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The Plio-Pleistocene glaciation in eastern Europe, Siberia, and the Caucasus: Evolution of thoughts

(Paper presented at the meeting of the International Commission on the History of Geological Sciences (INHIGEO), Neuchâtel, Sept. 9–11, 1998)

EVGENI E. MILANOVSKY

Key words: History of Russian glacial research, paleoclimate and glaciation, neotectonics and glaciation, permafrost, alternating volcanic and glacial deposits, glacial history of the Caucasus

ABSTRACT

The most convincing concept of the great Pleistocene glaciation in northern Eurasia was developed in the 1870s by the Swedish geologist O. Torell and the Russian geographer and geologist P. A. Kropotkin, who had discovered traces of an extensive glaciation in eastern Siberia and Finland, published in the fundamental book "Researches on the glacial period" (1876, in Russian). Our paper describes the complex history of glacial research in northern Eurasia by Russian geologists. Unlike Kropotkin, most of them regognized the existence of several glaciations separated by interglacial epochs. The main centers of glaciation were distinguished. The most important glaciation developed under the humid climates of northern Europe and western Siberia. In the relatively dry regions of eastern Siberia ice sheets were of more limited extent and thickness, but there, permafrost reached depths up to 1–1.5 km.

First observations on the Pleistocene and Recent glaciation of the Great Caucasus and the Armenian Highland (especially of the Elbrus and Ararat volcanoes) were made by G. Abich in 1844–1850. In the first half of the 20th century the Russian geologists A. P. Gerasimov, A. L. Reinhard, V. P. Rengarten and others established a history of Caucasian glaciations comparable with that developed by Penck and Brückner, even though disagreements about the correlations subsisted. In the central part of the Great Caucasus young volcanic rocks alternate with glacial deposits. The modern chronology of the Great Caucasus glaciations developed by the author and A. V. Kozhevnikov distinguishes: 1) a Late Pliocene Elbrus Glaciation (analogue of the Danubian Glaciation of the Alps?) – 2) an Eopleistocene Chegem Glaciation (analogous to Günz) – 3) an Early Pleistocene Eltübü Glaciation (analogous to Mindel) – 4) a Middle Pleistocene Terek Glaciation with several phases and stages (analogous to Riss) – 5) a Late Pleistocene-Early Holocene Bezingi Glaciation (analogous to Würm and Bühl of the Alps) – 6) advance and retreat of glaciers in the 17th to 19th centuries. The Late Pliocene – Eopleistocene glaciations belonged to the semi-sheet type, Pleistocene glaciations to the trough valley type. The maximal advance of glaciers was in the Middle Pleistocene. In the eastern part of the Great Caucasus and in the Minor Caucasus glaciations are were limited due to a more arid climate and lesser elevations.

ZUSAMMENFASSUNG

Der schwedische Geologe O. Torell und der russische Geograph und Geologe P. A. Kropotkin entwickelten in den 1870er Jahren ein höchst überzeugendes Konzept der grossen pleistozänen Vereisung im nördlichen Eurasien. Kropotkin hatte Spuren einer ausgedehnten Vereisung in Ostsibirien und Finnland entdeckt, publiziert in dem fundamentalen Werk «Untersuchungen über die Eiszeit» (1876, auf russisch). Unsere Veröffentlichung beschreibt die komplexe Geschichte der Erforschung der Eiszeit im nördlichen Eurasien durch russische Geologen. Abweichend von Kropotkin nahmen die meisten von ihnen das Vorhandensein von mehreren Vereisungen an, getrennt durch Interglazialzeiten. Die Hauptzentren der Vereisung wurden unterschieden. Die stärkste Vereisung entwickelte sich unter den feuchten Klimaten Nordeuropas und Westsibiriens. In den trockeneren Regionen Ostsibiriens waren die Eiskappen von geringerer Ausdehnung und Dicke, aber der Permafrost erreichte dort Tiefen von bis zu 1–1,5 km.

G. Abich machte 1844–50 erste Beobachtungen einer pleistozänen und rezenten Vereisung des Grossen Kaukasus und des Armenischen Hochlandes (besonders der Vulkane des Elbrus und des Ararat). In den ersten Hälfte des 20. Jahrhunderts entwickelten die russischen Geologen A. P. Gerasimov, A. L. Reinhard, V. P. Rengarten und andere eine chronologische Einteilung der kaukasischen Vereisungen, vergleichbar mit der von Penck und Brückner, obwohl manche Korrelationen umstritten blieben. Im Zentrum des Grossen Kaukasus wechsellagern junge vulkanische Gesteine mit Glazialablagerungen. Die moderne Chronologie der Vereisungen des Kaukasus, entwickelt vom Autor und A. V. Kozhevnikov, unterscheidet: 1) eine spätpliozäne Elbrus-Vereisung (analog der Donau-Vereisung der Alpen?) – 2) eine eopleistozäne Chegem-Vereisung (analog zum Günz) – 3) eine altpleistozäne Eltübü-Vereisung (analog zum Mindel) – 4) eine mittelpleistozäne Terek-Vereisung mit mehreren Phasen und Stadien (analog zum Riss) – 5) eine spätpleistozän-holozäne Bezingi-Vereisung (analog zu Würm und Bühl der Alpen) – 6) Vordringen und Rückzug der Gletscher im 17. und 19. Jahrhundert. Die spätpliozän-eopleistozänen Vereisungen entsprachen mehr oder weniger dem Eiskappentypus, während sich später im Pleistozän Talgletscher bildeten. Die maximale Ausdehnung der Gletscher wurde im Mittelpleistozän erreicht. Im östlichen Grossen Kaukasus und im Kleinen Kaukasus waren die Vereisungen wegen des trockeneren Klimas und der geringeren Meereshöhe weniger ausgedehnt.

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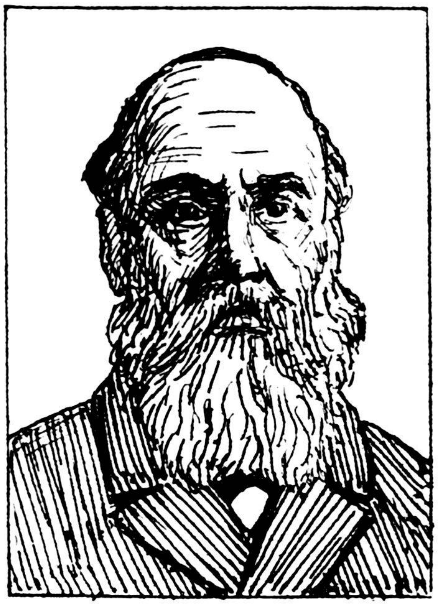


Fig. 1. One of the first researchers of ancient glaciation on the Eastern European plain academician Fedor Bogdanovich Schmidt (1832–1908).

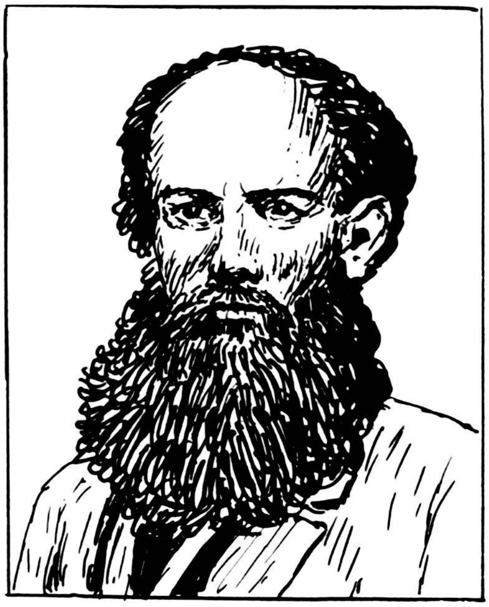
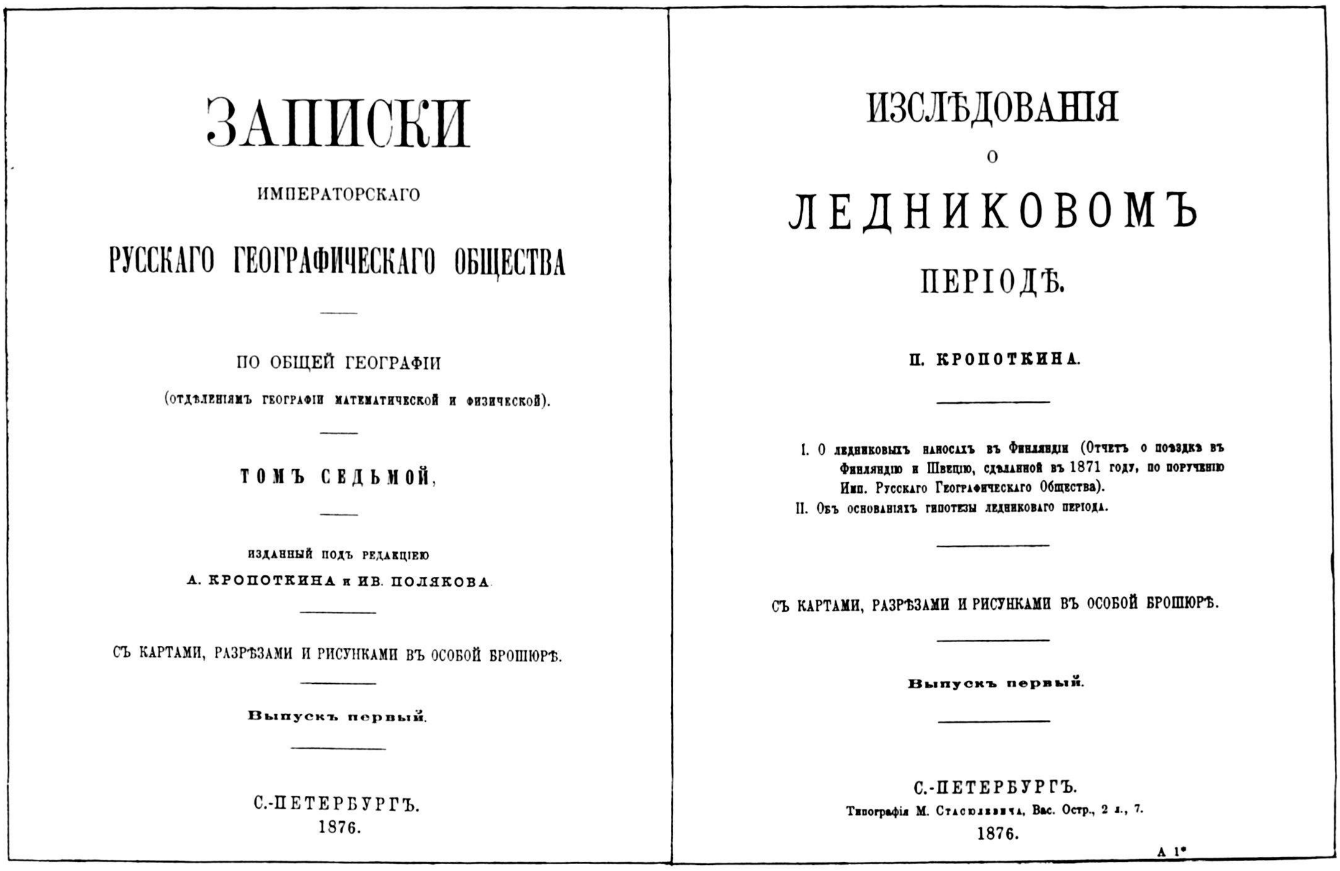


Fig. 2. One of the founders of doctrine on the Pleistocene glacial period, later – the famous Russian revolutionary Pietr Alexeevich Kropotkin (1842–1921).

