Annals of Glaciology 2 1981

GLACIER EROSION AND SEDIMENTATION IN THE VOLCANIC REGIONS OF KAMCHATKA

by

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ABSTRACT

The recent topography of Kamchatka was formed by the joint activity of endogenic and exogenic processes among which glacial erosion and sedimentation played the most important role. Glacial erosion is exhibited to different degrees on old and young mountains. Corrie and corrie-valley glaciers are common to the oldest and strongly eroded early Pleistocene volcanoes. The flanks of Holocene volcanoes are only slightly affected by exogenic processes. As a result, ice caps and ice belts as well as crater glaciers are developed on them.

During earlier glaciations, the influence of volcanism on glaciers and frozen strata caused the specific conditions for sub-ice eruptions, as a result of which strata of welded tuffs and pumices, and thick strata of fragmented material were formed. Recent and older glaciers in regions of active volcanism are covered by large amounts of pyroclastic material. During intense melting of glacier ice in these regions, thick fields of morainic deposits were formed. Similar conditions are found in Iceland, as described by Thorarinsson (1958, 1974) among others.

INTRODUCTION

The formation and development of topography in volcanic regions of Kamchatka (Fig.1) occur under the influence of endogenic and exogenic factors. Among them volcanism, volcano-tectonics, glaciofluvial, and glacio-niveal activity are the most important. In addition, some parts of the topography are affected by other exogenic factors, and gravitational processes, eolian activity, solifluction, and others.

Marine climate, intense cyclonic activity throughout the year, and heavy precipitation are the reasons that Kamchatka is a region with heavy snow-falls and is the largest centre of present-day glaciation in north-eastern Asia.

Throughout the geological history of the peninsula, glacial erosion and sedimentation have occurred with varying intensities depending on the degree of glaciation.

GLACIAL EROSION

Glacial erosion is apparent in varying degrees on old and young mountains, and is expressed by a number of definite morphological types of recent glaciers for each period.

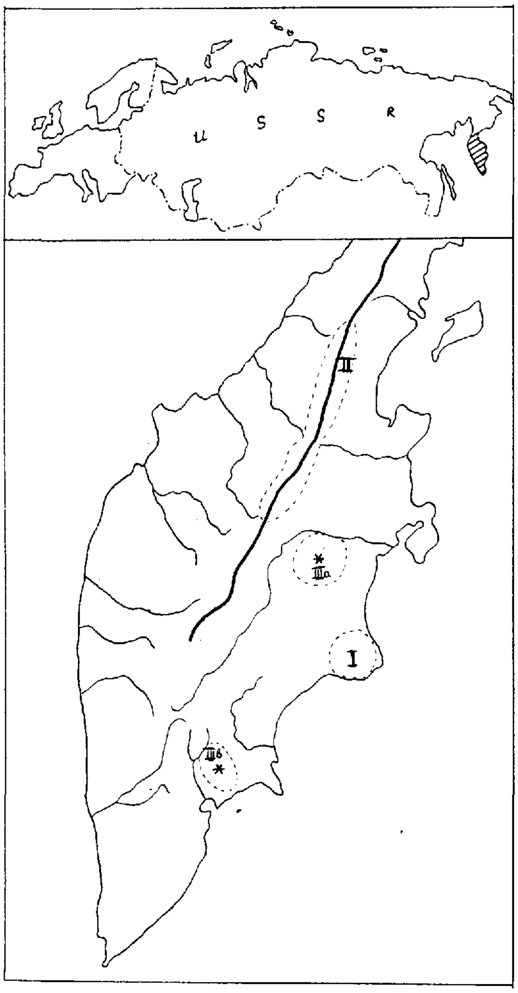

Fig.1. Location of Kamchatka, USSR.

I. Non-volcanic regions (Kronotskiy Poluostrov).

II. Regions of Quaternary volcanism (Sredinnyy Khrebet).

III. Regions of active volcanism (Klyuchevskoy group volcanoes (a) and Avachinskiy group volcanoes (b)).

https://doi.org/10.3189/172756481794352207 Published online by Cambridge University Press

The differences in morphology and geological structure of individual volcanoes and groups are caused by their age. Three periods of volcanic forms can be distinguished within the volcanic regions of Kamchatka (Vinogradov 1975); these are Middle-Upper Pleistocene, late-Upper Pleistocene-Holocene, and Holocene.

