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Late Pleistocene (Würmian) glaciation of the Caucasus

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Introduction

The shaping of the high mountain relief of the Caucasus is closely connected to the geological and geomorphological activity of ancient glaciations. As on other high mountains, the glaciers left deep traces on the relief of the Caucasus in the form of diverse and variously-sized landforms. Traces of the past glaciations in various states of preservation are found in the river basins. They allow detailed re-construction of the process of Upper Pleistocene and Holocene glaciation. The investigations of the old glaciations in the Caucasus started in the 19th century. After publication of the works of Penck & Brückner (1909/11), many scientists attempted to correlate the glaciations of the Caucasus with those in the Alps (e.g. Reingard, 1937; Vardanyants, 1937; Tsereteli, 1966; 'Papers of Caucasian expedition', 1960-62, Shcherbakova, 1973). According to these authors, the entire Caucasus was either covered or partially covered by ice, with glaciers emerging from the mountains and moving down to very low altitudes, implying depression of the firn line by some 1100-1300m. Maruashvili (1956) opposed a mechanical application of the Alpine scheme to the Caucasus. He considered that the Late Pleistocene glaciation was of a much more limited character, the depression of the firn line being only about 600-800m. Since then, a number of new investigations, using different methods for the recon-struction of the old glaciations have been published (e.g. Kovalev, 1961; Khazaradze, 1968; Gobejishvili, 1995; Bondarev *et al.*, 1997).

Method of investigation

The Caucasus is of great interest from a theoretical point of view because it allows the comparison of the great difference in regime and dynamics of glaciers formed under a maritime and a continental climate. Because the Caucasus is located mid-way between the Alps and the mountains of Central Asia, they can provide indispensible information for the modelling of natural processes across vast regions.

However, the reconstruction of the extent and morphology of the old glaciations in the Caucasus is difficult. This is because the glaciations have often left only weak traces and there is a widespread occurrence of landforms and sediments resembling glacial deposits. In many regions the original trough forms of formerly glaciated valleys have been greatly changed by weathering, erosion and slope denudation. In these situations, for example, lateral moraines are usually either mostly or completely destroyed. End moraines on the valley floors, which were greatly subjected to glaciofluvial redeposition and mud flows, may be completely removed by streams that redeposited glacial outwash from their original positions to lower altitudinal levels.

In addition, very active exogenetic processes may lead to the formation of assemblages of moraine-like landforms, debris cones and mud-flow deposits. Traditional glacial geomorphological methods do not always allow these features to be differentiated and to assign them to a particular age. Consequently, significant discrepancies exist in the reconstructions of the extent of former glaciations in practically all fthe ormerly glaciated Eurasian mountain regions. Until recently the evidence of modern glaciation have been practically ignored in all investigations into these palaeo-glaciological problems. In more recent studies, however, the relationship between feeding area and length of modern glaciers has been compared to similar parameters from the old glaciations. For example, the length of the Late Pleistocene glaciers and their cirque areas was evaluated by comparison with the data from well-investigated modern glaciated regions. This relationship can be illustrated by the formula

$$Lc/Sc = Ld/Sd$$

Where:
Sc = the snowline altitude of modern glaciers,
Lc = the length of modern glaciers,
Sd = the snowline altitude of Pleistocene glaciers,
Ld = the length of Pleistocene glaciers.

Using this formula the definitions of Sc and Lc were determined by evaluation of topographic maps for all valley glaciers of Georgia and for some large glaciers of the Tien Shan, Spitsbergen, Tibet and the Himalayas. According to the relationship

$$Lc/Sc = K$$

four groups of glaciers could be identified:

- Hanging valley glaciers and simple valley glaciers K= 0,81 (s = 0,96),
- Valley glaciers with multiple source areas K=0,50 (s = 0,95),

- Complex valley glaciers K=0,33 (s = 0,93),
- Dendritic glaciers K=0,13 (s = 0,86).

If the coefficient (K) is known, the following formula can be applied:

$$Ld/Sd = K$$
$$Ld = Sd \cdot K$$

Sd = the feeding area of the old glaciers is determined by the altitude of the old cirques.

Results

Morphological and morphometric analysis, as well as remote sensing techniques, have revealed that Late Pleistocene glacial cirques formed in crystalline rocks are quite well preserved in the Caucasus. The author and colleagues have mapped all glacial cirques in this region and calculated their area. At the same time the altitude of the lower rock threshold of the cirques, which is considered to indicate the height of the former firn line position, was determined. Using this material, it was possible to calculate the length of the Late Pleistocene glaciers and to determine the altitudes to which the glacier tongues extended (Fig.1).

