The author proposes reconsidering some of the fundamental issues of the Quaternary period. Based on own many-year long research carried out on the Baltic Shield, the author proves the fault-tectonic origin of such forms of the “glacial exaration” relief as roches moutonnes, fjords, etc. Referred by many to glacial accumulation, these land forms have actually emerged due to fault-folding processes. As has been shown by deep drilling of glaciers in the Antarctic and Greenland, the continental ice does not contain any boulders, but only trace amounts of dust-like substance. Since the lower strata are not involved in the general movement of glaciers, they conserve the glacier beds. In order to reveal the mechanism of boulder deposits formation, one should consider the actual geological processes, fault tectonic ones in the first place. The book is intended for geologists, geomorphologists, geographers, as well as general readers.

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Baltic Shield

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Contents

The glacial theory emerged during
the infancy of geology as a science in Europe.
Regrettably, it has become perpetuated,
however contradicted by both geological
evidence and the laws of physics.
N.A. Shilo, Academician RAS

Introduction

This book represents a translation into English of the first and second parts of the book “Quaternary period. A new geological concept” (in Russian) by Vasily Chuvardinsky, published by LAP LAMBERT Academic Publishing, Saarbrücken, 2013.

The Quaternary embraces a period in the history of the Earth from a million years ago till nowadays. It is also called Glacial and, sometimes, Anthropogenic.

Although the three terms are used interchangeably, it has long been claimed that the period should be exclusively named the “Glacial Age” due to severe frosts and continental glaciations. In Russia, this opinion of numerous Quaternary geologists and geographers is supported by a RAS Academician K.K.Markov.

According to the glacial theory, it is not too long ago that the currently blooming, vast areas of Europe, Asia, North America, and the Arctic shelf seas were covered with enormous ice sheets of 4.5 km in height. The Northern Hemisphere looked like the Antarctic nowadays, only four times the size of the latter. Moreover, it is asserted that glaciers kept advancing and receding, this occurring four to twenty times.

The glacial theory has been indisputable for about 150 years. It is called upon to explain the origin and formation of a great variety of relief features such as fjords, rocky skerry landscapes, roches moutonnees, and also major diastrophism in the Earth’s platform cover, huge erratic blocks, and terminal swells of moraines.

This theory is also invoked to explain the origin of abundant “glacial debris”, i.e. boulder blocks found in Quaternary deposits and on the surface of pre-Cambrian rocks on the Baltic and Canadian crystalline shields. Moreover, boulders and blocks of granite and other rocks, occasionally encountered in Quaternary deposits on platform plains thousands of kilometers away from the pre-Cambrian shields are also considered to have been scattered by glaciers.

All geological charts of Quaternary deposits, paleogeographic, geomorphological, engineering-geological maps, and climatic reconstructions are developed with due regard for the glacial theory. The same refers to researches in such related sciences as zoogeography, botanical geography, archeology and landscape design.

Factual evidence in support of the glacial theory has been accumulated in decades making it seem unassailable. However, the more abundant the material, the less it fits with the glacial criteria; instead of reinforcing the glacial theory, this same evidence actually contradicts it.

In the first place, evidence on the origin of “exaration relief”, i.e. fjords, skerries, lake grabens, sheepback rocks, striation and polishing on crystalline rocks, regarded as a mainstay of the glacial theory, actually suggests its fault-tectonic origin. Unwittingly, the glaciations advocates have also contributed to substantiating of the fault-fold genesis of terminal till billows, erratic blocks and shifts in the cover of the Russian platform and West Siberia. Thus, far-reaching researches have been reported by R.B.Krapivner and P.P.Generalov. As became evident from field and laboratory studies of loam debris on North Eurasia plains, it has been formed by sea ice (I.D.Danilov, A.I.Popov, and many others).

As disclosed by recent studies in geocryology and hydrogeology (especially those carried out by L.N.Kritsuk), the embedded ice on Siberian plains was formed not by glaciers but by permafrost.

A still clearer understanding of the so-called “geological activity” of glaciers came with full-depth drilling of Greenland and Antarctic ice sheets and the ice caps of the Arctic islands. The many-kilometer long ice cores from drilled glaciers did not contain any boulder debris. Instead, there were found incrustations of fine earth, mostly represented by volcanic ash.

Almost as important are the biogeographic data, including the radio-carbon dating, demonstrating that, instead of being cloaked in an ice sheet, Northern Hemisphere during the Quaternary used to be covered by vegetation similar to that of nowadays, with mammoths, reindeer, and horses feeding and breeding on it.

Of the diverse exogenic and endogenic relief-forming processes there will be considered only those most important for understanding of the so-called glacier-related formations.

Emphasis will be placed on processes occurring in glaciers, in fast shore ice, and mud torrents. The central point discussed in this book is geomorphogenesis of the Baltic Shield, including the actual origin and mechanism of formation of "glacial exaration" and "glacial accumulation" types of relief representing the backbone of the glacier theory.

Ample evidence to the contrary, provided in the book, reveals the fault-tectonic and folded-fault origin of these formations generally believed to be glacier-related. It is shown that they are created by neotectonic processes.

