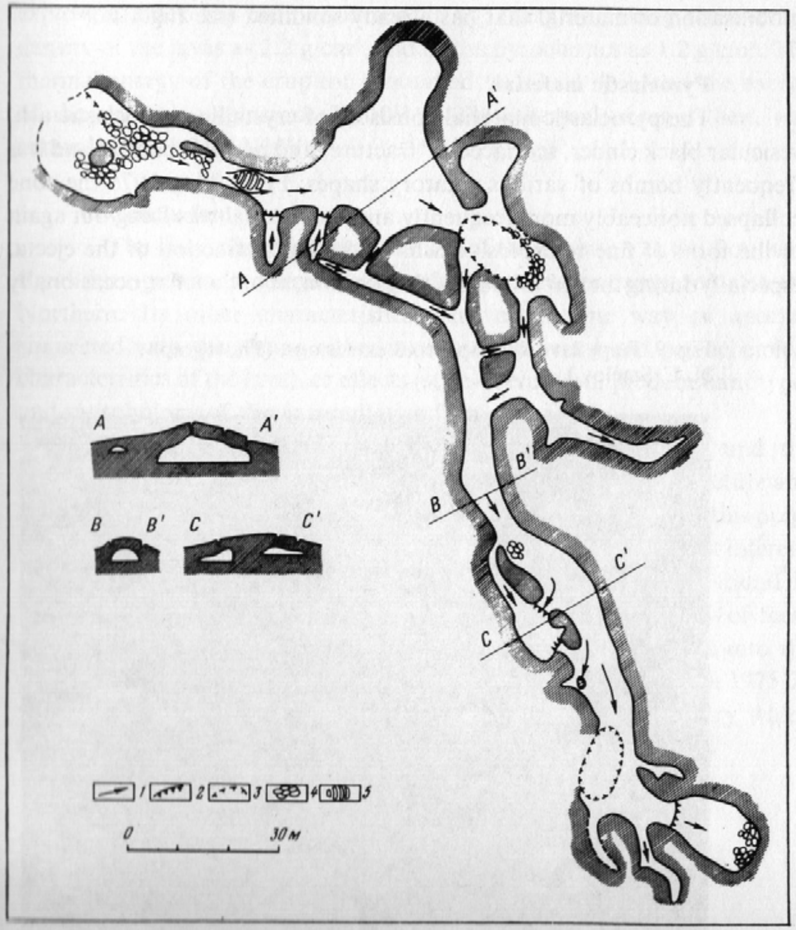
A lava field is the result of the superimposition of numerous 'single' flows (Walker, 1972) issuing from groups of intermittently functioning boccas. The longest of these flows (up to 9 km) were emitted at the end of 1975. In general the field has a stepped surface. There are various reasons for this. Some of the steps represent the front of flows emitted from relatively narrow feeder-boccas functioning for not more than a week. When the discharges are small, around 10–20 m^3/s, several steps may be formed on one flow, as lava breaks through secondary vents at the front of the practically stationary flow. This effect is caused by changes in the overall flow regime and may be satisfactorily described in terms of a rheological model that takes into account the fact that the lava has a yield point but can also flow slowly at stresses below this limit (Slezin, 1972; Hulme, 1974). The spreading of the lava was facilitated by the formation of lava tubes similar to those described on the Hawaiian volcanoes (MacDonald & Abbott, 1970). Areas where lava flowed along concealed tube conduits of up to several hundred metres' length, occurred all over the lava sheet within the individual steps. When lava had stopped flowing, these lava conduits were partially emptied, but their rather complex structure can be seen in places where the roof has collapsed. Fig. 8 is a plan of a cave discovered by F. A. Fedotov which is a typical empty conduit in a lava sheet that was formed when a neighbouring cone erupted not more than a few hundred years ago. The height of the roof in the individual passages varies from 0.5–4.5 m and is on average 1.5–2 m. The