The first steps in the study of the Pleistocene glaciation in Russia

Although in the Alps, I. Venetz, J. Charpentier, and L. Agassiz had found definite evidence of the Pleistocene glaciation in the 1830s–40s (Hallam 1983), in northeastern Europe and Siberia the origin of sediments, which we now identify as glacial moraine, remained unclear until the early 1870s. In the 1820s–30s, some geoscientists suggested the existence of a former glaciation not only in the Alps, but also in the highlands and the plains of Norway (J. Esmark), Germany (R. Bernhardi, K. Schimper), and Scotland (L. Agassiz, W. Buckland). However, the authority of Charles Lyell who published a popular "drift hypothesis" explaining the dispersion of erratic boulders by floating ice (Lyell 1863), and of Roderick Murchison (1845) who confirmed Lyell's ideas during his geological expedition to European Russia in 1840–41, impeded the recognition of former glaciations in the East European Plain. Several outstanding Russian geologists (Shchurovsky 1856, Helmersen 1869, Schmidt 1865) generally supported the drift hypothesis. F. B. Schmidt (1832–1908, Fig. 1) described the Quaternary boulder-bearing sediments in Estonia. He used an Estonian word "rikh" for glacial moraine deposits. He also indicated that clastic material was transported from north to south (from Finland and Sweden) based on the analysis of the composition of boulders and of the direction of scratches below the boulder-bearing deposits. At the same time, Schmidt in Russia and some Scandinavian geologists interpreted osar as coastal banks formed under the influence of ice blocks floating in the cold seas of the Glacial Period. These geologists attempted to combine the elements of drift and glacial hypotheses. Later on, following the works of Kropotkin, Schmidt became, however, a convinced supporter of the glacial theory (Schmidt 1879).

Fig. 3. Routs of P. A. Kropotkin's expeditions in Baikalian region of Eastern Siberia in 1865 and 1866.



ЗАПИСКИ

ИМПЕРАТОРСКАГО

РУССКАГО ГЕОГРАФИЧЕСКАГО ОБЩЕСТВА

ПО ОБЩЕЙ ГЕОГРАФИИ

(ОТДѢЛЕНІЯМЪ ГЕОГРАФІИ МАТЕМАТИЧЕСКОЙ И ФИЗИЧЕСКОЙ).

ТОМЪ СЕДЬМОЙ,

ИЗДАННЫЙ ПОДЪ РЕДАКЦІЕЮ

А. КРОПОТКИНА и ИВ. ПОЛЯКОВА

СЪ КАРТАМИ, РАЗРѢЗАМИ И РИСУНКАМИ ВЪ ОСОБОЙ БРОШЮРѢ.

Выпускъ первый.

С.-ПЕТЕРБУРГЪ.
1876.

ИЗСЛѢДОВАНІЯ

О

ЛЕДНИКОВОМЪ

ПЕРІОДѢ.

П. КРОПОТКИНА.

I. О ледниковыхъ наносахъ въ Финляндіи (Отчетъ о поѣздкѣ въ Финляндію и Швецію, сдѣланной въ 1871 году, по порученію Имп. Русскаго Географическаго Общества).
II. Объ основаніяхъ гипотезы ледниковаго періода.

СЪ КАРТАМИ, РАЗРѢЗАМИ И РИСУНКАМИ ВЪ ОСОБОЙ БРОШЮРѢ.

Выпускъ первый.

С.-ПЕТЕРБУРГЪ.
Типографія М. Стасюлевича, Вас. Остр., 2 л., 7.
1876.
А 1*

Fig. 4. The title pages of P. A. Kropotkin's book "Researches on the glacial period". *On the right page is written (in English translation):*
Researches on the glacial period by P. Kropotkin.
I. On the glacial deposits in Finland (Report on the journey into Finland and Sweden in 1871 by proxy of Imperial Russian Geographic Society)
II. On the foundations of hypotheses on the glacial period with the maps, sections and pictures in the separate brochure. First issue, S-Petersburg, M. Stasjulevich typography. Vassilijevsky ostrov, 2 L. 7. 1876.
On the left page (in English translation):
Memories of Imperial Russian Geographic Society on the general geography (sections of mathematical and physical geography). Volume seven issued under edition of A. Kropotkin and I. V. Poljakov, with the maps, sections and pictures in the separate brochure. First issue, S.-Petersbourg. 1876.

The most complete and convincing justification of the concept of the great Pleistocene glaciation in northern Eurasia was given in the 1870s in the classic works by O. M. Torell (1828–1900), who was the founder and first director of the Geological Survey of Sweden, and by Prince Petr Alekseevich Kropotkin (1842–1921), an outstanding Russian geographer and geologist, who later became a famous revolutionary and theorist of anarchism (Fig. 2).

In 1864–66, Kropotkin was a young officer of the East Siberian Administration and also a military geographer. During his expeditions to the Vitim Highlands in Transbaikalia (East Siberia), he had found polished and scratched boulders in the river valleys. These were boulders of granites, absent in situ and therefore undoubtedly transported from adjacent regions. Kropotkin also noted signs of smoothing and glacial furrows on the hardrock surface beneath the boulder accumulations (Fig. 3). He concluded that these boulders could only have been transported and redeposited by a large and thick glacier, which formerly covered the surrounding mountains and descended down to an altitude of 700 m, whereas the present glaciers in East Siberia do not reach farther down than 3,000 m (Kropotkin 1873).

Fascinated by the problem of a former continental glaciation in Siberia, Kropotkin critically studied all European and American literature on this topic. Due to his great success, he was soon awarded the membership of the Russian Geographical Society (1967) and became the secretary of its physical geography section (1868). In 1871, the Society sent him on an official journey to Finland and Sweden to study the evidence for a former glaciation. During this very fruitful expedition,

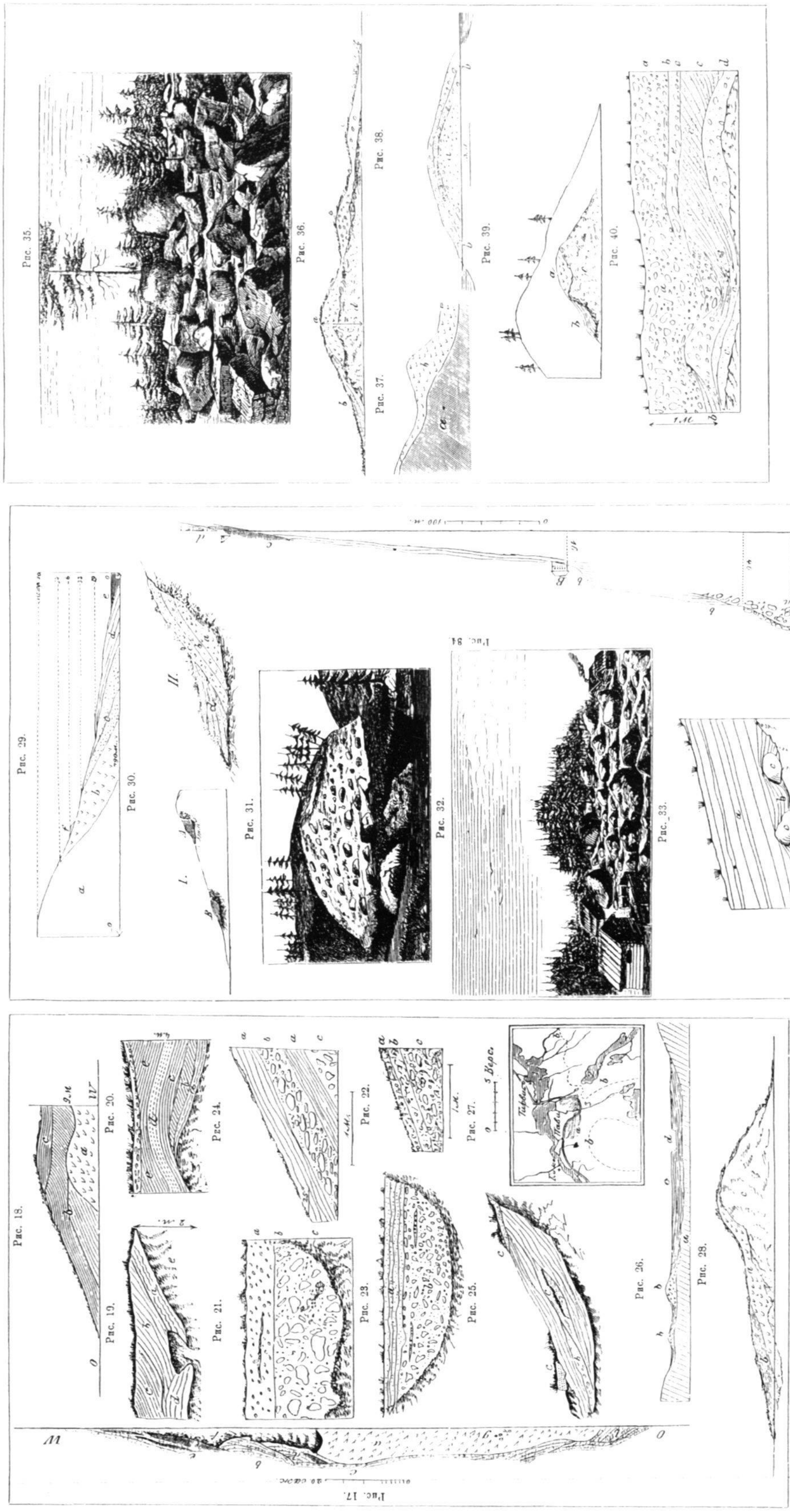


Fig. 5. Several illustrations to the 1. issue of P. Kropotkin's book "Researches on the glacial period" [1876].

Kropotkin collected most valuable field data and studied also collections in the Swedish museums. These data and the critical analysis of world literature definitely convinced him that the former glaciation had a very wide extension in northern Europe, Siberia, and North America. His lecture and preliminary report had a great success in the Russian Geographical Society (Kropotkin 1874). Later, he published his "Researches on the Glacial Period" (Kropotkin 1876), a fundamental two-volume monograph, where he reported on the results of his observations in Scandinavia and Siberia and outlined the principal problems and hypotheses concerning the glacial period. In this monograph, Kropotkin discussed in detail different aspects of morphology, structure and origin of glacial and related sediments and forms of glacial landscapes. Perhaps the most significant part of this work, which preserves its value up to the present day, is an original concept of the dynamics of a continental ice sheet as a result of slow plastic flow, induced by its own weight. The flow was believed to start from the highest internal area of the ice sheet, where the ice was of the greatest thickness and might be several kilometers thick (Pavlov 1976, Shanzer 1976). On the other hand, some aspects of Kropotkin's glacial theory disagree with modern opinions. For instance, he believed in one unique glaciation and his interpretation of the origin of osar did not survive.