Volcanoes of Middle-Upper Pleistocene age, determined by correlating the traces of the two phases of Upper Pleistocene glaciation and by the palaeomagnetic method, show the oldest formations. Rocks from individual volcanoes occur in moraines of phases I and II of Upper Pleistocene glaciation. Tops of volcanic cones have been removed, flanks are dissected by well-formed troughs terminating in their upper parts with corries. Corrie and corrie-valley glaciers are characteristic of this comparatively small group of volcanoes (Malaya Zimina, Aag, Arik) and of non-volcanic regions of Kamchatka (Kronotskiy Poluostrov). Flanks of two opposite corries destroyed by glacial erosion have sharp-crested walls (the Shishel' volcano).

Younger formations are represented by late-Upper Pleistocene-Holocene volcanoes. This is the most numerous group, and includes the Ostryy Tolbachik and Ploskiy Tolbachik volcanoes, the upper parts of the Dal'nyaya Ploskaya and Blizhnyaya Ploskaya volcanoes, some of the Avachinskiy volcano, Koryakskiy, Zhupanovskiy, and others. Flanks of these volcanoes are crevassed by deep barrancos. In places there are remnants of sculptured forms of the maximum phase of Upper Pleistocene glaciation which have been maintained as scarps in the lower part of the cones of strato-volcanoes. Barranco, caldera, and stellate glaciers, as well as complex caldera-valley and atrio-valley glaciers, have developed mainly on these volcanoes (Fig.2). Glacier types of this distinct morphology are common only in volcanic regions (Melekestsev 1965).

The Holocene age of volcanoes was determined by correlation with glacial forms of the maximum phase of Upper Pleistocene glaciation in Kamchatka. These are the Klyuchevskoy (the highest volcano in Eurasia), Bezymyannyy, Ovalnaya Zimina, and Ostraya Zimina volcanoes, and the young active cone of the Avachinskiy volcano. Slopes of Holocene volcanoes are affected slightly by exogenic processes; therefore they are covered by unusual types of glaciers that do not occur on volcanoes of more mature age. They are the ice caps covering the tops of volcanoes and ice belts around them where ice is absent because of heat escaping from the crater of the volcano. A typical ice belt occurs on the Klyuchevskoy volcano.

We can distinguish between the temporal cycles of the development of glacial erosion related to volcanic activity, as follows:

The *initial cycle* of glacial erosion is characteristic of regions of active volcanism in which there are groups of recent volcanoes. Glacial erosion in these regions is minimal and the transformation of topography here is primarily due to explosive volcanism (for example, the eruptions of the Bezymyannyy volcano in 1956 and the Shiveluch volcano in 1964) and to effusive activity (for example, the filling with lava of the summit crater of the Klyuchevskoy volcano in 1978).

The *intermediate cycle* of glacial erosion is characteristic of regions of Quaternary volcanism where active volcanoes are absent, but volcanic forms are still fresh. Here glacial erosion is quite distinct. Sculptured forms, represented by large areas of lava sheets polished by glaciers (for example, the Ostraya-Khuvkhoytun massif to the north of Sredinnyy Khrebet), are widely developed here.