The Western Caucasus

In spite of their much more lower elevations in comparison to the Central Caucasus, extensive mountain valley glaciation developed here in the Late Pleistocene as a result of the high humidity. The principal glaciation centre was at the Main Range. The southern slope of the Western Caucasus was a significant glaciation centre during the Würmian Stage. The lower rock thresholds of former glaciers are found at 1900-2000 m, defining the lower boundary of the nival zone at this time. The largest glaciers occurred in the Kodori river basin, where the glacier tongues from the Chkhalta, Klich and Sakeni valleys converged. The river Chkhalta is the largest right-bank tributary of the Kodori river. Here field investigations revealed that the former glaciers descending through this valley terminated at different heights. Two independent glaciers existed in the upper part of the Chkhalta river valley; the Adange and Marukhi glaciers which descended from a common source area. Valley-type glaciers formed in the Chkhalta river valley on the Caucasian range. Only three of these descended to the valley floor. Two tongues of the Sofruju glacier terminated at 1050 m a.s.l., whereas the tongues of the Aciashi and Ptishi glaciers reached down to 760 and 600 m.

By contrast, large complex valley-type glaciers in the Kodori river basin descended from the Klich valley. Here there are well-exposed ancient cirques. The lower rock thresholds of these cirques are found at a height of 2000 m. Glaciers descending from those cirques converged into one tongue and advanced down to the mouth of the river Sakeni (700 m a.s.l.). Remnants of moraines from this advance are found at the villages of Gencvishi and Gvandra (Tsereteli, 1966; Khazaradze, 1968). The Klishi glacier reached a length of 19,5 km during the Würmian.

Another thick glacier formed in the upper reaches of the Sakeni river. Both in the Würmian and at present, the principal glaciation centre was found on the north-west slope of the Kodori ridge. The glaciers that formed there merged with other glaciers and moved in one ice stream to the valley of the Sakeni river, terminating near the village of Sakeni at an elevation of 1000 m a.s.l. This glacier reached a length of 25 km. The fact that in the Late Pleistocene glaciers descended down to Sakeni village was confirmed by glaciofluvial terraces found in the village of Sakeni (Tsereteli, 1966). In the Late Pleistocene glaciers not only developed on the southern slope of the Caucasus, but also on the Gagra, Bzibi, Chkharta and Kodori ridges. Their crests occurred in the nival zone, and some massifs reached into the glacial zone. In the Late Pleistocene numerous small corrie-type glaciers developed here, as well as corrie-valley and valley glaciers. Glaciers of 1-3 km length were situated on the northern slope. The glacier tongues reached down as far as 1600-1700 m.

The main glacial streams on the north slope of the Western Caucasus originated from the Main Range. Small glaciers joined them and descended as a single tongue within the Kuban and Teberda valleys down to 1100-1200 m a.s.l. The glaciers reached a length of 50-55 km.

In the basins of the rivers Marukhi, Aksaut and Zelenchuk the glacier tongues terminated at 1500-1700 m. The length of those glaciers was 30-35 km. The lower rock threshold of the ancient cirques was at 1800-1900 m a.s.l.

The Central Caucasus

High altitude longitudinal and traverse valleys, and depressions favourable for the accumulation of firn-ice, as well as the supply of sufficient humidity, favoured the development of strong glaciation in this region both during the Late Pleistocene and the Holocene. Glacial landforms are well-preserved in the landscape shaped by the Late Pleistocene glaciers. Studies have revealed that the lower rock thresholds of old cirques occur at different altitudes and rise significantly from west to east from 2100 to 2500 m. Large Late Pleistocene glaciers from the Central Caucasus descended into the Inguri, Rioni, Terek, Baksan, Cherek, Urukh and other river valleys.