Unfortunately, Kropotkin was not able to complete his work. In the early 1870s he visited western Europe just after the French revolution of 1870–71. For a long time he became involved in secret revolutionary activities. In 1874 he was arrested and held prisoner in the Peter-and-Paul Citadel in St. Petersburg. Nevertheless he continued his scientific work in prison, completing the first volume of his monograph, supplemented with a short summary of the contents of the second volume. An unfinished manuscript of the second volume is preserved, but was never published.

The first volume contains 828 pages (Fig. 4) and a separate fascicle with graphic supplements including 100 maps, cross-sections, and original drawings (Fig. 5). His brother and true friend Alexander helped to publish a monograph in the Memoirs of the Russian Geographical Society, volume 7, which came out in 1876 almost simultaneously with Kropotkin's escape from the prison hospital. He was forced to live for more than 40 years in different countries of western Europe and devoted himself almost completely to revolutionary activity. He continued his scientific work anonymously and only in passing because of his illegal position. He was a scientific reviewer of "Nature" and other magazines, where he published about 200 papers (Markin 1985). He could return to Russia only after the 1917 revolution shortly before his death in 1921.

In Russia, Kropotkin's fundamental work made a great impact. It convinced the majority of Russian scientists of the glacial theory. His work showed the evolution of this theory and methods of glacial research employed in western Europe and America. However, this outstanding work was only published in Russian and remained almost unknown in western Europe and America.

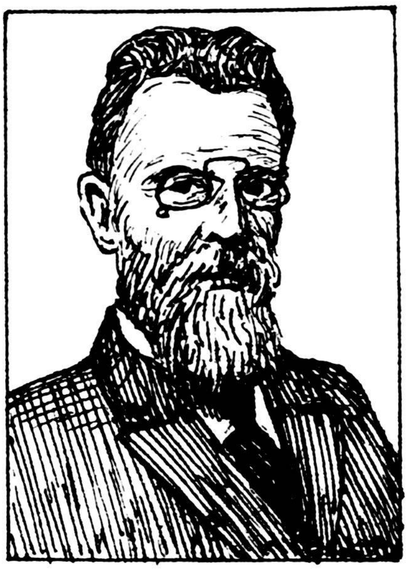


Fig. 6. Russian geologist academician Alexej Petrovich Pavlov (1854–1929) who for the first time (in 1888) established the plurality of Quaternary glaciations on the East-European plain.

Evolution of thoughts on the former glaciation in northern Europe and Siberia and its present status

During the 40 years preceding the Russian October Revolution in 1917, significant progress was made in research on the glacial period. The systematic geological mapping of the European part of Russia started in the 1880s. The area of the Baltic Shield and the Polar Urals were recognized as centers of the glaciation, and its maximal extent to the south was outlined. The study of lithological successions of the various Quaternary deposits showed the presence of several moraine and non-glacial levels, i. e. several glacial and interglacial epochs were recognized. The existence of two moraine horizons in one section was discovered in 1888 by the outstanding Russian geologist A. P. Pavlov (1854–1929, Fig. 6) in the western part of the central Volga region, and in 1890 by N. I. Krishtafovich near Moscow. Later, Pavlov recognized at least three Quaternary continental glaciation events on the East European Plain (Pavlov 1922). However, some Russian geologists continued to recognize only one Pleistocene glaciation.

Even more important results in the study of glaciation of the East European Plain and of the plains and highlands of Siberia were achieved between the 1917 Revolution and World War II, and in the 1940s–80s before the breakup of the USSR in 1991. The latter event caused considerable reduction of research in Earth sciences in Russia. A. P. Pavlov (1922), G. F. Mirchink (1936), I. P. Gerasimov (in: Gerasimov & Markov 1939), V. I. Gromov (1948), S. A. Yakovlev (1956), A. I. Moskvitin (1967), K. K. Markov (in: Markov et al. 1965), G. I. Goretsky, I. I. Krasnov and many other outstanding Russian geologists and paleogeographers obtained significant results in

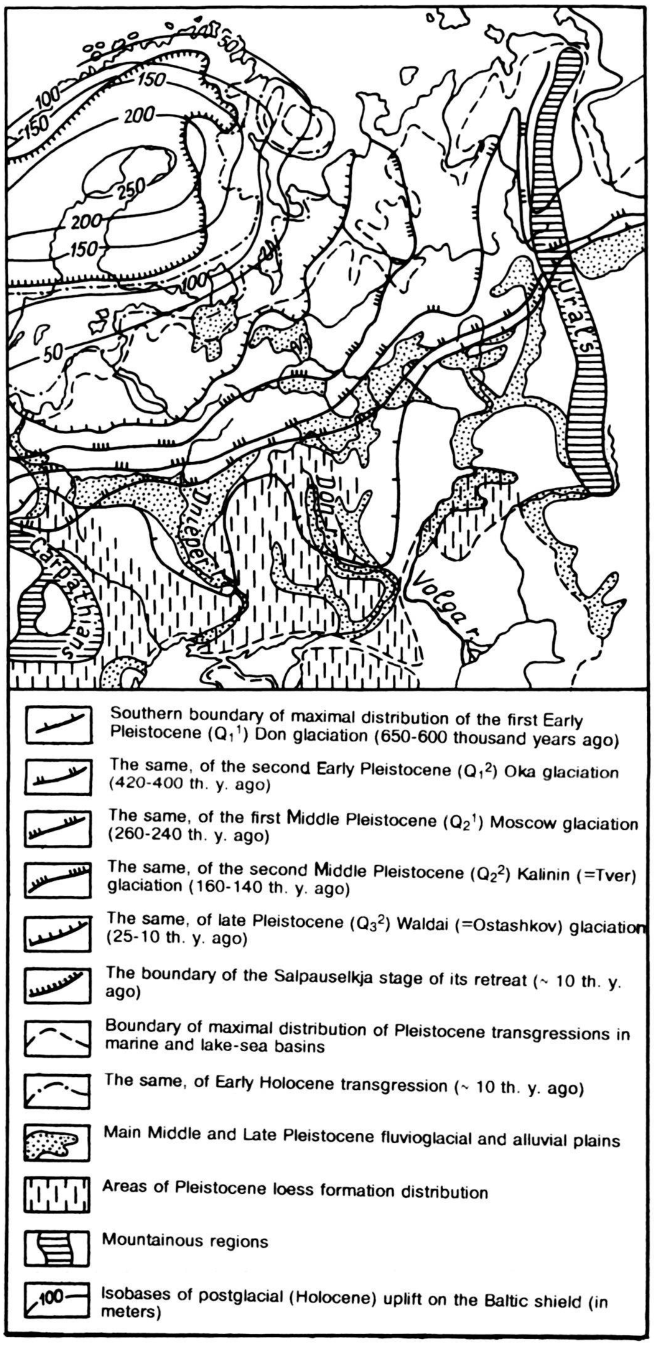


Fig. 7. Distribution of Quaternary glacial sheets of different age and some other elements of Quaternary palaeogeography on the territory of East-European plain *Compiled by E. E. Milanovsky* [1987].

studying late Cenozoic glaciations on the territory of the former USSR. In the framework of this paper it is impossible to discuss all the ideas expressed on the Cenozoic glaciation of northern Eurasia, and I will only mention the most important results.

During this period, geologists definitely accepted the glacial origin of the boulder-bearing clayey sediments covering the northern half of the East European Plain. However, even in the 1940s–50s, the Ukrainian paleozoologist I. A. Pidoplichko (1946–1956) believed in the drift origin of boulders. There are also diverging opinions about the origin of glacial boulder-bearing and pebble-bearing thin-bedded sediments in the northern part of the West Siberian and Pechora Plains. One group of geologistes considers them as proper glacial sediments, whereas the other group perceives them as glacial-marine sediments, including coarse clastic material transported by icebergs and floating blocks of ice. The third group believes in a combination of two types. Now all Russian geologists recognize several Quaternary glacial and interglacial epochs. However, Gromov (1948), an authoritative researcher, believed that there were permanent ice sheets in the northern part of eastern Europe and West Siberia during the Pleistocene, which periodically expanded or retreated in connection with global climate changes. Among polyglacialists there were, however, different opinions about the number of individual Quaternary glaciations. Most of them recognized three or four events, whereas Yakovlev Moskvitin (1967) revealed up to six or even eight glaciations.

In these works the limits of the maximum expansion of the glacial sheet in eastern Europe and West Siberia, which propagated from the main Scandinavian center and smaller centers of the Polar Urals and the Putorana Plateau, were accurately traced and mapped. Several relatively small glacial sheets in East Siberia were located mainly on highlands and mountain ridges (Fig. 7, 8). These differences in distribution of ancient glaciations in the northern parts of western and eastern Eurasia are due to arid climatic conditions in East Siberia, where, instead of an expansion of glacial sheets, an extremely intensive permafrost developed during very cold Pleistocene epochs. The depth of permafrost exceedes 1,000 m.

During this period of study, the geologists established the limits of glaciations which had taken place before and after the main event. But in spite of great progress in stratigraphic, paleontological (palynological), isotopic-geochronological, magnetostratigraphic research and geological mapping of the late Pliocene-Quaternary glacial and interglacial deposits in eastern Europe and Siberia, many problems remain unresolved up to the present time, such as the correlation with glaciations in western Europe, North America, the Caucasus, and the Alps, the number of glaciations and the age of the earliest glaciation in eastern Europe, West and East Siberia.

The earliest glaciations in Europe occurred in the middle and late Pliocene (3.5–2 Ma ago). Although reliably established in Iceland, inferred in the Alps and recently discovered in the Caucasus, their presence in the continental regions of Eurasia is not yet trustworthily established. But the late Pliocene glaciation took probably place on the archipelagos and islands of the Arctic Ocean, in Scandinavia and some other northern regions of eastern Europe.