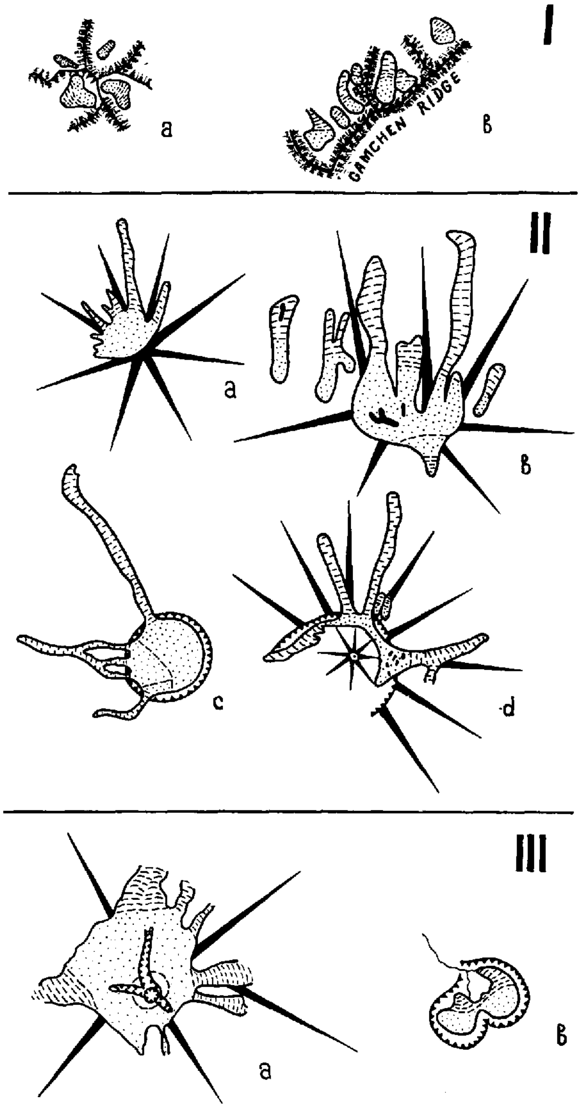

Fig.2. Morphological types of glaciers on volcanoes of different ages. I(a): corrie glaciers of the Shishel' volcano; I(b): corrie-valley glaciers of the Gamchen ridge; II(a): stellate glaciers of the Kronotskiy volcano; II(b) barranco glaciers of the Zhupanovskiy volcano; II(c): caldera-valley glaciers of the Dal'naya Ploskaya volcano; II(d): atrio-valley glaciers of the Avachinskiy volcano; III(a): ice belt at the Klyuchevskoy volcano; III(b) crater glaciers of the Mutnovskiy volcano.

The *mature cycle* of glacial erosion is widespread on old Middle-Upper Pleistocene volcanoes and folded massifs of non-volcanic regions. Having undergone Upper Pleistocene glaciation, these massifs were intensively affected by glaciers, resulting in numerous glacial corries. In many places where present-day glaciers are absent there are hollows indicating the sizes of former glaciers; these are sometimes occupied by present-day lakes.

Completing the review of glacial erosion, it is of interest to note that fjords, analogous to Glacier Bay in Alaska (Field 1969), are found on mountain massifs of the eastern Shipunskiy and Kronotskiy peninsulas and in the southern part of the eastern coast of Kamchatka. They were formed by Upper Pleistocene glaciers descending along trough valleys directly into the ocean.

ICE-TYPE LITHOGENESIS

Following Strakhov's data (1962), this is a constituent part of the process of sedimentation caused by melting of a glacier contaminated with fragmented material. In the volcanic areas of Kamchatka, ice-type lithogenesis is closely related to the volcanic-sediment type. Here sediments are derived from lava, ash, and hydrothermal and exhalation materials. Often during volcanic eruptions ice-type lithogenesis follows the volcanic-sediment type.

In former glaciations, during emplacement of hydrothermal systems, acidic material intruded into a stratum of frozen rocks and glaciers which formed a thermal insulation screen. Concurrently, specific hydrogeologic conditions were created which caused agglutination and even partial fusion of sedimentary rocks, as well as the generation of welded tuffs (Belousov and Sugrobov 1973). Cooling of extrusive gas-saturated material at the contact with the glacier in the presence of water has led to the formation of pumice in the region of the Geyzernaya river and within the caldera of the Uzon volcano in east Kamchatka.