Deep drilling of ice sheets in Greenland and Antarctic, performed within several international projects, has made available unique materials testifying that the near-bottom ice strata are immobile and thus unable to transfer boulders. The ice bodies were found to contain only rare inclusions of clay and sandy loam, mainly volcanic ash.

Venturing on a piece of facetiousness, the author suggests that glaciers have disclosed their secret after a secular silence only to shatter the glacial theory past retrieval.

Chapter 1.
Glaciological processes and phenomena

Here is presented a brief survey of certain geological phenomena so far inadequately researched but significant for understanding of the Quaternary period.

1.1. Dynamics and geological activity of glaciers

"The role of basal moraine in relief formation is but negligible. Glaciers cannot be regarded as an effectively eroding factor."
M.I. Iveronova

As asserted by the glacial theory, Quaternary glaciers razed the bedding rock of Fennoscandia to the depth of several hundred meters, relocated boulders to thousands of kilometers, ploughed lakes, and even seas.

Traces attributed to glacial exaration on the Baltic and Canadian shields include polishing and striation on rocks, roches moutonnnees and sheepback rocks, skerries, fjords, and lake hollows. The idea of glacial transport is fundamental in boulder prospecting.

Therefore checking of the validity of glaciations criteria should involve studying of the dynamics and geological activity of contemporary glaciers.

Glacial drift is caused by dissimilar mechanisms of ice deformation mostly depending on inclination of the subglacier floor and shape of glacier surface.

The movement of ice sheets, resting on flat beds, depends on the slope of glacier surface. The activating factor here is the gravitational load of ice, the tangent stresses near the floor being insignificant or close to zero. Ice from such domes spreads slowly, obeying the law of ductile body flow.

In mountain-plain glaciers, with an ice body moving down an inclined plane, the gravitation pressure is reinforced considerable tangent stresses emerging at the floor. It is these stresses, together with temperatures peculiarities, that cause the glacier to drift.

Ice can start warping even under small, but sustained, stresses. This happens because the structure of natural ice masses is represented by packets of thin and indiscernible elementary plates shifting relatively each other in response to slightest stresses. Tangent stresses of about 0.1 MPa produce greater spalls impelling the ice plates to slide along the spall planes. Under the impact of tangent stresses, great vertical loads, and ice temperatures close to zero, ice begins to melt on the slipping planes, which promotes the sliding of both elementary plates and strata along the inter-glacier spalls (Shumsky, 1969).

Ductile sliding of ice and shifting along the inter-glacier spalls, be it the elementary ice plates or plate packages, can hardly plough the glacier bed; nor can it transport boulders in the glacier bottom. Not surprisingly, these glacial regularities were not hailed by glacial proponents arguing that "ice flows along inter-glacier spalls, in other words, sliding of ice along ice, does not explain anything". It does not, indeed. But such is the movement of ice masses and the dynamics of continental glaciers, and it has to be taken into consideration. At any rate, this raises the question of whether glaciers can plough their beds.

A better insight into the ice body dynamics was gained when ice movement was studied in glacier sections. Observation of the borehole curves in valley glaciers has revealed that the basal ice strata move 2-10 times slower than the overlying strata. The same regularity was observed for mountain-valley glaciers, although they have inclined beds (Badd, 1975; Paterson, 1972; Shumsky, 1969).

The speed of underlying strata in cover glaciers is almost zero; ice there fastens the rock. This agrees with what P.A.Shumsky, a well-known Russian glaciologist, maintained as far back as in 1978: "Excluding shifting through the geological time, the glacier bottom should be considered static."

Let us consider now the dynamics and geological activity of great continental glaciers in Greenland and Antarctic, and the ice caps of Arctic islands.

As was discovered from ice-core samples and natural cross-sections in the Antarctic, Greenland and Arctic islands, neither the bottom strata nor any other glacier parts contain any rock fragments of boulder size. What the ice did contain was traces of dust-like and fine-grain substances, mostly of volcanic ash. There were no indications of movement in glaciers' underlying parts resting heavily upon their beds and conserving the earth's surface.

It is claimed that contemporary continental glaciers in Greenland and Antarctic, and of ice-caps on the Arctic islands serve as incontrovertible evidence in favor of glaciations in the Northern Hemisphere during the Quaternary. In addition, there have been developed criteria of erstwhile glaciations in Europe, North America and Northern Asia.

In the first place, these criteria include fjords, skerries, lake hollows, sheepback rocks, polishing, striae and furrows on rock. It has been affirmed that glaciers have moved boulders and blocks of crystalline rock to thousands of kilometers, dislocated the platform cover rock down to the basement, and transferred millions of cubic meters of huge erratic rocks to hundreds of kilometers, scattering them over an area of dozens of square kilometers.

It is widely believed that continental glaciers used to plough and lacerate the earth acting like monster bulldozers. In awesome computer reconstructions of today, glaciers are seen advancing inexorably, crashing the bedrock and scattering enormous boulders aside.