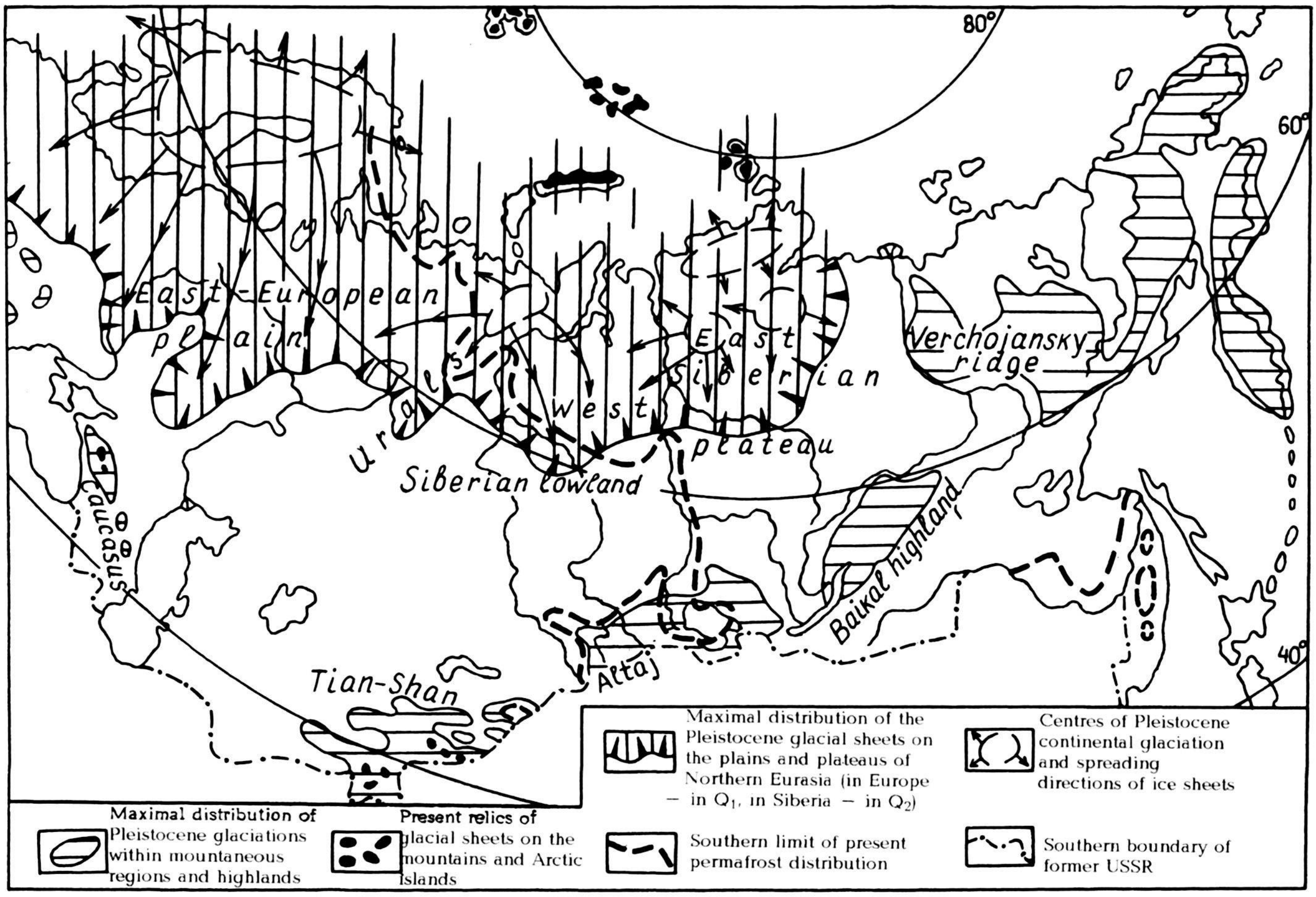


Fig. 8. Maximal distribution of the Quaternary continental glaciations and permafrost on the territory of northern Eurasia. *Compiled by E. E. Milanovsky.*

In the Great Caucasus, on the arctic islands and the Baltic Shield (Table 1), the geologists observed and inferred Eopleistocene glaciation events (Eopleistocene according to the Russian stratigraphic scale or Early Pleistocene according to the West-European scale), corresponding to the time interval between 1.8 and 0.7 Ma ago. These events are considered to be equivalents of the Danube and Günz Glaciations in the Alps.

Between 0.7 and 0.375 Ma ago (Early Pleistocene of the Russian scale) the continental ice sheet covered not only the Baltic Shield and the Polar Urals, but also spread to the south over the vast plains in the northern and central parts of central and eastern Europe. By the end of the Early Pleistocene, it expanded to the northern part of the West Siberian Plain. In the 1980s, most Russian geologists believed that in contrast to central Europe, where the maximal glacial extent was attained in the Early Pleistocene (= Elster or Krakow), the Early Pleistocene (= Oka) Glaciation in eastern Europe was considerably smaller than the Middle Pleistocene (= Dnieper) Glaciation whose main "tongues" expanded to the south along the lowlands of the present Dnieper and Don, reaching 48° N. However, recent studies have shown that the glacial deposits of the Don "tongue" and possibly also of the Dnieper "tongue" (?) belong in reality to the Early Pleistocene glacial epoch (Velichko 1981) and thus correspond approximately to the Krakow Glaciation in Poland or the Elster Glaciation in Germany. This means that the Early Pleistocene glaciation had its maximum not only in central but also in eastern Europe.

In this case, the Moscow Glaciation in eastern Europe, which was originally correlated with the upper part of the Middle Pleistocene and considered as a second phase of the Dnieper Glaciation, corresponds to the entire Middle Pleistocene of the Russian scale (0.375–0.1 Ma ago). The Moscow Glaciation can thus be correlated with all of the Saale Glacial Epoch of central Europe, whereas it was only compared with its late (= Warta) phase before.

Until recently, the Valdai (last) Glaciation of eastern Europe (Gerasimov & Markov 1939, Markov et al. 1965) which corresponds to the Vistula (or Weichsel) Glaciation of central Europe, was correlated with the Late Pleistocene (0.1–0.010 Ma ago). It consists of two phases: the first (main) Early Valdai (or Kalinin) phase and the second (smaller) Late Valdai (or Ostashkov) phase (0.025–0.010 Ma ago). The most

Table 1. Chronological correlation of the Pliocene and Quaternary glaciations in Eastern Europe, Great Caucasus and Siberia with Central Europe and the Alps

Compiled by E.E. Milanovsky, 1998

abs. age th. y.	geolog. age			Alps	Central Europe	Eastern Europe	Great Caucasus	West. - Middle Siberia	Altaj mountains
		Western - European scale	Russian scale						
10		Holocene Q_4							
				Würm – 2 – glaciation	Wistula glaciation	Late Waldai (Ostashkov) glac.	Bezengi – 2 glaciation	Zyrian – 2 (Sartan) glaciation	Akkem glac.
50		LATE PLEISTOCENE							
				Würm – 1 – glaciation	Szchecin cool epoch	Early Waldai cool epoch	Bezengi – 1 glaciation	Zyrian – 1 glaciation	Chibit glac.
100				R – W interglacial	Eem interglacial				
				Riss – 2 glaciation	Saale – 2 (Warta) glaciation	Kalinin glaciation	Terek – 2 glaciation	Taz glaciation	Chuja glac.
			MIDDLE		Treene interglacial				
200				Riss – 1 glaciation	Saale – 1 (Drente) glaciation	Moscow glaciation	Terek – 1 glaciation	Samarovo glaciation	Eshtykol glac.
300	QUATERNARY	MIDDLE	PLEISTOCENE Q_2	M – R interglacial	Golstein interglacial	Likhvin interglacial		Tobol interglacial	
400	=	PLEISTOCENE		Mindel glaciation	Elster (Crakow) glaciation	Oka (Berezina) glaciation	Eltübü – 2 glaciation	Shaitan glaciation	Late Katun glac.
500 600	ANTHROPOGENE		EARLY PLEISTOCENE	G – M interglacial	Kromer interglacial	Belovezha interglacial			
			Q_1	Haslach glac. (?)	?	Don (Dzuki) glaciation		?	Early Katun glac.
700	Q						Eltübü – 1 glaciation		
800		EARLY	EOPLEISTOCENE	Günz glaciation	Menapian cool epoch	Olonets glaciation (?)	2.eopleistocene glaciation?		Bashkatau glac.
1000 1200		PLEISTOCENE	Qeo	D – G interglacial	Vaal warm epoch	Scyphian warm epoch			
1400			(Apsheronian stage)	Danub (Donau) glaciation	Eburon cool epoch	Domashkino cool epoch	1.eopleistocene glaciation?		
1600				B – D interglacial	Tegelen warm epoch				
1800		LATE							
2000	PLIO-	PLIO-	Akchagyl	Biber glaciation	Pre – Tegelen epoch		Chegem glaciation		
2500 3000	CENE N_2	CENE N_2^2	stage				Elbrus glaciation		
3500 4000 4500 5000		EARLY PLIOCENE N_2^1	Kimmerian (Balakhan) stage						
5500		Late Miocene							

recent study showed that the cooling of the first half of the Late Pleistocene was not significant enough to cause a considerable glaciation on the East European Plain and that the only undisputable Late Pleistocene Ostashkov, or proper Valdai Glaciation, which spread from the Baltic Shield to the northern part of the East European Plain, occurred at the end of the Late Pleistocene between 25,000 and 10,000 years ago and completely disappeared in the first half of the Holocene (Velichko 1981).

The interglacial epochs of the Pleistocene and the postglacial Holocene Epoch correlate with considerable glacioeustatic rises of the ocean level and consequently with transgressions of the marginal seas of the Arctic Ocean, Black Sea and Baltic Sea in the Holocene. They also correlate with the marine ingression in the river valleys of Severnaya Dvina, Pechora, and Enisei. In contrast, transgressions and ingressions of the isolated Caspian Sea coincided with the termination of the glacial epochs and the beginning of interglacial epochs.

On the West Siberian Plain, the first (Shaitan) Glaciation occurs only at the end of the Early Pleistocene, later than the first glaciation on the East European Plain. The most significant Samarovo Glaciation spread southward to 60°N–62°N. The less important Taz Glaciation took place in the Middle Pleistocene. The relatively limited Zyrian (early Zyrian) and Sartan (or late Zyrian) Glaciations in Siberia are of late Pleistocene age.

The glacial sheets in West Siberia spread southeastward from the Polar Urals and southwestward from the Putorana Highlands in the northwestern part of the East Siberian Plateau. They completely (or almost completely) joined each other in the central part of the West Siberian Plain. These glaciers formed temporary glacial and moraine barriers which dammed the main West Siberian rivers Tobol, Irtysh, Ob, and Enisei, flowing to the north. This created great lakes and a huge West-Siberian Lake to the south of this glacial barrier. During such epochs, water partly leaked to the southwest into the basins of the Aral and Caspian Lakes. Some geologists, however, believe that a considerable part of "glacial" sediments in the northern part of West Siberia is in fact of marine-glacial or even marine origin.

In East Siberia, where Quaternary climatic conditions were the coldest and driest compared to West Siberia and eastern Europe, the epochs of global cooling intensified the process of freezing in the upper part of the Earth's crust. Glacial sheets in

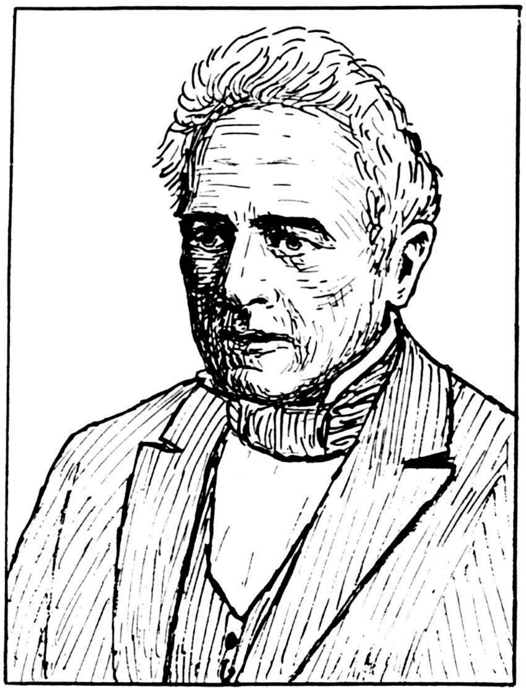


Fig. 9. The German Wilhelm Abich (1806–1886) – "father of Caucasian geology", the first researcher of the modern and recent glaciation of Caucasus. Member of St.-Petersburg Acad. Sci.