In considering the problems of emplacement and activity of hydrothermal systems, Belousov (1978) described a few types by their geological structure. One of these types is related to the activity of an ice cap at the top of a volcano. Volcanoes inherit the structure and character of eruptions from volcanic centres which have a long history of development. The interior is characterized by very complex sequences of lava-pyroclastic strata and volcanic sediments, often broken by intrusive bodies. The presence of a few eruptive centres of andesite-basaltic material within the structure is a characteristic peculiarity of Pleistocene-Holocene volcanoes. These centres form lines along which volcanism of a flood basalt type occurs. At the final stages of development of hydrothermal structures, subglacial extrusions of dacite occur which partially melt the glacier. This creates the main condition for the formation of rocks (Fig.3) of opal-alunite composition.

During groundwater infiltration, clay intercalations were formed in the upper part of volcanoes which served as an upper water barrier for underlying strata. Up to the present, glaciers are found in the craters of the Mutnovskiy volcano. In the past there was probably a hydrothermal system at the Bolshaya Zimina volcano in the Klyuchevskoy volcanic group. Here exposures of alunite-rich rocks were found near the summit of the volcano in a sheer wall 200 m long with an exposed thickness of up to 100 m. Fragments of these rocks are found in large quantities on the surface of, and within, the glacier owing to which the glacier is yellow and therefore named Zheltyy (Popkov 1948).

In mountainous areas of Kamchatka, traces of early Pleistocene glacial activity were destroyed by younger glaciers and by subsequent erosion, and in volcanic areas they were buried under fragmented material. Furthermore, the glacial deposits here are often indistinguishable from similar coarse volcanic formations (Krayevaya 1977). Nevertheless, at present the area occupied by glacial sediments in volcanic

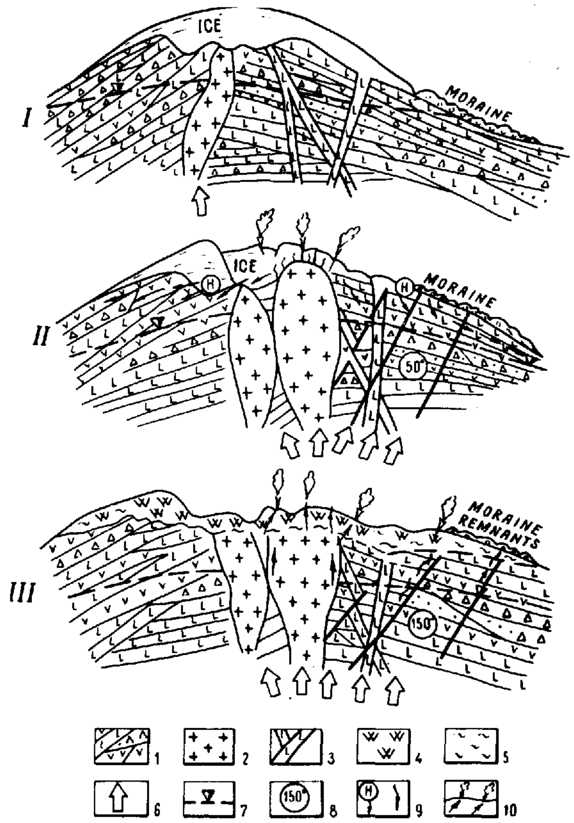

Fig.3. Scheme showing geologic development of hydrothermal structures of volcanoes covered by ice cap (after V.I. Belousov). I: structure before the intrusion of extrusive dome; II: interaction between the heated extrusive dome and a glacier; III: formation of high temperature conditions in the interior of the volcano after the formation of a cover by hydrothermal rocks. Key: 1, lava-pyroclastic complex of rocks of volcanic edifice; 2, extrusion of acid composition; 3, basalt dykes; 4, opal-alunite rocks; 5, clays; 6, anomalous heat flow accompanying the intrusion of extrusive dome; 7, level of underground waters of volcano; 8, probable temperatures of hydrothermal waters; 9, infiltration of condensate and mixed acid waters; 10, routes of migration of vapour and gases generated during the intrusion of extrusive dome and during boiling of hydrothermal waters in the interior of newly-formed hydrothermal system.

regions is extensive (about 17% of the area in the Klyuchevskoy volcanic group and more than 30% of the area in the Avachinskiy volcanic group). Reconstructions made by Melekestsev show that the original area of these formations is not less than 3 000 km^2 in the Klyuchevskoy volcanic group and 850 to 900 km^2 in the Avachinskiy volcanic group. Wide fields of glacial sediments encircle the entire bases of most of the largest volcanoes. The outer edge of these belts is very uneven and in plan it has a complex blade-like configuration. Each of these belts consists of several separate, clearly defined massifs which tend to occur near certain volcanoes (Melekestsev and others 1970).