Old morphostructural landforms (troughs, moraines, cirques) in the Inguri river basin have been mapped at scales of 1:150000 and 1:200000 on the basis of satellite images of the same scale. The glacial landforms map revealed that old cirques are fully developed not only on the Main Range, but also on the minor ridges. The evaluation of topographic maps showed that the height of the old cirque rock thresholds in the river Nenskra basin and on the north slope of Svaneti range lie at 2100 m a.s.l., whilst they

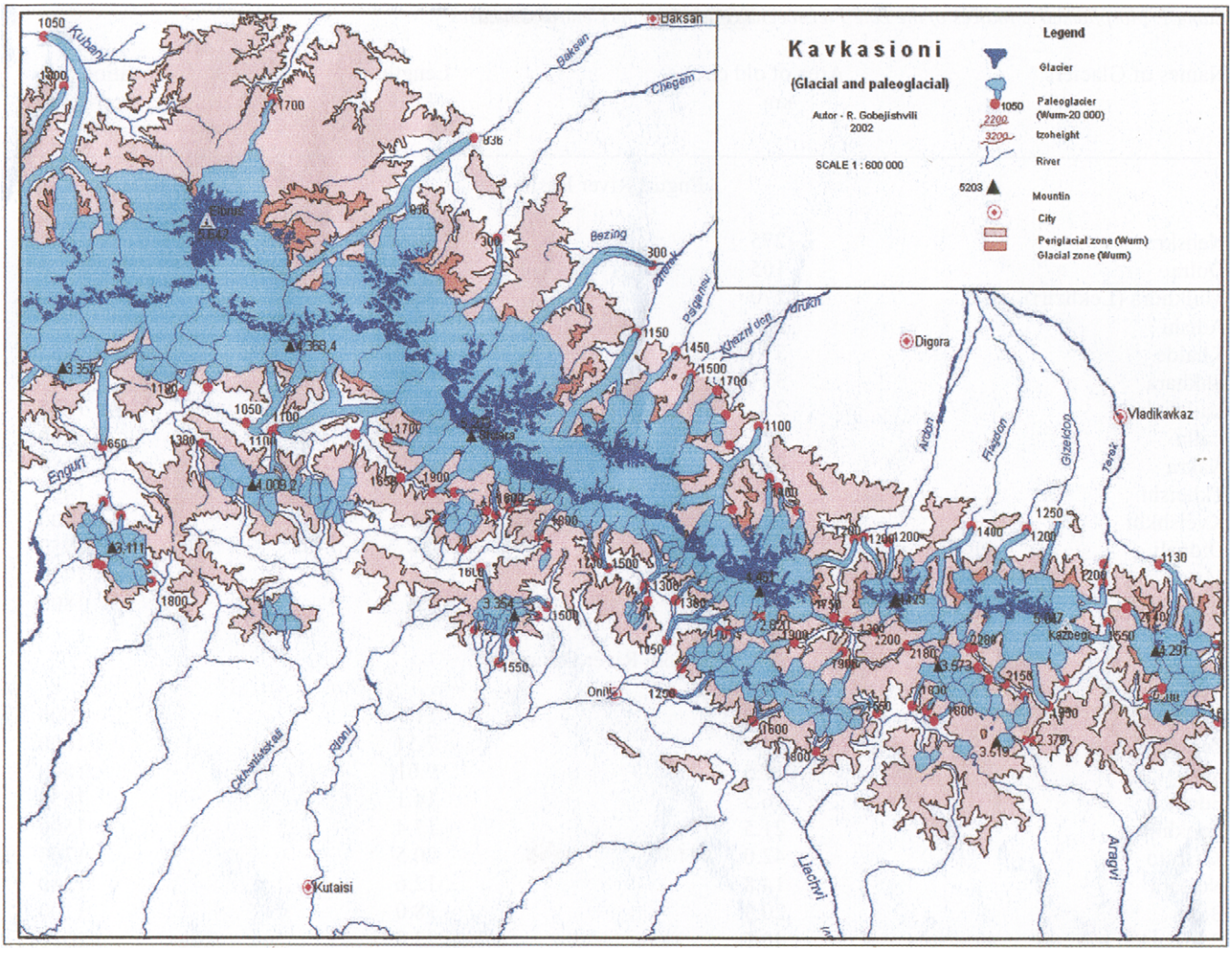

Fig. 1. Extent of the Würmian glaciation and periglazial zone in the central Caucasus region.

are found at 2200 m in the basins of the rivers Nakra, Dolra and Mulkhura, as well as in the upper course of the Inguri river. The old cirque rock thresholds in the Samegrelo range are *c.* 200 m lower. This is thought to reflect the height of the Late Pleistocene firn-line. Comparatively well-formed lateral moraines are found in some valleys of the Inguri, Nenskra, Dolra, Mulkhura, Adishura, Khaldechala, Inguri and Lailchala river basins. Where the lateral moraines are cut out, they indicate the location of former end moraines, which were almost completely subsequently removed in some valleys. On the basis of some published sources and new evidence, the altitude of the end moraines has been determined and the length of glaciers measured (Tabl. 1). Large and complex valley-type glaciers descended from the Main Range to the Rioni river basin. The southern slope of the Main Range from Naumkvan to Pasismta borders on the Tskhenistskali river basin (the largest right-bank tributary of the Rioni river). During the last glaciation, three glaciation centres formed in this area: Kolurdashi, Zeskho and the upper reaches of the Tskhenistskali river. All the bglaciers were of the simple valley-type.