East Siberia periodically appeared on the highlands of Putorana, Anabar, Taimyr, Transbaikalia and Anadyr and also in the high mountain ridges of Altai, Western and Eastern Sayan, Stanovoy, Verkhoyansk, Chersky, Koryak, and Kamchatka Peninsula.

Extensive and thick glacial sheets probably survived the whole Quaternary time until present on the archipelagos and large islands of the Arctic Ocean on Svalbaard, Franz-Josef-Land, Novaya Zemlya, Severnaya Zemlya, Novaya Sibir, etc. According to M. G. Grosswald (1983) vast, but thin shelf glacial sheets of the present Ross Sea type in Antarctica formed during glacial epochs in the shallow shelf seas of the Arctic Ocean (Barents, Kara, Laptev, East Siberian Seas etc.). These seas reveal glacioeustatic falls of ocean level in such epochs.

Evolution of thoughts on the former glaciation in the Caucasus

The geological and glaciological research in the Caucasian mountainous region began after its conquest by Russia in the 1850s–60s, i. e. later than in the Alps. From the very beginning, the Russian scientists believed in a significant former glaciation in the Greater Caucasus, because these mountains are much higher than the Alps. The size of glaciers in this region is similar to that of the Alps, where the bygone great Pleistocene glaciation was already convincingly established.

In 1844–50, the German Wilhelm Abich (1806–1886) (Fig. 9), a pioneer of Caucasian geology, collected first scientific data on present and former glaciations in the Greater Caucasus and the Armenian Highlands. In particular, he visited the highest volcanic mountains of Elbrus (5,642 m) and Ararat (5,165 m). At the southern foot of the Elbrus, near the source of the Baksan River, he found and described the signs of the very recent advance of glaciers sliding down from this biggest volcano (Abich 1849, 1852, 1871). One tongue of the Elbrus glacier "intruded" into a pine forest at the bottom of the Azau Trough. Today, 150 years after Abich's observation, the termination of the Azau Glacier has retreated by several kilometers, which is typical for many Caucasian glaciers.

In the second half of the 19th century, glaciologists discovered terminal moraines in some trough valleys in the central part of the Greater Caucasus. They correspond to different stages of the still continuing late Pleistocene-Holocene glaciation. On the slopes of the valleys, remains of older stacked troughs produced by valley-type glaciers during preceding glacial epochs were found, but these ancient glacial forms remained poorly studied.

In the first half and in the middle of the 19th century, outstanding Russian geologists worked in the Caucasus: A. P. Gerasimov (1911), A. L. Reinhard (1936, 1947), V. P. Rengarten (1932), L. A. Vardanyants (1932, 1948), N. V. Dumitrashko (1949, 1977), P. V. Kovalev (1960), S. L. Kushev (1964), G. K. Tushinsky (1949, 1958), L. I. Maruashvili (1956, 1971), I. N. Safronov (1959), A. V. Kozhevnikov and many others had elaborated a detailed scale of the Caucasian glaciations. It was similar to the scale proposed for the Alps in 1901–09 by A. Penck and E. Brückner (Günz – Mindel – Riss – Würm), but the detailed correlation between the two scales remained uncertain. At first, it was suggested that the ancient glaciers on the northern slope of the Central Caucasus expanded to the Ciscaucasian Foredeep Plain during their maximum advance, because in some places moraine-like accumulations were found, consisting of large boulders and blocks from the internal part of the Caucasus (Shvetsov 1928). However, in the 1950s–60s, it was shown that these coarse clastic accumulations were transported and deposited by mud flows in sudden catastrophic inflows from the mountains into the foredeep plains. In fact, in contrast to the Alps, even during the coldest stages of the Pleistocene the glaciers on both slopes of the Greater Caucasus did not expand to the foothill plains but stayed in the trough valleys. In the Caucasus, both present and former glaciations reached their maximum in the highest central segment of the Greater Caucasus, where many summits are as high as 4,000–5,000 m and even exceed 5,600 m on the Elbrus volcano. The eastern segment of the Greater Caucasus is also very high (up to 4,000 m and more), but its climate is dry. The present and former glaciations are much more limited there than in the central segment. In the Lesser Caucasus and in the Armenian Volcanic Highlands the altitudes do not exceed

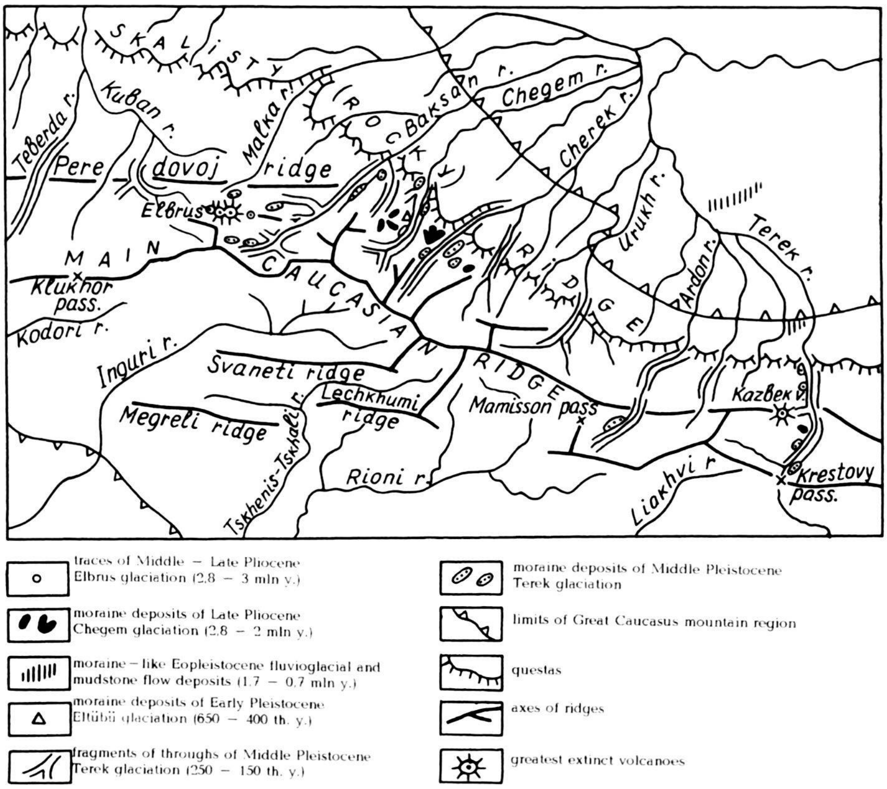


Fig. 10. Distribution of traces of the ancient (pre-Late Pleistocene) glaciations on the northern slope of Central Caucasus. *Compiled by E. E. Milanovsky* [1966].

3,000–4,000 m except for the Ararat volcano. The local climate is even more arid. The ancient glaciation was insignificant, and now only small glaciers exist on the Ararat (5,000 m) and Aragats (4,000 m) volcanoes.

In most Eurasian mountainous systems the in situ pre-Würm and pre-Riss moraines were denudated. However, in many places of the central high mountains of the Greater Caucasus and especially on its northern slope, moraines were preserved under young lavas, ignimbrites and tuffs, erupted during several volcanic phases in the Elbrus and Kazbek volcanic areas from the late Pliocene to the Holocene. The stratigraphic and geomorphological correlation of glacial deposits and young volcanic rocks provides a unique opportunity to date glacial deposits "protected" under a volcanic armour (Fig. 10).

In the 1950s–60s the author and his colleagues from the Moscow University (A. V. Kozhevnikov, N. N. Koronovsky) analyzed relationships between late Cenozoic glacial and volcanic complexes by geological mapping and special research in the central part of the Greater Caucasus. We proposed a chronostratigraphic scale of the late Pliocene-Holocene glaciations in the Caucasus (Milanovsky 1966) on the basis of the universally-adopted stratigraphic scheme of the Caucasus (Kozhevnikov et al. 1977, Dumitrashko & Milanovsky 1977, Kozhevnikov & Milanovsky 1984). The study of the late Pliocene rhyolite-dacite ignimbrites was very important for the age determination of late Pliocene and Eopleistocene glacial sediments. The volcanic rocks underlie and overlie the oldest moraines, widely distributed on the northern slope of the Central Caucasus and in the Elbrus volcanic area. They extend from the Elbrus volcano in the west to the Verkhniy Chegem Highlands in the southeast and to the Nizhniy Chegem Highlands in the northeast. The isotopic age of these ignimbrites is 2.8 Ma according to very precise recent data (Lipman et al. 1993).

On the eastern slope of the Elbrus volcano, Milanovsky & Koronovsky (1960, 1961) found the oldest moraine deposits in the Caucasus (the Elbrus Glaciation). This 20 m thick moraine occurs at an altitude of 3,700 m. It overlies a weathered crust of the Paleozoic basement, whereas layered ignimbrites unconformably overly its top. The ignimbrites are unconformably overlain by the Holocene moraine of the modern Elbrus glacial sheet (Fig. 11). The moraine deposits of the ancient *Elbrus Glaciation* are evidently older than 2.8 Ma. Taking into account the unconformable contact of the overlying ignimbrites, the moraine might be as old as 3–3.5 Ma. It would thus correspond to the beginning of the late Pliocene and coincide with the first glaciation in Iceland. This means that the axial zone of the central Greater Caucasus, situated at 42°–43° N, experienced a neotectonic uplift which attained a considerable altitude, at least 2,000–3,000 m, which are necessary to produce a mountain glaciation. It has to be taken into account that the Elbrus volcano was very active and formed a considerable caldera during

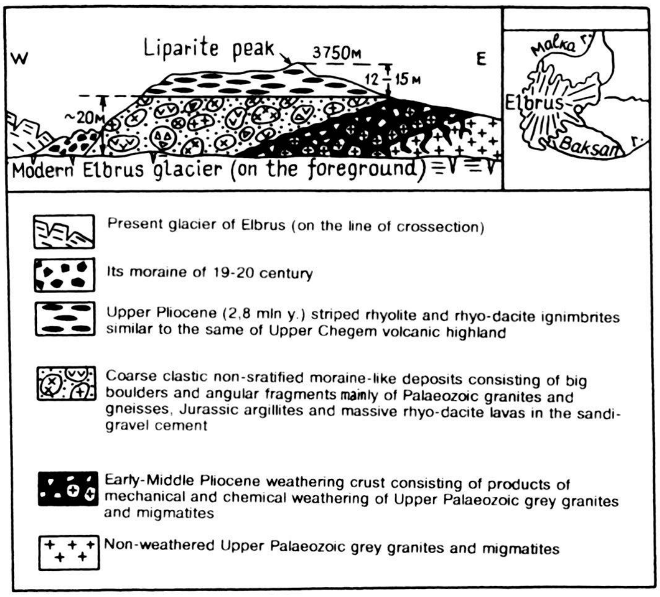


Fig. 11. Traces of Middle (?) – Late Pliocene Elbrus glaciation on the eastern slope of Elbrus volcano under the "Liparite peak" between Irik-chat and Jika-Uchen-Kez glaciers. The geographic position of this section is shown in the right corner. *Compiled by E. E. Milanovsky and N. V. Koronovsky* [1961].