During Upper Quaternary glaciation, the largest volcanoes fed the piedmont glaciers which extended far out from them. At the end of the Upper Quaternary, when glaciation decreased, the piedmont glaciers broke down into a number of blocks of dead ice. The specific character of the melting of the dead-ice massifs brought about the unusual features of the abandoned glacial deposits which form a hill-trough topography near the bases and on the lower slopes of the volcanoes. There is a wide distribution of glaciofluvial and glaciolacustrine strata, and a layered moraine series as well as other extraordinarily varied facies. Complex relationships are found between all these deposits (Krayevaya and Melekestsev 1969).

Glacier deposits, whose accumulation areas were volcanic, differ markedly from glacier deposits from non-volcanic regions. The distinctive features of glacial strata in the regions of young volcanoes are, in addition to peculiarities of the petrographic composition of fragmented material (almost exclusively effusive), their great thicknesses (up to 100 m and more) and the fresh appearance of fragments. Furthermore, the filler of these deposits contains 2.5 to 3 times fewer pelite particles than the analogous deposits in non-volcanic regions. However, occasionally we may observe more clay in the filler together with hydrothermally altered rocks in the area of glacier accumulation.

Glaciofluvial deposits are widespread near the bases of the Kamchatka strato-volcanoes where they form rather extensive, gently-sloping plains or sandar. The oldest of them was formed during the second phase of Upper Quaternary glaciation, and they begin from the edges of piedmont glaciers. At present the sandar are significantly eroded, and only small massifs with plane and slightly wavy surfaces are preserved. In the immediate vicinity of the edges of the glaciers of Upper Quaternary glaciation glaciofluvial deposits of this age are represented by boulder-pebble material with sand-clay matrix. Peripheral areas show a fine-grained structure. They are formed by sands and sandy loam in the upper and middle parts of cross-sections, and by pebble-sand series in the lower parts (Krayevaya and Melekestsev 1969).

Areas of hill-trough and ridge-trough topography composed of loose deposits (ridges of terminal moraines, hill-trough topography from the basal moraine, kames, and eskers) are widely developed in the intermountain depressions, mountain valleys, and sub-montane regions. The presence of these features and their structure and origin point to the character of ancient glaciation and to peculiarities of its degradation. Of greatest interest are the traces of activity of piedmont glaciers that lay near the foot of previously active volcanoes and left a specific accumulative topography which is often called hill-moraine, although it is composed not only of morainic but also of glaciofluvial deposits.

One such area is found near the western foot of the Klyuchevskoy volcanic group in the Studenaya and Pakhchi river basins to the west of the Ostryy Tolbachik volcano. Its area is about 130 km^2. It is divided by rivers into several parts. Sandur areas are composed of well- and medium-rounded sand and boulder-pebble deposits with glacial ooze.

An almost solid outcrop, some parts of which are shown successively in Figure 4, may be observed for a distance of 4 km on the right bank in the middle reach of the Pakhchi river.

As is shown in Figure 4 (I), the purely glacial deposits are exposed below glaciofluvial deposits. A number of inclined subparallel fissures are observed in a strongly compacted moraine. It is dissected into layers with a