Questioning the scale of glacial exaration on land and seabed has long been inadmissible. The irrefutable argument is this: "What other proof for the existence of blanket glaciations in the Quaternary does one want? Just look at the ice sheets covering the Antarctic and Greenland!".

However, a sound theory does not need to resort to lofty pronouncements. It needs reliable information about the regularities in the movement and geological activity of continental glaciers. In fact, ample evidence has been obtained during many-year long studies of glaciologists, geologists, drilling technicians, and geophysicists in Greenland, Antarctic and ice-capped Arctic islands. But, contrary to expectations, instead of reinforcing the glacial theory, the contemporary glaciers have contributed to its refutation.

Continental ice sheets spread out due to the ductile flow of ice and gliding of elementary ice plates along inter-glacier spalls. The speed of ice flow varies in different parts of the glacier cross section. Being at its highest in the upper and middle parts, it diminishes almost to zero in the bottom strata, while the basal strata adjoining the underlying rock are practically immobilized, preserving the original, pre-glacier surface.

However, these glaciological data are completely disregarded (for what will be left of the glacial theory without its main pillar?). Speaks D.Yu.Bolshiyanov, expert in Antarctic and Arctic glaciers (2000) in his *Problems of Arctic and Antarctic*: "It is peculiar nowadays how the findings of glacier physics, dealing with glacier movement regularities, are ignored by the glacial theory." There is abundant evidence "attesting to the inability of cold Arctic glaciers to perform the mechanical work of transforming the glacier bed" (p.85).

The next stage in addressing of Quaternary issues came with deep drilling of glaciers which revealed the full length of ice cores down to the bedrock, as was achieved in Greenland and the Antarctic.

The drilling data were invaluable in refuting the classic conception of the existence in the glacier bottom of a thick basal moraine interspersed with great rock segments and boulders.

Nevertheless, all Russian manuals on general and Quaternary geology and geomorphology, all reference and popular-science books feature the schematic structures of debris-laden ice sheets, with huge boulders of crystalline rock at the bottom. Thus, the textbook *General Geology* (2006) of N.V.Koronovsky, an MGU professor, demonstrates debris-laden ice (almost entirely consisting of large rock segments) occupying about 1/3 of the entire glacier's body (Fig.2). In a scheme constructed by V.M.Kotlyakov, a RAS Academician (1986), the moraine-containing ice with boulders is hundreds of meters thick (Fig.1). If we proceed from N.V.Koronovsky's assumption, the melting glacier should have left an almost 300 m high (!) basal moraine predominantly composed by huge rock segments. In V.M.Kotlyakov's scheme, the moraine is but slightly less impressive.

Now it is time to return to the full-depth drilling findings and detailed ice-core studies. Very significant, and unexpected, was lack of debris throughout the core lengths, including the basal parts of enormous glaciers. Note again: all textbooks, reference and popular-science books picture the glacier bottom parts as continuous, hundreds of meters thick, strata of debris containing bedrock boulders and segments, some of them dozens of meters in diameter. Paradoxically, factual data are quite the opposite: there is no debris in ice cores except individual sand grains and aggregates of volcanic ash.

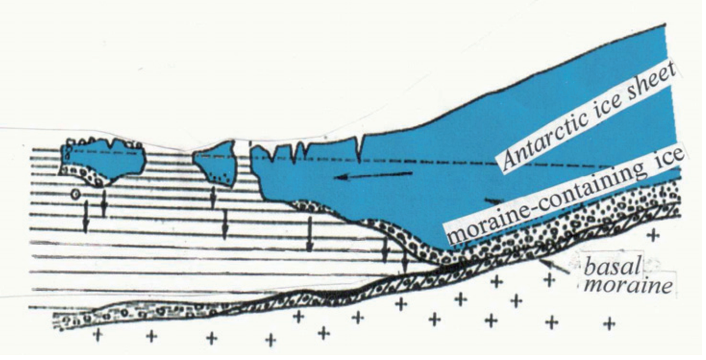

Fig. 1. Ideal section of the Antarctic ice sheet with a thick moraine-containing ice both in the continental and shelf glacier (according to V.M.Kotlyakov).

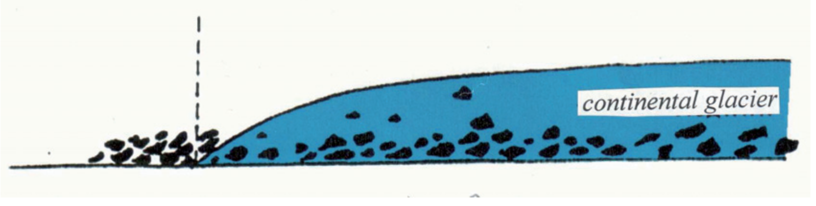

Fig. 2. Generalized model of a Quaternary continental glacier with an impressive moraine-containing ice occupying 1/3 of the glacier volume (according to N.V.Koronovsky).