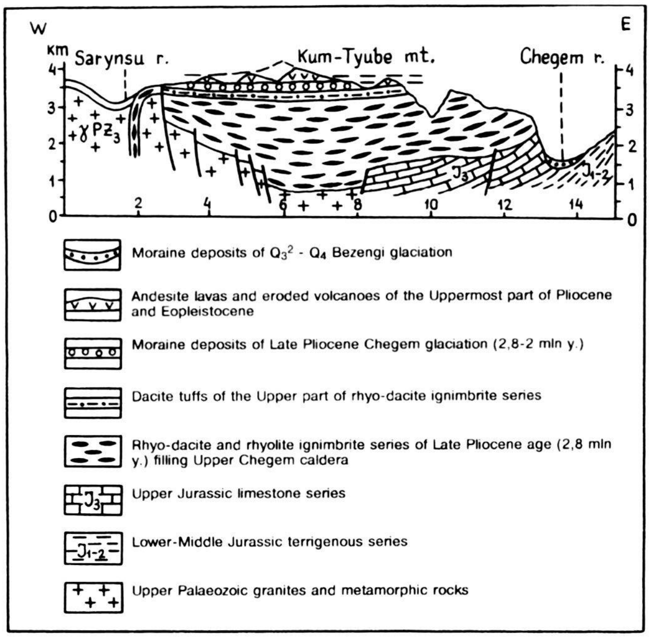


Fig. 12. Latitudinal cross-section of Upper Chegem volcanic highland showing the stratigraphical and geomorphological position of the Upper Pliocene moraine deposits of Chegem glaciation. *Compiled by E. E. Milanovsky.*

the late Pliocene and the Quaternary. The moraine deposits of the Elbrus Glaciation occur inside the eastern slope of this caldera and were involved in its relative subsidence.

In the Verkhniy Chegem Volcanic Highlands, at an altitude of 3,500 m, up to 2,000–3,000 m thick rhyolite-dacite ignimbrites are conformably overlain (but with a hiatus) by 50 m thick typical moraine deposits of the Chegem Glaciation. This moraine includes large boulders of Paleozoic granites and metamorphic rocks (Fig. 12) and is covered by andesitic lava flows, with a hiatus, but without unconformity. This lava erupted in centers on the Verkhniy Chegem Plateau, where moraine deposits are preserved. It represents a last post-caldera phase of the volcanic cycle in the Verkhniy Chegem Volcanic Area, which began with a grandiose explosion of ignimbrites (Milanovsky 1960, 1964, 1966, Milanovsky et al. 1962). The age of the Chegem Glaciation, which took place between these two volcanic phases, does not significantly differ from that of the underlying rhyodacite ignimbrites and that of the overlying andesite lavas. Unfortunately, the andesite volcanics overlying the moraines of the Chegem Glaciation are not studied isotopically. The Chegem Glaciation may correspond to the interval of 2.8–2.5 Ma, but in any case it occurred earlier than 2 Ma ago: The moraines and the overlying andesite lava are located on the horizontal surface of the 3,500 m high volcanic plateau, which was formed before the onset of the erosion of the Chegem River gorge, whose bed is now at 1,500 m, 2,000 m below the moraine of the Chegem Glaciation.

Other fragments of the Chegem moraine occur farther east, on the waterdivide between the left tributaries of the Terek River (Chegem, Nalchik, Cherek Bezengiysky, and Cherek Balkarsky) at 2,500–3,500 m altitude, more than 1,000 m above the present beds of these rivers (Milanovsky 1960, 1964, 1966). The fluvioglacial sediments of the Elbrus and Chegem Glaciations are found within the Upper Pliocene-Eopleistocene molasse deposits in the Terek Foredeep Depression. Geomorphological observations suggest that the Chegem Glaciation was of sheet or half-sheet type and developed when the internal parts of the rapidly rising mountain ridge of the Greater Caucasus was not yet dissected by deep river valleys.

In contrast, the following Quaternary glaciations of the Greater and the Lesser Caucasus were of mountain-valley type. Glaciers were localized in glacial cirques and trough-like U-shaped valleys. The valleys were successively deepened by exaration and erosion during several glacial and interglacial epochs, taking place during an arch-like uplift of the Greater Caucasus. The amplitude of the uplift was more than 1,000 m. Detailed geological and geomorphological studies of the successive Quaternary glaciations on the northern slope of the central Caucasus, in the trough valleys of the major rivers (Kuban, Terek und their tributaries Malka, Baksan, Chegem, Cherek, and Urukh) provide a basis for the chronostratigraphic correlation of the Quaternary glaciations in the Caucasus (Milanovsky 1966). This chronostratigraphic scale consists of three main glacial and interglacial epochs subdivided into phases and stages, corresponding to the Early Pleistocene, the

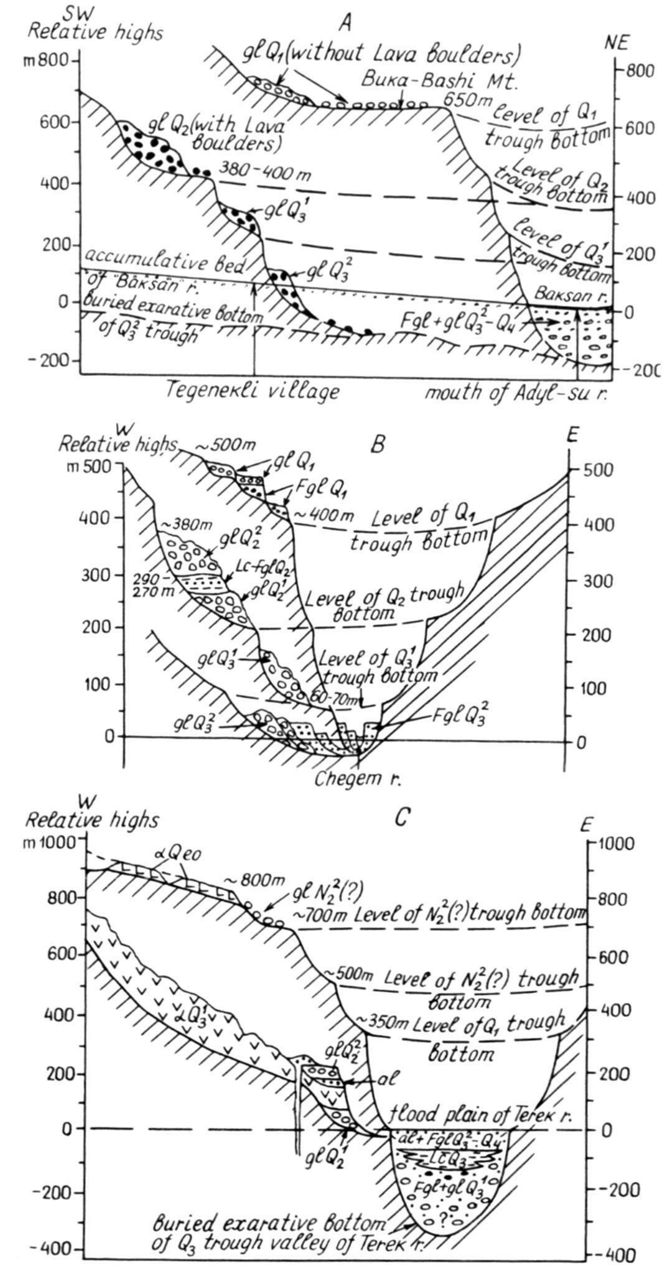


Fig. 13. Conditions of occurrence and interrelations of glacial and other types of Eopleistocene and Pleistocene continental deposits and forms of relief in the trough valleys on the Northern slope of Central Caucasus. Compiled by E. E. Milanovsky (1966).

A. Crossection of the trough valley of Baksan river near its source between Tegenekli village and the mouth of Adyl-su river.

B. Crossection of the trough valley of Chegem river near Eltübü village.

C. Crossection of trough valley of Terek river to the south from Kazbegi settlement.

Middle Pleistocene, and the Late Pleistocene-Holocene. The glacial epochs of the Eltübü, Terek, and Bezingi Glaciations are chronological equivalents of the Mindel, Riss, and Würm-Bühl glacial epochs in the Alps (see Table 1).

During the Quaternary, the rivers gradually deepened and narrowed their valleys against the background of 1,000 m tectonic uplift of the Greater Caucasus. During intensive exaration, the valleys became U-shaped troughs, whereas during interglacial epochs, river erosion transformed them into V-shaped gorges or canyons. Fragments of the bottoms and "shoulders" of the relatively broad troughs of the *Early Pleistocene Eltübü Glaciation* are preserved in the upper parts of the slopes, 400–700 m above the river bed. In some places, especially in the Chegem Valley near the Eltübü Village and in the upper part of the Baksan Valley, remnants of the Quaternary moraine are preserved on their shoulders (Fig. 13). The relatively narrow and deep troughs of the *Middle Pleistocene Terek Glaciation* occur inside the Early Pleistocene Eltübü troughs. As a rule, fragments of their bottoms can be traced at 180–350 m above the beds of the present valleys. Even narrower and deeper troughs of the *Late Pleistocene Bezengi Glaciation* occur inside the troughs of the Terek Glaciation (Fig. 14). In some places, there are moraine deposits on the bottom of the Middle Pleistocene troughs. In the upper part of the Baksan and Terek valleys, this moraine is covered by Middle Pleistocene lava, thus proving that it belongs to the Terek Glaciation. The bottom of troughs formed by the *Late Pleistocene-Holocene Bezengi Glaciation* are usually near the bed of the present rivers. Most of them belong to the late Bezengi Phase which started about 25,000 years ago, reached its maximum 15,000–20,000 years ago and is still continuing. But in some valleys, the bottom of the Late Pleistocene troughs is under the river bed. For instance, in the upper part of the Baksan Valley, it is 100 m below its bed, in the upper part of the Kuban Valley 200 m, and in the upper part of the Terek Valley 300–450 m (!). Drilling revealed very thick glacial, fluvioglacial and glaciolacustrine sediments (Fig. 13A, 13C). The glacial deposits of the Bezengi Glaciation, formed during its second phase and several stages of retreat, and the features of the glacial accumulative and exarational topography are very well preserved and exposed. In several trough valleys, lacustrine sediments accumulated in glacial lakes during different phases and stages of the Bezengi Glaciation. These temporary lakes formed between the termination of valley glaciers and dams of moraine, landslide or avalanche origin.

Conclusion

A chronological scheme of the Pliocene-Quaternary glaciations in different regions of northern Eurasia, resulting from 150-years of research is shown in Table 1. Distribution and development of glaciations depend on geographic position, climatic conditions, topography and neotectonic movements in the regions where the glaciations occurred.