Investigations have shown that the Koruldashi glacier was the largest in the Tskhenistskali river valley. The length of this glacier was 12 km; its tongue terminated at 1600 m a.s.l. This is confirmed by reliable glacial morphological evidence such as the trough form of the valley, as well as fragments of lateral- and end-moraines. Other glaciers were shorter than the Koruldashi, but their tongues also ended at 1600-1800 m altitude.

The upper course of the Rioni river drains the part of the Main Range between the town of Pasismta and the Mamisoni Pass. Here the Würmian glaciers descended from the Main Range and terminated at different heights. This suggests that they did not form a single glacier lobe. The Buba-Boko and the Kirtisho supported complex valley glaciers. The Kirtisho glacier reached a length of 21 km in the Würmian and terminated at 1300 m at Gebi village. Four cirques and lateral moraines are quite well developed in the river Chveshura basin at Jojokheta. Numerous erratic

Table 1. Morphometric Indices of the Late Pleistocene Glaciers of the Central Caucasus

Names of Glaciers	Area of old cirque km^2	Length km	Elevation of glacier terminus (m a.s.l.)
	Enguri River Basin		
Nenskra	275	36.0	680
Dolra	105	34.8	1050
Mulkhura (Lekhziri)	270	35.0	1000
Adishi	24	18.0	1700
Khalde	31	16.0	1650
Shkhara	35	17.0	1900
Lailchala	23	12.0	1100
Laila	17	13.0	1300
Nakra	63.0	20.0	1180
Tkheishi	7.0	5.6	1450
Kveishkhi	4.5	3.6	1600
Didgali	6.0	4.8	1350
Magana	7.5	6.0	1450
Khobistskali	8.0	6.4	1800
	Rioni River Basin		
Koruldashi	15.0	11.7	1600
Zeskho	9.0	7.5	1600
Shari	11.5	9.0	1800
Edena	16.5	14.1	1650
Zopkhito	21.5	17.4	1500
Kirshito	42.0	20.5	1300
Notsara	14.8	12.6	1280
Boko	20.9	18.0	1100
Buba	40.5	23.0	1050
Chanchakhi	13.1	11.0	1750
Garula	17.5	14.0	1250
Jejora	19.8	17.5	1600
Latashuri	11.0	8.5	1500
Sokhortuli	7.5	6.0	1600
Ghobishuri	8.5	7.0	1800
Shodura	5.4	4.0	1600
	Liakhvi River Basin		
Zekara	8.5	7.0	1900
Kvesheleta	10.0	8.0	1800
Jomagi	11.2	9.1	1550
Sba	9.2	7.5	1800
Cheliata	8.0	6.5	1850
Kalasani	11.0	9. 0	1800
	Tergi River Basin		
Devdoraki	38.5	14.2	1220
Gergeti	21.0	17.0	1550
Mna	23.0	18.0	1950
Suatisi	32.0	15.0	2150
Tergis Satave	20.0	10.0	2270

blocks are found around this village. Glacial material in the Rioni valley cannot be traced up to Saglolo. Instead, the morainic material in Saglolo derives from glaciers from the Chanchakhi river basin. The length of the Buba-Boko-glacier was 23 km; it terminated downvalley of Saglolo at 1100 m. In the tributary valleys of the Rioni-Edenura, Zopkhitura and Notsarula rivers glaciers of 14-17 km length occurred during the Würmian. The lower rock threshold of cirques in the Rioni river basin was at 2200 m a.s.l.

Erratic boulders are encountered on the flood plain of this valley at the town of Oni (800 m a.s.l.).The largest of these boulders (14 x 12 m) has a volume of *c.* 670 m^3. It is a monoclinic granite, derived from the axis zone of the Central Caucasus. The interpretations of these boulders differ greatly. Some consider them to be of glacial origin, while others interpret them as a result of a mud flow. In the author's opinion, these boulders were brought by an advance of the Buba-Boko glacier during the Würmian.