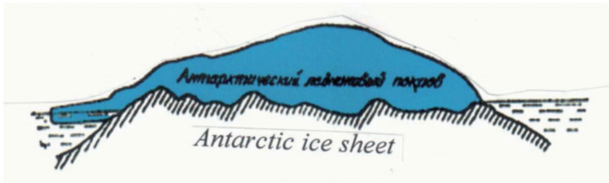

Fig. 3. Actual Antarctic ice sheet (according to K.S.Losev).

Full-depth drilling of continental and shelf glaciers in the Antarctic has failed to reveal any boulders or large rock segments with the exception of occasional incrustations of dust-like substances, mostly represented by volcanic ash.

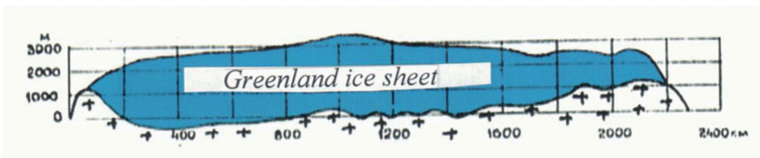

Fig. 4. Axial section (north to south) of the Greenland ice sheet (according to B.Fristrup). Absence of any debris as revealed by full-depth drilling, except for layers and aggregates of volcanic ash.

Mineral inclusions in bottom ice cores are of a size discernible only in a microscope. What about boulders and rock segments supposedly forming the moraine body and considered to be the main proof of moraine's glacial origin? The answer will be far-reaching because it will change our vision of former continental glaciations with boulders scattered over the European and other plains. The baffled author has not once appealed to the Quaternary community for elucidation, but to no avail. No boulders or rock segments, even individual, in ice sheets (Fig. 3, 4) – and no theory whatsoever to account for it.

Let us mention briefly some data on full-depth drilling of glaciers on Arctic islands, in Greenland and the Antarctic.

1.2. Ice sheets on the Arctic islands

The glaciological findings presented here were obtained on ice caps of Arctic islands by D.Yu.Bolshiyanov and V.M.Makeev (1995), V.S.Zagorodnov and I.A.Zotikov (1981), S.A.Arkhipov and T.A.Vostokova (1990), R.Koerner and D.Fischer (1979).

The Severnaya Zemlya Archipelago

The dome-type glaciers drilled to the bedrock were Vavilov (October Revolution Island) and Academy of Sciences (Komsomolets Island). On Vavilov Glacier, seven 459-557 m deep boreholes have been drilled. The most informative were the boreholes of 459.3 m and 557 m. Ice in these, and other, boreholes, was pure, only at the foot revealing some mineral inclusions of about one micron in size, individual grains of up to 3 mm, and also small aggregates of a sand-clay substance.

The ice layer containing these scattered mineral inclusions is 2.5 m deep. The bottom of Vavilov Glacier is immobilized through freezing to the bed; shearing deformations are observed only at 457.93 – 458.3 m.

One hole has been drilled on "The Academy of Sciences" Glacier, which reached the bedrock at 761 m. The glacier bottom contained mineral inclusions of a sand-clay size in small concentrations. The near-bottom ice strata are not involved in the glacier's general drift.

The Spitzbergen (Svalbard) Archipelago

Glaciers on the Spitzbergen are of two types. In West Spitzbergen they are mountain-valley, with surfaces covered with boulders and rock segments fallen from mountain slopes. East Spitzbergen is covered with ice sheets having, naturally, no surface moraines. The ice sheets have been drilled down to the bedrock in several places.

The Amundsen plateau glacier

Ice from the borehole, reaching the bedrock at 586.7 m, was found to consist of layers of transparent and non-transparent ice. The non-transparent layers contained micron-size mineral inclusions. These micro-inclusions concentrated at the depth of

511.6 and 566.7 m. As shown by laboratory analyses, they were composed by mica scales, quartz micro-particles, volcanic ash and slag, spores and pollen.

The Lomonosov plateau glacier

Although located in West Spitzbergen, the Lomonosov plateau glacier belongs to the ice sheet type. The bed of Fridtjof Glacier was reached at 220 m. The ice core from the glacier bottom contained dust-like, micron-size inclusions, and the borehole foot struck the bedrock. The ice core from the Grenfjord Glacier foot (211 m) also contained micron-size mineral inclusions.

Ice dome on Devon Island (Canadian Arctic)

In boreholes that were drilled down to 298.9 and 299.4 m, a concentration of micro-particles was recorded at 2.6 to 4 m from the bed. Another micro-particle concentration was recorded at 1.2 m from the hole foot (Koerner, Fisher, 1979). No data on the mineral composition or percentage of the micro-particles have been reported.

1.3. Greenland

The ice sheet in Greenland is the thickest in the Northern Hemisphere (up to 3416 m) (Fig. 4). In size, it is comparable with the hypothetical Scandinavian continental glacier. The Greenland ice sheet has been drilled in different parts by five deep boreholes, with total recovery of the core.

Northwestern part of the ice sheet

Let us consider the data reported from the Camp Century station in 1968. The borehole reached the bedrock at 1391 m. The ice was pure throughout the core length up to 15.7 m from the bottom. The subglacial part was interstratified with thin layers of pure and dirty ice containing dust-like, fine-earth substances. The particle size in this "moraine-containing ice" (as the authors chose to term it) varies between 2 micron to aggregates of up to 3 cm (Herron, Langway, 1979).