Table 1. *The growth in area of the lava field*

Period	Complete increase (km^2)	Rate (km/24 h)
18 Sept. 1975 – 20 Sept. 1975	1.7	0.57
20 Sept. 1975 – 4 Oct. 1975	4.4	0.31
4 Oct. 1975 – 24 Oct. 1975	4.1	0.20
24 Oct. 1975 – 26 Nov. 1975	9.2	0.28
26 Nov. 1975 – 18 Dec. 1975	4.0	0.18
18 Dec. 1975 – 8 April 1976	5.6	0.05
8 April 1976 – 7 Sept. 1976	3.5	0.023
7 Sept. 1976 – 10 Dec. 1976	1.8	0.019

roof is vaulted, has sagged and melted in places and has lava icicles up to 15 cm long and 0.5–1 cm in diameter. The floor is flat, with a predominantly ropy surface. Judging by the thickness of the roof (in places as much as 2–3 m), this lava conduit came into operation after a fairly long interval – probably of some weeks. The distension and cracking of the roof indicate the hydraulic retention that existed during this intermission.

Fig. 8. Plan and sections of lava conduit cavern.
1, flow direction of lava (direction of curves on ropy surface); 2, steps or 'lava falls'; 3, roof collapse; 4, piles of fallen blocks; 5, lava 'plug'.
(Compiled by Yu. B. Slezin.)



The surface of the lava field is complicated by numerous structural elements characteristic of mobile basalts: gently sloping domes (tumuli) and longitudinal levées, strips of smooth lavas reminiscent of airport runways and extending tens and hundreds of metres, pit-craters, empty lava channels and tunnels, hornitos, lava fingers and blisters of various shapes and sizes. The main morphological lava types are cinder-blocks (aa) and flat-blocks with smooth surfaces merging into hummocky ones. Regularly, but less frequently, one comes across ropy (Fig. 9), thickly coiled entrail-like (see Fig. 3) and pancake lavas. Some parts of the embankments look like large-blocked lavas; in reality they do not reflect the morphology of the moving flow, but have been created by a mechanical mobilisation of material that has already solidified (see Fig. 3).

Pyroclastic material

The pyroclastic material consisted of crystalline vitroclastic ash, vesicular black cinder, scoriaceous 'fracture' and nodular bombs, and less frequently bombs of various rotatory shapes. From May 1976 the cone collapsed noticeably more frequently and its material was flung out again in the form of fine re-explosive ash. In the lapilli fraction of the ejecta, especially during the first months of the eruption, abundant flat, occasionally

Fig. 9. Ropy lava with spheroid extrusions. (Photograph: N. L. Smelov.)

cruciform and spherical aggregates of plagioclase crystals were present. In the first few months fragments of white and light-grey pumice were found in small quantities, though fairly regularly.

Geological and energy aspects

The result of the eruption, which lasted 450 days, was a cone with a final height of 160 m and a volume of 0.018 km^3. In addition, 0.022 km^3 of the pyroclastic material was dispersed over the surface of the lava flows, while 0.025 km^3 of it was ejected beyond the cone during explosions. The area of the lava field is 34.3 ± 0.6 km^2, while its volume, according to preliminary estimates of the distribution of thicknesses, is 0.5–0.7 km^3. The explosion index has been reckoned at 4% (weight), taking the average density of the lavas as 2.2 g/cm^3, and of the pyroclastics as 1.2 g/cm^3. The thermal energy of the eruption amounted to 1.3×10^{18} J, and the energy of the volcanic explosions 3×10^{14} J. This thermal energy, then, was equivalent to 3.3×10^{10} W.

Conclusion

The basic distinguishing feature of the eruption at the Southern Breakthrough was its unmistakably effusive character compared with the Northern. Its other characteristics were all in one way or another connected with this, being either its causes (physical and petrochemical characteristics of the lava), or effects (style of eruption, predominant types and morphology of the accumulative formations).

The closest analogies with the Southern Tolbachik zone and the eruptions that occurred in it in 1975/76 may be found in the structure and activity of the rift zones of the Hawaiian shield volcanoes. From this point of view the events at the Southern Breakthrough are of the greatest interest. Lava sheets formed by eruptions of a similar type are often found in various regions of ancient and more recent volcanism. A study of them in the actual process of formation provides invaluable insights into the geology of these regions. The eruption in the Tolbachik region in 1975/76 was the first of this type in historical times on USSR territory which scientists could directly observe and study in all its detail.