The Liakhvi and Rioni river basins on the south slope of the Central Caucasus were also intensely glaciated. Glaciers up to 14-16 km long formed in the Garula and Jojora valleys (both are tributaries of the Rioni river) during the Würmian, and their tongues terminated at 1400-1600 m. Some 8-10 km long valley glaciers also formed in the Liakhvi river basin. Their tongues descended down to 1700-1900 m, and the lower rock thresholds of these cirques were situated at 2300-2400 m a.s.l.

The upper valley of the Terek river basin occurs on the north slope of the Main Range of the Central Caucasus. The lateral Khorskhi ridge was the principal glaciation centre in the Late Pleistocene as it is today. An ice cap was situated in the eastern part of this range on the Kazbegi massif in the Late Pleistocene (as well as today). From here hanging-valley glaciers and valley glaciers moved in all directions. The largest glaciers were the up to 14-17 km long Devdoraki, Gergeti, Mna and Suatisi glaciers (Tab l.) which descended down to the Terek Velley. The tongue of the Devdoraki glacier terminated at 1200 m, whilst those of the Gergeti glacier terminated at 1550 m, the Mna glacier at 1950 m and the Suataisi glacier at 2150 m. There is no doubt that the 'Ermolov Stone' erratic block was transported by the Devdoraki glacier during the Late Pleistocene, perhaps during a major oscillation of the ice margin. The glacier tongues moved down to the valley floor and crossed the valley, creating favorable conditions for glacial mud-flows, for which the headwater region of the river Terek area is famous.

The termini of Late Pleistocene glaciers reached to 1000-1200 m a.s.l. on the northern slope of the Central Caucasus, and as a rule, ended at the south slopes of Skalisti (Rocky) Range, the length of glaciers being some 34-35 km. Only the Bezinga glacier crossed the Skalisti Range and terminated at 700-750 m a.s.l. This comparatively large glacier moved along the Baksan valley for some 70 km. It is obvious that the glaciers on the northern slope were almost twice the size of those on the southern slope. This arose from the trend direction and from the favourable north slope topography.

The Eastern Caucasus

The topography of the Eastern Caucasus greatly differs from the Central Caucasus, both in its morphology and by its altitude. The low altimetric position and significant aridity restricted the development of glaciers in this region. In the Würmian, like today, glaciers were largely limited to the highest massifs that rise above 3500 m. The author's calculations suggest that the lower limit of the glacial zone lay at this altitude. The nival zone was well represented in the Eastern Caucasus, especially on the Main Range during the Würmian. Numerous corrie glaciers and several valley glaciers formed in the Eastern Caucasus in the Late Pleistocene. Here the maximum glacier length was *c.* 6-8 km with glacier tongues reaching down to 1700-1800 m. The cirque lower rock thresholds lie at an altitude of 2400-2500 m. On the whole, the extent of glaciation on the Eastern Caucasus in the Late Pleistocene can be compared with present day glaciation on the southern slope of the Central Caucasus.

The Minor Caucasus

Investigations in the Minor Caucasus have revealed that the character of its glaciation was similar to that of the Eastern Caucasus. The Würmian firn line was lowest on the ranges located closest to the Black Sea (2200-2300 m), and highest on the ranges situated in the east (2500-2600 m). The nival zone encompassed the crests exceeding 2200-2400 m altitude. The strongly-degraded cirques in this area are distinguished by their small size. The largest valley glaciers formed on the Samsari Range, where they were 4-6 km long (Maruashvili, 1956). The cirque lower rock threshold was located at 2500-2700 m a.s.l.

Conclusions

The Late Pleistocene (Würmian) glaciation of the Caucasus was of mountain-valley character, with ice caps only on some peaks. The largest glaciers on the northern slope had a maximum length of 50-70 km, but glaciers of a considerable size (17-35 km length) occurred on the both slopes of the Central Caucasus. The glacier tongues which terminated at the lowest altitude were those of the Nenskra Glacier on the south slope at 600-680 m, and of the Bezingi Glacier on the north slope at 700-750 m. a.s.l. Tongues of other large glaciers descended down to 1600-1200 m. In the Late Pleistocene the firn line at the Central Caucasus was found at 2000-2500 m increasing in altitude from west to east. This implies that the firn line in the Caucasus was depressed by some 1200-1300 m during the Late Pleistocene (allowing for neotectonic activity) and increased from west to east. This is equivalent to a fall of mean annual temperature by *c.* 7-8° (with a gradient of 0,6°/100m altitude).

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