In weight, the average concentration of the “morainic matter” is 0.24%; in volume – 0.10-0.12%. This “moraine-containing ice” (or “basal moraine” in terms of V.M.Kotlyakov) contains no rocks of boulder size.

In another publication, the authors described the same core section as a 17-meter stratum of moraine-containing ice with a ‘high content’ (please note the 0.24 wt %!) of morainic matter, with particle sizes slightly increasing towards the stratum’s upper part. The matter is described as micron-size (in no way resembling a basal moraine) but still, a moraine it is somehow made to look! If this “moraine” melts down, it will leave behind a cover of dust-like clay, 1.5-2 cm thick substance.

Southern part of the ice sheet

1981 saw the completion of drilling at Dye-3 station (GISP-1, USA-Europe project). The ice was 2037 m thick. The core samples at different marks (500 m, 901 m, and 2030-2035 m) contained mineral inclusions composed by volcanic ash in concentrations varying between weak to noticeable, to strong. The ice age at the bottom is estimated at 125-150 thousand years (Marshall, Kuivinen, 1981).

Central part of the ice sheet

Ice sheet in the centre of Greenland was drilled in two places: GRIP-1 borehole (European project) and GISP-2 borehole (USA project). The former reached the bedrock at 3029 m in 1992. The latter, located 30 km southwest of the former, was completed in 1993. It went down to 3053 m of which 1.55 m penetrated inside the bedrock (P.G. Talalay, 2005), all in all - over 3051 m. So, the mysterious central part of the ice sheet has been drilled twice. Might not one anticipate exposing of breccias concentrations forming a powerful basal moraine? But they were nowhere to be seen. In fact, the subglacier part concealed nothing but occasional spots of dust-like aggregates.

Northern part of the Greenland ice sheet

This area, important from the glaciological viewpoint, has been drilled within the framework of the North Greenland Ice project. The borehole was located in the centre of North Greenland at 2921 m above the sea level. Drilling was started in 1996 and completed in 2004 at the depth of 3091 m. A description of drilling operations is cited here from the book of P.G.Talalay (2005).

In 2003, when the borehole was 3085 m deep, it was flooded up to 43 m by a heavy flow of brownish fresh subglacial water. After the interruption, drilling was resumed in 2004, when the bore head reached the bedrock at 3091 m striking into the underlying rock (red sandstone). Judging by the available description of the total core length, it did not contain any noticeable mineral particles.

The colour of subglacial ice was uncommonly brownish (the same as that of flooding water, later frozen). There was a sensational discovery: a bit of relict wood found in a core sample of the lake ice. Apparently, drilling had stirred the water of an ancient lake so that the lightest of the lake ground fractions (a piece of wood) got stuck into the newly frozen ice.

The Tuto glacier tunnel

In Northwest Greenland, a special tunnel has been passed along the glacier contact with bedrock. The ice contained mineral particles and was designated as moraine-containing (Whalley, 1982). It was reported (without specifying the quantity) that mineral inclusions were of micron size and impregnated into the glacier's base as a result of sticking-freezing processes. Electron microscopy has shown the grains and scales to be quartz, feldspar and silica without any traces of treatment, i.e. all the grains were weathered.

As the result, both the five boreholes and the Tuto ice tunnel have provided unique materials on the so-called basal moraine. It was discovered that neither ice sheets nor outlet glaciers (as will be shown below) contain boulders or large ore segments; what they do contain are dust-like, fine-earth inclusions. Such is the case with the present bottom moraine – it will be a thin cover of sandy-loam substance, dusty when dry.

Moraine-containing ice in sections (ruptures) of the Greenland ice sheet

The presence of mineral inclusions in Greenland ice was first reported by L.Koch, A.Vegener, and E.Drigalsky. That was the so-called blue lamellar ice with dust-like fine-earth substances.

A photo in Yu.A.Lavrushin's book (1976) provides an impressive view of moraine-containing ice in the frontal barrier of Frederikshob-Insblink outlet glacier (Southwest Greenland). The same photograph decorated the book's cover and appeared again, after a quarter of a century, in another publication of this author and O.G.Epstein (2000).

The legend reads: "A series of moraine-containing ice at the foot of Frederikshob-Insblink Glacier edge". In the later publication, the legend was slightly corrected: "A thick (about 30 m) pack of moraine-containing ice at the foot of Frederikshob-Insblink Glacier".

The photograph displays a thick stratum of a stripy texture, apparently consisting of layers of mineral-contaminated and pure ice. A researcher interested in more detailed studies of this unique section would, naturally, require the following information. What are the minerals in the mineral substance? What are their volume weight and percentage in the ice? What is the grain size of the substance? Alas, no such information can be found in Dr. Lavrushin's book.

As for the later publication, it is more informative. We are told that the structure is represented by layers of pure and dirty ice, the "dirt" referred to as "moraine impurity" or "mineral particles", or "a mineral substance". But now again, no analytical data on the grain size of the "moraine impurity", or mineral composition, or percentage are reported.