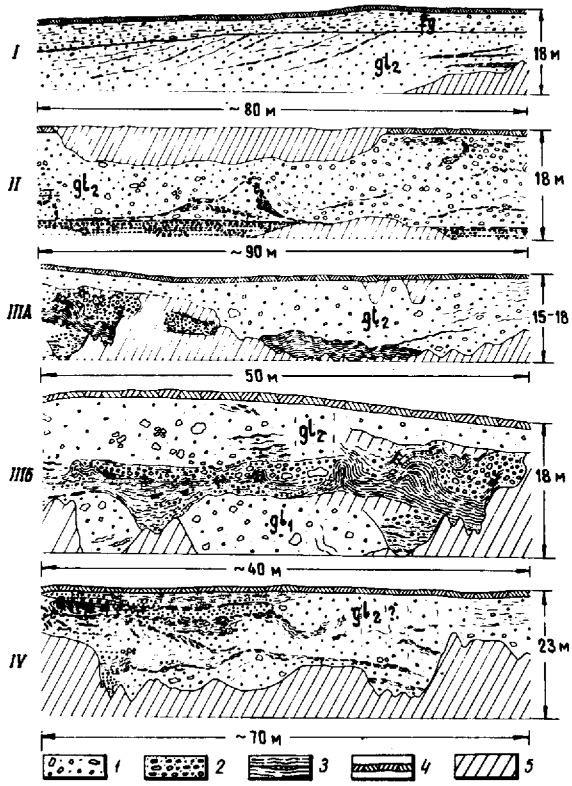

Fig.4. Schematic sketches reflecting the texture of the bottom moraine of late Pleistocene glaciation found in the valley of the Pakhchi river, western foot of the Ostryy Tolbachik volcano (after T.S. Krayevaya). Key: 1, boulder-debris-grus material of moraine with aleurite-sand filler; 2, glaciofluvial boulder-pebble-sand deposits with weakly developed subparallel bedding; 3, glaciofluvial aleurite-sand deposits containing fine-pebbled lens with strongly developed subparallel bedding; 4, soil-pyroclastic cover; 5, talik.

thickness of 1.5 to 3.0 km.

In Figure 4 (II) the moraine has a strongly developed sheet jointing. One may distinguish layers with different thicknesses along their strike. Less thick (not more than 1 m) intercalations of pebble-gravel-sand deposits can be observed for a distance of tens of metres between morainic strata.

Figure 4 (III B) is a partially overlapping enlargement and continuation to the left side of Figure 4 (III A). This figure shows two moraines: lower and upper (respectively, gl_1 and gl_2). It should be noted that in a massif of hill-trough topography dissected by the Pakhchi river two positions of a moraine corresponding to maximum (gl_1) and post-maximum (gl_2) phases of late Pleistocene glaciation can be distinguished.

Figure 4(III B) shows that between two strata of a moraine there are glaciofluvial boulder-pebble-sand deposits deformed without a break in continuity.

Figure 5 shows a basal moraine with the peculiarities of structure which are analogous to those shown in Figure 4 (II, IIIA). Thus, Figure 4 illustrates characteristic structures indicative of basal moraines deposited in the zone of thrust structure of the glacier (Krayevaya 1976).

In exposures of glacial formations in the valley of the Pakhchi river other basal moraine series may also be seen. Thus, Figure 5 (B) shows a detail of the upper portion of the down-stream part of exposure portrayed in Figure 4 (I). Here we see a distinct sub-horizontal orientation of long axes in large boulders as well as weakly developed striation of deposits. Similar structural peculiarities are the indications of the formation of moraine under the conditions of plastic flow of ice.

Figure 5 (A) shows subparallel banding structure of ice in the tongue part of lednik Erman in the Klyuchevskoy volcanic group. These structures may be compared to relict structures of ancient ice inherited by the basal moraine shown in Figure 5(B).

Thus the structural peculiarities of the Upper Pleistocene piedmont glaciers, described above, allow a comparison of these deposits with a basal moraine.

Glacial deposits in the region of the Pakhchi river were formed by the reworking by glaciers of large masses of volcano-clastics and lava of basalt and andesite-basalt composition, which participated in the building of volcanoes. In the course of glacial transportation an intense crushing and abrasing of captured material occurred.