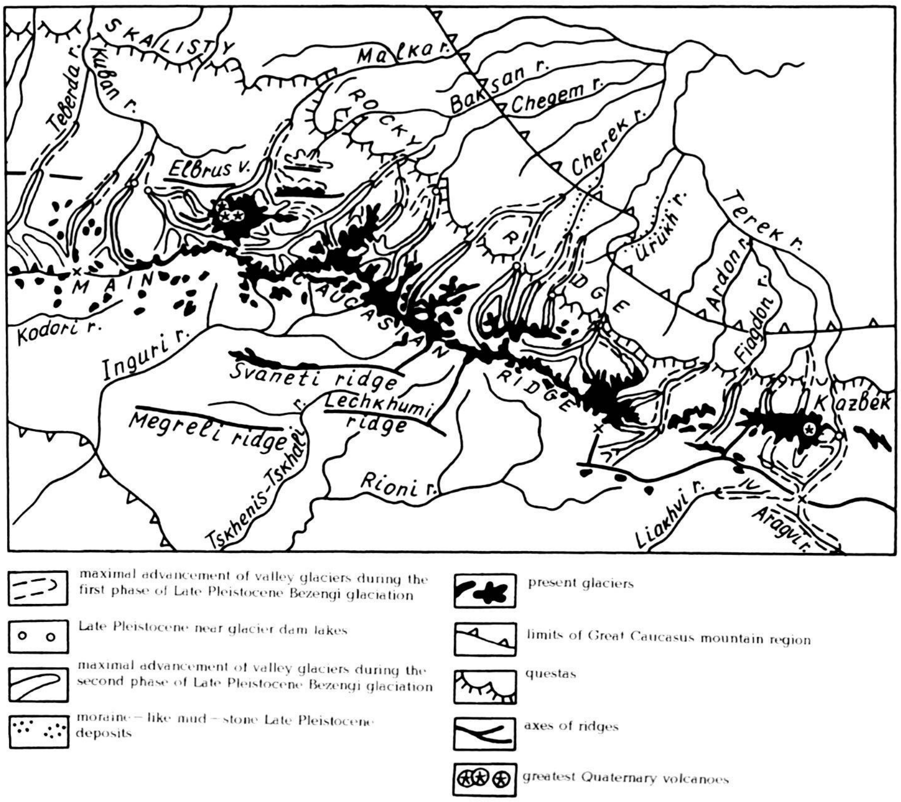


Fig. 14. Distribution of the Late Pleistocene Bezengi glaciation on the northern slope of Central Caucasus. *Compiled by E.E. Milanovsky* (1962).

1. This correlation scheme shows that in the time span 3–3.5 Ma there was repeated alternation of cold and relatively warmer climates in northern Eurasia in particular, and on the whole Earth's surface. Glaciations periodically occurred on vast plains, plateaus and in mountainous regions of Eurasia, whereas during warmer epochs the glacial sheets considerably diminished or completely disappeared. First evidence of the Cenozoic global-scale cooling is recorded in Antarctica, where glaciation started in the Oligocene, whereas in parts of northern Eurasia, Greenland, and North America the first glaciation was only Pliocene. In general, the glaciation in the western part of northern Eurasia reached its maximum between 0.7 and 0.4 Ma ago, i. e. in the Early Pleistocene according to the Russian Chronostratigraphic Scale, whereas in the eastern part of northern Eurasia it happened about 0.2 Ma ago, i. e. by the end of the Middle Pleistocene, and then significantly diminished in size in the Late Pleistocene.
2. The regional extent of glaciations, the maximum thickness and volume of glacial sheets in different parts of northern Eurasia depend on *climatic factors* such as average annual temperature, relative humidity and therefore on precipitation in the form of snow. During the Pliocene and the Quaternary the average annual temperature and precipitations decreased considerably towards the East of northern Eurasia. This eastward increase in aridity manifested itself in a decrease of glaciation intensity and in a gradual delay of the beginning of the first and of the maximal glaciation. For instance, in Scandinavia and on the plains of central and eastern Europe glaciation started in the Eopleistocene, reaching its maximum in the Early Pleistocene, whereas on the West Siberian Plain the first glaciation took place at the end of the Early Pleistocene, reaching its maximum in the first half of the Middle Pleistocene; its extent was considerably smaller than the Early Pleistocene glaciation in central and eastern Europe. In East Siberia, the first glaciation took place at the end of the Early Pleistocene, with a maximum in the Middle Pleistocene, but it was even more restricted than in West Siberia, occurring only on the plateaus, highlands and mountains, where precipitations were much more abundant than in the lowlands and plains.
At the same time, the dominant arid climate in the East led to an extensive development of permafrost: in eastern Europe (Kola Peninsula and Pechora Lowlands) permafrost is limited to the North of the Arctic Circle (67°N), to 60°N in West Siberia, whereas in the northern part of the West Siberian Lowlands and to the East of the Enisei River, permafrost exists practically everywhere to the North of 48°–50°N: near the southern border of Russia, in North Mongolia and North China (Fig. 8). In many places of East Siberia the depth of permafrost attains 1,000 m or even 1,500 m.

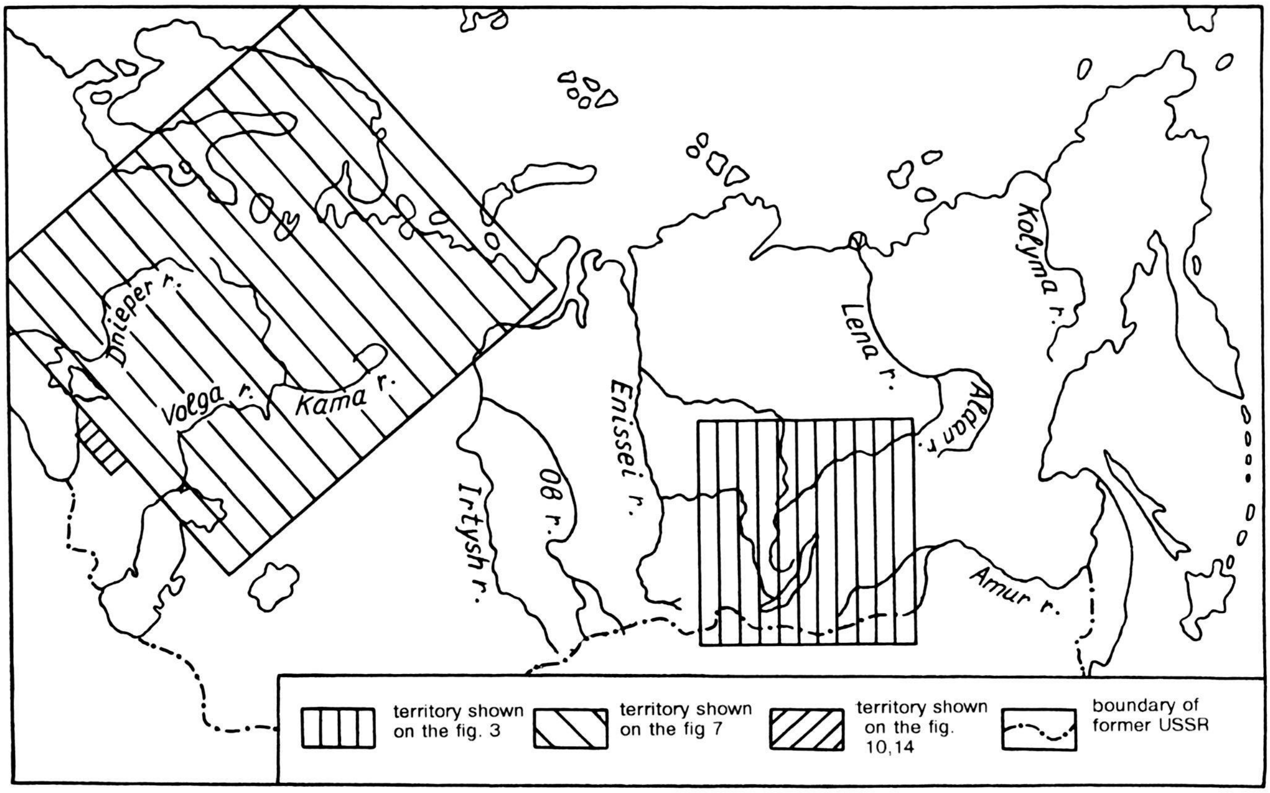


Fig. 15. Map indicating the frames of territories represented on the fig. 3, 4, 10 and 14.

3. The *orographic factor* played also an important role. The decrease of the average annual temperature is in direct correlation with the altitude, so that precipitations are in the form of snow during the winter. In the high mountains between 40°N and 52°N, such as the Alps, the Greater Caucasus, the Altay, the first glaciation started in the late Pliocene (Alps, Caucasus) or in the Eopleistocene (Altay), whereas farther north in the plains of Eurasia glaciation began only at the end of the Eopleistocene in Europe or in the Early Pleistocene in Siberia.
Although the elevations of the Greater Caucasus are higher than those of the Alps, the ancient and present glaciation are much more important in the Alps. During the Würm glacial epoch, almost the whole Alps, except small waterdivide peaks, were covered by a thick (up to 1,000–2,000 m) glacial sheet, which spread out onto the northern piedmont plains in some places (van Husen 1987). However, in the Greater Caucasus the glaciers of the Late Pleistocene (Bezengi) glaciation remained in glacial cirques and trough valleys as 50–60 km long ice tongues, covering only about 12 % of the whole area. Their thickness did not exceed some hundred meters. These differences between the Alps and the Greater Caucasus on the one hand, and between the Tien-Shan and high mointainous regions of Siberia compared with the Caucasus on the other hand, reflect a general eastward increase of aridity in northern Eurasia.
4. The *neotectonic factors*, such as the intensity, extent and time of orogenic uplift played also a very important role in the development of the late Cenozoic glaciation. The first significant glaciation in the center of the Great Caucasus and in the Alps took place in the first half of the late Pliocene (2.5–3 Ma ago), i. e. much earlier than the first glaciation on the plains of eastern and central Europe. It was almost synchronous with the first glaciation in Iceland, near the Arctic Circle. This shows that the axial zones of the alpine orogenic systems were already uplifted to the altitudes which were necessary to produce glacial sheets. Markov et al. (1965) estimated that the mountains were 2,000–3,000 m or even 3,000–4,000 m high. The present altitudes are of 4,000–5,000 m in the Greater Caucasus (5,600 m on the Elbrus volcano) and 3,000–4,800 m in the Alps. The amplitude of neotectonic uplift after the first glaciation, i. e. during the last 2.5 Ma, was at least 1,000–2,000 m in the axial zones of the central Greater Caucasus and 500–1,500 m in the Alps. Erosion produced very deep river valleys on the slopes of the Greater Caucasus. In the process of intensive uplift, the late Pliocene and

Eopleistocene sheet-type glaciers were gradually replaced by mountain-valley or trough-type glaciers during the Pleistocene.