The following question arises: why wasn't performed the easy job of collecting samples for mineralogical and granulometric analyses, and the volume content of the moraine substance? This would have required hacking off some ice lumps, the more so that it cuts off readily, at places. The easiest thing to do was analyzing the weight content of the mineral substance. This amounts to melting ice in a laboratory flask and determining the weight and volume of moraine residue. Samples from different ice layers could have been taken and compared. It is inexplicable why the article should not present this information. Excuse this piece of facetiousness, but are we to presume that ice sampling is somehow tabooed, or are weight data classified?

It also looks like the authors of the paper are intentionally confusing the reader by mixing up photographs and referring Fig.3 (Frederikshob-Insblink Glacier) to the East Antarctic Shield. The reader is also perplexed by being repeatedly referred to mountain glaciers of Alaska and Spitzbergen allegedly invoked to clarify the situation with Frederikshob-Insblink Glacier. In point of fact, it is known that mountain and mountain-valley glaciers are characterized by different types of material accumulation. On the latter, boulders and rock segments, scattering the surface, have appeared as the result of collapsing of mountain sides and rockslides, and solifluction occurring on gentler slopes. This coarse material sinks then into the moraine, gradually falling into its basal part under the influence of gravitation and other processes.

Fortunately, we can refer to other, foreign, sources. Indeed, the moraine-containing ice of Frederikshob-Insblink outlet glacier consists of layers of pure and "dirty" ice. The "dirt" is reported to be a fine-earth and dust-like substance present in contents, averaged from the "moraine-containing" ice section, of mere hundredth parts of percent (Herron, Langway, 1979).

No boulders or detritus have been found in this huge outlet glacier. Time has come for geologists and glaciologists to admit that the "moraine" of cover glaciers is nothing but fine-earth, dust-like sediments with no boulders whatsoever. The section of moraine-containing ice, now under consideration, is the basic argument for the Greenland glacier shield. In *Glaciers,* a fundamental monograph of L.D.Dolgushin and G.B.Ossipova (1989) it is stated: "The major outlet glacier of Southwest Greenland, Frederikshob-Insblink, creeping to the shore with a broad edge of 25 km across." It is separated from the sea by fluovioglacial and submarine plains. It is a support structure produced by the great Greenland ice sheet, being at the same time a key section of the mighty glacier edge. In the course of glacial fluctuations during the

Quaternary period, this powerful edge used to be advancing towards the marine plain and receding from it.

As explained by the glacial theory, this awesome ice torrent was bound to crush everything facing its broad edge. Fancy a mammoth bulldozer plowing out its bed, shearing, crashing and dislocating rocks, and erecting pressure-tight moraine ridges following the glacier's edge geometry! But there was no such thing. In reality, the glacier edge flows down its grading bed without gnawing into the underlying rock, or crashing it into boulders, or creating grabens and deep, narrow fjords. It does not form any terminal moraines, either. It has not left any traces of plowing or shearing within the bounds of the submarine plain. Note again the absence of any boulders or debris incorporated either in "dirty" or pure ice. On thawing, this edge may leave a thin loamy-clayey stratum. Although its composition cannot be specified due to unperformed mineralogical analyses, it consists, supposedly, of either fine terrigene material absorbed by the glacier or volcanic ash windborne from not-too-distant Iceland.

There had been another puzzle successfully resolved during the glacier edge studies. The glacier has been gliding alternately over a rocky bed (the ice is pure there) and over marine clay interspersed with sea shells. Some of the shells have been frozen into the glacier foot and 'are in a very good shape", as remarked by Yu.A.Lavrushin who is impressively unperturbed by this absurdity.

Glaciers in Iceland are mostly of the ice-sheet type. Their surface has been repeatedly overstrewn with ash, sand, and slag erupted by the local volcanoes. Next, this material penetrates into the ice and gradually sinking to the bottom.

In the glacial theory, this pyroclastic material is termed "glacial till, or moraine", probably following the logic that if a pyroclastic is incorporated into a glacier body, it is bound to be glacier-related.

Another peculiarity of Icelandic dome glaciers is the fact that they generate outlet glaciers. Abundant snowfalls also contribute to dynamic advancement of glacier edges.

As it is known, there was a period in the IX and XVII – XIX centuries characterized by rapid advancement of glacier edges, frequently protruding to the Vikings' fields and pastures. While receding early in the XX century, the glaciers brought to light the previously cultivated land and ruined farmsteads, but almost intact fields and pastures strewn in places with loam drift of pyroclastic origin.

1.4. The Antarctic

The area occupied by the Antarctic ice sheet is 13,650,000 km^2; the greatest ice depth is 4700 m (L.D.Dolgushin, G.B.Ossipova, 1989) (Fig.3). It has been drilled to the bedrock 6 times, in different places. Boreholes have also been drilled at the shelf glaciers: Ross, Ronne-Filchner, Amery, Lazarev, and Shackleton.