After melting, glacial waters produced an intensive sorting of morainic material. Coarse unsorted and unlayered mudflow benches as parts of lacustrine-glacial accumulations are analogous in bulk composition to glacial deposits. The boulder-pebble and pebble benches are composed of lava fragments rounded to different degrees. Fine-pebbled and gravelly intercalations and lenses consist of angular fragments of lava and pyroclastics represented by scoria. Fine-grained sand and aleuropelitic lacustrine-glacial sediments consist of crushed pyroclastics and are close in composition to the corresponding fractions of glacial deposits.

Sandar of Holocene and recent glaciers are more widely developed. They are composed of strata of a dark-grey colour with distinct bedding parallel to the surface of plains. The boulder-pebble deposits with a filler composed of differently-grained sand are observed near the glacier. With distance from the glacier the particle sizes gradually diminish. Peripheral parts of sandar are composed predominantly of pebble-sand material (Krayevaya and Melekestsev 1969).

Recent glaciers in the regions of active volcanism are overlain by a cover of pyroclastic material from eruptions, as well as that brought down from steep debris slopes and snow slides. The thickness of this cover increases from the névé line to the ends of tongues. Its average thickness is 0.3 to 0.4 m, reaching in some parts 1 m. In the accumulation area of lednik Kozelskiy, on the watershed, the thickness of scoria produced by the 1945 Avachinskiy eruption is 1.6 m. The depth of fragmental material on the surface of the glacier favours the preservation of ice and the formation of areas of dead ice in terminal parts. These consist of 70 to 80% ice and 20 to 30% fragmental material. Currently, in the course of melting of glaciers containing large amounts of fragmental material, vast fields of morainic deposits are formed on the surface and within the stratum.

In conclusion, it has been possible to identify specific morphological types of glacier related to stages in a cycle of glacial erosion of volcanic areas of Kamchatka. In addition, opal-alunite rocks in hydrothermal areas are produced by glacial sedimentation processes.

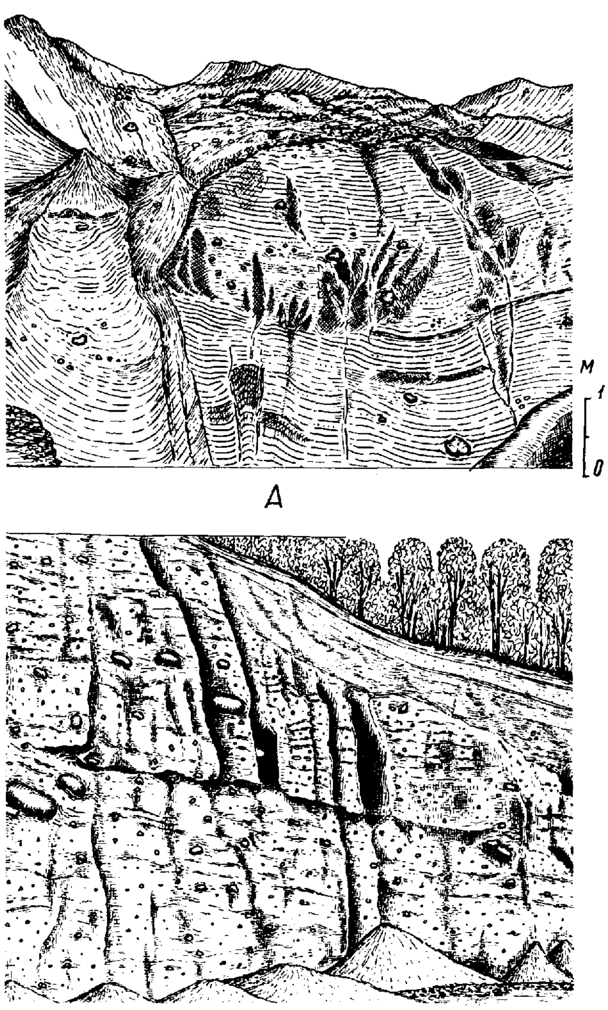

Fig.5. Banded structures in the glacier body and in moraine reflecting the layered-plastic ice movement. A: banded structure of ice in the tongue of lednik Erman (Klyuchevskoy volcanic group). B: banded basal moraine of Upper Pleistocene piedmont glacier with subhorizontal arrangement of long axes in boulders (Krayevaya 1977).

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