5. In contrast to the glaciated mountainous regions of Eurasia, the central part of the Greater Caucasus reveals a *close interaction of glacial and volcanic processes* with volcano-tectonic deformations of the Earth's crust (in particular formation of calderas). The alternation of glacial epochs and phases of volcanic activity led to the formation of a relatively hard volcanic "armour" protecting moraines from total denudation in the Caucasus. For instance, in the Verkhniy (= upper) Chegem Highlands and in the Elbrus volcanic massif, the late Pliocene glacial deposits were preserved inside calderas. Glaciation might there be synchronous with subglacial volcanic eruptions, which represent a widespread phenomenon in Iceland.

REFERENCES

ABICH, G. W. 1849: Über die Schneegrenze und die Gegenwart im Kaukasus – Bull. Acad. Imp. Sci. St.-Petersburg, XXIV/2.

– 1852: Explanation of the Geological Sequences on the Northern Slope of the Caucasus from Elbrus to Beshtau. – In: Kavkazskiy Kalendar 1853, Tiflis, Part 4, 440–471 (in Russian).

– 1871: Study of Contemporary and Ancient Glaciers in the Caucasus. In: Collection of Data on the Caucasus (1, p. 85–126). – Tiflis (in Russian).

DUMITRASHKO, N. V. 1949: About the Ancient Glaciation of the Lesser Caucasus. – Trudy Inst. Geograf. Akad. Nauk SSSR, 43 (in Russian).

– 1977: Ancient Glaciation. In: General Characteristics and Development History of the Relief of the Caucasus (p. 90–110) – (in Russian).

DUMITRASHKO, N. V. & MILANOVSKY, E. E. 1977: History of Ancient Glaciation of the Caucasus. In: General Characteristics and Development History of the Relief of the Caucasus (p. 239–243) – (in Russian).

GERASIMOV, A. P. 1911: Northeastern Foots of Elbrus. – Trudy Geol. Komit., XXX/2, St.-Petersburg (in Russian).

GERASIMOV, I. P. & MARKOV, K. K. 1939: Glacial Period on the Territory of the USSR. – Akad. Nauk SSSR, Moscow–Leningrad (in Russian).

GROMOV, V. I. 1948: Palaeontological and Archaeological Basis of the Stratigraphy of Continental Deposits of the Quaternary Period on the Territory of the USSR. – Trudy Geol. Inst. Akad. Nauk SSSR, 64/17 – Moscow (in Russian).

GROSSWALD, M. G. 1983: Ice Sheets of the Continental Shelves. – Nauka, Moscow (in Russian).

HALLAM, A. 1983: Great Geological Controversies. – Oxford Univ. Press.

HELMERSEN, G. P. 1869: Studien über die Wanderblocke und Diluvialgebicade Russland. – Mem. Acad. Sci. St.-Petersburg, VII/7.

KOVALEV, P. V. 1960: Traces of Ancient Glaciation in the Kabarda-Balkarian ASSR. – Mater. Caucas. Exped. (1), Kharkov Univ. (in Russian).

KOZHEVNIKOV, A. V. & MILANOVSKY, E. E. 1984: The Caucasus. In: Krasnov, I. I. (Ed): Stratigraphy of the USSR. Quaternary System (2, p. 158–193) (in Russian).

KOZHEVNIKOV, A. V., MILANOVSKY, E. E. & SAADYAN, YU. V. 1977: An Outline of the Anthropogene Stratigraphy of the Caucasus. – Akad. Nauk Armyan. SSR, Erevan (in Russian).

KRASNOV, I. I. (Ed) (1984): Stratigraphy of the USSR. The Quaternary System (2). – Nedra, Moscow (in Russian).

KROPOTKIN, P. A. 1873: A Report of the Olekma-Vitim Expedition on Investigations of the Cattle-Drive Way from Nerchinsk to Olekma Districts. – Dokl. Ross. Geograf. Obsc. Obshch. Geograf., 3/XIII, 175 (in Russian).

– 1874: About the Study of Glacial Deposits in Finland. – Dokl. Ross. Geograf. Obsc., 10/6, Sect 1, 323–332 (in Russian).

– 1876: Research on the Glacial Period. – Mem. Ross. Geograf. Obsc. Obshch. Geograf., 7/1 (with a separate booklet of maps, cross-sections and drawings) (in Russian).

KUSHEV, S. L. 1964: The Bezengi Glaciation of the Central Caucasus. – Trudy Mezhd. Konf. Oleden. Kavkaza (10, p. 184–202). – Mosk. Univ. (in Russian).

LIPMAN, P. W., BOGATIKOV, O. A., et al. 1993: 2.8 Ma Ash Flow Caldera at the Chegem River in the Northern Caucasus Mountains (Russia), Contemporaneous Granites and Associated Ore Deposits. – Journ. Volcanol. Geotherm. Res., 37, 85–124.

LYELL, C. 1863: The Geological Evidences of the Antiquity of Man. – London.

MARKIN, V. A. 1985: Petr Alexeevich Kropotkin (1842–1921). – Nauka, Moscow (in Russian).

MARKOV, K. K., LASUKOV, G. I. & NIKOLAEV, V. A. 1965: The Quaternary Period: the Glacial and the Anthropogene Periods (I & II) – Mosk. Univ. (in Russian).

MARUASHVILI, L. I. 1956: Expediency of Revision of the Existing Thoughts on the Palaeogeographic Conditions of the Glacial Period in the Caucasus. – Akad. Nauk Gruz. SSR, Tbilisi (in Russian).

– 1971: Glacial and Ancient Glacial Forms of the Quaternary Period (Post-Kimmerian). In: Geomorphology of Georgia. – Tbilisi (in Russian).

MILANOVSKY, E. E. 1960: About Traces of the Late Pliocene Glaciation in the High Mountainous Part of the Central Caucasus. – Dokl. Akad. Nauk SSSR, 130/4, 158–161 (in Russian).

– 1964: About the Upper Pliocene Glaciation of the Central Caucasus (Selected Works Int. Geophys. Year, 10, p. 9–43) – Mosk. Univ. (in Russian).

– 1966: Principal Problems of the Ancient Glaciation History of the Central Caucasus. In: Problems of Geology and Palaeogeography of the Anthropogene (p. 5–49) – Mosk. Univ. (in Russian).

MILANOVSKY, E. E. & KORONOVSKY, N. V. 1960: Geological Structure and Formation History of the Elbrus Volcano. – Mater. Geol. & Metallogeny Central Caucasus. Trans. All-Union Aerogeolog. Trust (6, p. 92–127). – Gosgeoltekhizdat, Moscow (in Russian).

MILANOVSKY, E. E. & KORONOVSKY, N. V. 1961: New Data on the most Ancient Development Stages of the Elbrus Volcano. Dokl. Akad. Nauk SSSR, 141/2, 433–436 (in Russian).

MILANOVSKY, E. E., KAMINSKY, F. V. & SEDENKO, S. M. 1962: Geological Structure and Formation History of the Verkhniy Chegem Volcanic Highlands. In: Geology of the Central and Western Caucasus. Trudy Kavkaz. Eksped. Mosk. Univ. (3, p. 362–397). – Gostoptekhisdat, Moscow (in Russian).

MIRCHINK, G. F. 1936: Correlation of the Quaternary Continental Deposits of the Russian Plain and Corresponding Deposits of the Caucasus and the Pontian-Caspian region. In: Materials on the Study of the Quaternary Period in the USSR. – Akad. Nauk SSSR, Moscow (in Russian).

MOSKVITIN, A. I. 1967: Stratigraphy of the Pleistocene of the European Part of the USSR. – Trudy Geol. Inst., Akad. Nauk SSSR, 156 (in Russian).

MURCHISON, R. I. 1845: The Geology of Russia in Europe and the Ural Mountains. Vol. 1. – London.

PAVLOV, A. P. 1922: Epoques Glaciares et Interglaciaires de l'Europe et leur Rapport à l'Histoire de l'Homme Fossile. – Bull. Soc. Natur. de Moscou, XXXI, 23–81.

– 1976: Kropotkin as a Geologist-Glacialist (a Lecture in Moscow Naturalists' Society Read in 1926). – Bull. Moscow Society of Naturalists, Geol. Sect., LI/4, 57–63 (in Russian).

PENCK, A. & BRÜCKNER, E. 1901–09): Die Alpen im Eiszeitalter (Bd. 1–3). – Leipzig.

PIDOPLICHKO, I. A. 1946–56: About the Glacial Period (Part I & IV). – Kiev (in Russian).

REINHARD, A. L. 1936: Stratigraphy of Glacial Period of the Alps according to Beck and the Glaciation of the Caucasus. In: Materials on the Study of the Quaternary Period in the USSR. Akad. Nauk SSSR, Moscow (in Russian).

– 1947: The Quaternary System and the Geomorphology of the Northern Caucasus. In: Geology of the USSR, Vol. IX. Northern Caucasus. – Gosgeolizdat, Moscow (in Russian).

RENGARTEN, V. P. 1932: A Geological Essay about the Military Georgian Road Region. – Trudy Vsesoyuzn. Geol.-Razv. Objed., 148 – Leningrad (in Russian).

SAFRONOV, I. N. 1959: On the ancient glaciation of the North-West Caucasus. – Trudy Stavropolsk Pedagog. Ins., estestv.-geogr. Fac. 18 (in Russian).

SCHMIDT, F. B. 1865: Untersuchungen über die Erscheinungen der Glacial Formation in Estland und auf Oesel. – Bull. Acad. Sci. St. Petersburg, Bd. 8.

– 1879: Continental Origin of the Ancient Glaciation. – Trans. St.-Petersburg, Natur Soc., 2 (in Russian).

SHCHUROVSKY, G. E. 1856: Erratic Phenomenon. – Russ. Vestnik, 5/1–2 (in Russian).

SHANZER, E. V. 1976: Role of P. A. Kropotkin in Formulation of the Glacial Theory. – Bull. Moscow Society of Naturalists. Geol. Sect., 1/4, 64–76 (in Russian).

SHVETSOV, M. S. 1928: Geological Structure of the Western End of the Kabarda Range. – Trudy Nauch. – Issled. Neft. Inst., 3 (in Russian).

TUSHINSKY, G. K. 1949: Modern and Ancient Glaciation of the Teberda Region: the Conquested Summits. In: Ezhegodnik Sov. Alpinizma. – Geographgiz, Moscow (in Russian).

– 1958: Post-lava Glaciation of Elbrus and Its Dynamics. – Selected Works Int. Geophys Year, 2, Elbrus Eksp. Mosk. Univ. – Mosk. Univ. (in Russian).

VAN HUSEN, D. 1987: Die Ostalpen in den Eiszeiten. – Wien.

VARDANYANTS, L. A. 1932: The Glacial Epoch in Northern Ossetia. – Trudy Ross. Geograf. Obsc., 6 (in Russian).

– 1948: Post-Pliocene History of the Caucasus-Black Sea-Caspian Region. – Akad. Nauk Armyan. SSR, Erevan (in Russian).

VELICHKO, A. A. 1981: Pleistocene Ice Sheets of Eastern Europe: a General Review, Problems and Perspectives. In: Pleistocene Glaciations on the East-European Plain (p. 68–80). – Nauka, Moscow (in Russian).

YAKOVLEV, S. A. 1956: Principles of the geology of the Quaternary deposits of the Russian Plain. – Trudy VSEGEI, Nov. Ser., 17 (in Russian).

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