The Byrd station (USA) is located in West Antarctic. 1968 saw the completion of a borehole reaching the bedrock at 2164 m. The ice cores have revealed a 4.85 m stratum of moraine-containing ice in the subglacier part (the basal moraine, in terms of V.M.Kotlyakov). The core exhibited alternating layers of pure ice and ice containing mineral inclusions of loam size. Although there are no data on the percentage of the mineral inclusions, one would easily see if there were any boulders or coarse rock segments. As for fine earth, it is believed to have gotten into the ice while freezing and sticking of the bed to the glacier's bottom (Gow, Epstein, Sheehy, 1979).

The Vostok station (Russia), located in the central part of the Antarctic.

Borehole 5G was started in 1990. By February 2011 the ice had been drilled to the depth of 3720.4 m. The borehole hit the ice of a large subglacial Vostok Lake. According to media reports, in Febriary 2012 the lake ice had been bored to the water of Vostok Lake. The total length drilled is about 3769.3 m.

Vostok Lake is larger than Onega Lake and much deeper (according to geophysical data, it is 700 m, at places 1200-1500 m, deep (Masolov et al., 2001; Leichenkov et al, 2012).

The ice drilled by the 5G-1 borehole was found to contain mineral and organic inclusions at the depths of 3538 m, 3608 m and 3311 m (Lipenkov et al, 2000; V.M.Kotlyakov, 2004) explains that these inclusions, consisting of volcanic ash, micro-particles of meteorites (space dust), and plant spores and pollen, are “moraine”, without providing such data as percentage of the dust-like particles, or of boulders, or other debris in the drill cross section.

The Konen station (Germany) is located on the Queen Maud Land; the ice sheet here is 2774 m deep. In 2006, at this depth the borehole was flooded with water which rose to 80 m. According to available data, the subglacial part does not contain any mineral substances (Bolshiyanov, 2006). The age of ice at the borehole bottom is 900 thousand years (Talalay, 2007).

Dome F station (Japan). Located in East Antarctic (laterally the Indian Ocean) on the so-called Dome F. In the course of 2003-2007, the borehole reached the glacier bed at 3044 m. Dust-like inclusions were observed near the borehole bottom. The age of ice near the bedrock is about 1 million years (Talalay, 2007) which means that the glacier had stayed there, immobilizing the pre-glacier surface, throughout the Quaternary. The same refers to the ice of the Konen station (900 thousand years old).

Dome C station (European project). The station is located in the East Antarctic interior (laterally the Pacific Ocean) on Ice Dome C. The thick ice was bored in 2000-2005 until the bedrock was reached at 3270 m. Drilling did not reveal any mineral inclusions either in the ice cross section or in subglacial parts. The ice at the borehole bottom is assessed as 800 thousand years old (Talalay, 2007).

The Law-Racovita Station (Australia). Located near the East Antarctic coast. Ice from the borehole reaching the bedrock at 1196 m in 1993. There were no traces of moraine in the glacier section, merely dust (Talalay, 2011).

The staggering absence of coarse rock segments and boulders has to be given one or another explanation. So, it is sometimes argued that large ore blocks had been ground and milled by the powerful glaciers. However, this hypothesis is contradicted partly by scanty quantities of the “glacier-milled” substance, and partly by their material composition of volcanic ash, microscopic terrigine and outer-space substances. Are we to believe in the glacier's ability to mill meteorites to dust? On the other hand, what about the perfect degree of preservation of delicate plant spores? For some reason, the grinding must have been highly selective.

During a debate following my report on these Quaternary peculiarities (Chuvardinsky, 2011) it was argued that, when striking upon rounded boulders, boreholes had to bend round them, thus boulders remained unrecorded. The conception of a boring head writhing its way among boulders is nothing but bizarre. Resorting to reptiles for argumentation can hardly enrich a respected theory.

Shelf glaciers

The Antarctic shelf glaciers are fed by ice sheet discharge, mainly of its outlet glaciers, and also by snowfalls. According to full-depth boring and geophysical data, the average thickness of ice shelves is 400 m. Since the ice shelves are mainly built by ice discharged from outlet glaciers, it is natural to expect them to contain moraine material. However, boring at Ronne-Filchner (465 m) and Ross (416 m) ice shelves did not produce any mineral inclusions or fine earth whatsoever, to say nothing of boulders, from top to foot (Zotikov, Gay, Jacobs, 1985).

From the paleographic point of view, it is important to understand the processes occurring within Amery, an ice shelf fed by discharge from Lambert Glacier. As asserted by glaciations proponents, this glacier has ploughed the Lambert graben, the largest in the Antarctic. However, since neither drilling at Amery (as deep as 252 m to 450 m) nor underwater examination revealed any debris in the ice body, it can be concluded that Lambert Glacier cannot be held responsible for plowing of a rift structure in bedrock. It was created by tectonic processes.

The Lazarev ice shelf has been drilled in two places. The first borehole dipped down to 374 m striking the ground; the second drilled 356 m of ice and struck seawater. There was no morainic material or individual mineral inclusions. The same refers to Shackelton ice sheet (Bolshiyanov, 2006). Nevertheless, Russian glaciations proponents are in no hurry to reconsider their views of a thick basal moraine lying within shelf glaciers (Kotlyakov, 1986, Fig.1).

Moraine-containing ice in natural cross sections in the Antarctic

The Antarctic, particularly in its western part (Victoria Land), abounds in mountain-valley glaciers. It has been known since R.Priestley's research (during R.Scott's last expedition) that the glaciers' surface is strewn with rocks and boulders fallen from steep mountainsides. In this section, focus will be placed on the enormous Antarctic ice sheet with natural outcrops and vertical shears. Let us consider the well-known Ross ice shelf generated by the ice sheet. Its vertical side, plunging into the sea from a height of 50 m and known as the Ross Ice Barrier, is 900 km long. Studies of this precipice have not revealed any morainic debris.

However, there have been reported traces of dust-like and fine-granular substances in the Antarctic ice. Speaks K.S.Losev in the book *Antarctic glaciers:* "Bearing in mind the negligible amount of insoluble inclusions in the Antarctic ice sheet, it can be presumed that the bottom of the subglacial lake is covered with an unsubstantial silt deposit." Further we read: "With drifts as nominal as these, it would take millions of years to fill up even shallow impounded bodies, if at all" (p.91). Note the inability of a mighty glacier to deposit a noticeable amount of silt on a lake bottom.

Contrary to this evidence, we are made to believe that it has taken much less time for Quaternary glaciers to transform the relief by plowing and dislocating, shearing off, crashing gneiss, granite, and diabase massifs to blocks and boulders, and also polishing and striating rock. Moreover, according to Academician V.M.Kotlyakov (1994), grinding was most vigorous in the centre of Quaternary glaciers. It is puzzling how meek the real (not hypothetical) continental glaciers are nowadays. But not so puzzling if we admit that the processes were not glacial but fault-tectonic.

Nonetheless, it is essential to have a closer look at glacial activity regarding sedimentation and exaration.

The most informative in this respect are the glaciers of Bunger Oasis in East Antarctic, specifically, the glacier edge resting on crystalline rock in proximity of the Bunger Hills. Work within a YGY project was specifically aimed at exposing to view morainic debris and ascertaining the extent of glacial exaration. The results have been summarized by E.A.Yvteev in a series of minor publications and a monograph. Debris in the Bunger Hills was found to be 40 m thick. Still thicker it is (100 m) at the junction of Scott and Denman outlet glaciers (Yvteev, 1959, 1964).

The alleged moraine debris in Bunger Hill ice outcrops was sampled at 8 sites. The weight content of debris was determined as 0.11% in the upper part of the ice shelf (at the 40 m elevation). It gradually increased downward to achieve a maximum of 11.84% at the ice contact with bedrock. The average content of moraine debris in the "moraine-containing" stratum was 1.87% (in Yevteev's book – 1.6%).

As for the 100 m stratum of moraine-containing ice at the Scott-Denman outlet glaciers' junction, it yielded so little material that it seems not to have been analyzed.

As a result, the figure of 1.6% was extrapolated to the entire Antarctic to derive a formula whereby the ice sheet cuts 0.05 mm of bedrock annually. This was followed by a conclusion about an enormous exaration activity of continental glaciers plucking hundreds of meters of crystalline rock during one geological epoch. I think it is about time we determine the proportion of volcanic ash and terrigene fine earth in this 1.6%. It seems we may find that the extent of glacial plucking of heaven was greater than that of subcelestial rock!

True, the figure of 0.05 mm/year has been arrived at through much wavering. It varied in Dr.Yevteev's publications between 0.01 mm/y to 0.06 mm/y, which even became subject of P.S.Voronov's and M.Grossvald's criticism (1966) pointing out in their review that the author did not disclose the procedure of his computation "differently assessing one and the same material. Thus, the ice drift in 1959, 1961 and 1964 was determined, respectively, as (mm/y) 0.05, 0.01, and 0.05".

Thereupon, the figure of 0.05 mm/y has stabilized with Yevteev, ut not so with Acad. V.M.Kotlyakov. This is what he writes in his book *The World of Snow and Ice* (1994): "Judging by fragmentary experimental data, the glaciers grind 2 to 15 mm of hard rock every year" (p. 190). How paltry now appears the case of the reprimanded 0.01-0.05 mm/y and how majestic – the willful boosting 300fold of the glacial exaration power resulting in profound plowing, shearing and dislocation!

Both this figure and ensuing geological consequences have been hailed by glaciations advocates. No matter that the experiments were not quite sound: in laboratory conditions ice was frozen together with numerous different-size, hard impurities whereupon this "moraine-containing ice" was ground electromechanically against a marble plate. No matter that in so doing the rate of ice abrasion was much higher than that of the marble plate.

In natural environment, such processes would have abraded the glacier down to the bottom. Prior to escalating the glacial exaration, the glaciations proponents should have familiarized themselves with the book of the RAS Academician N.A.Shilo (1981) stating that "there can be no comparison between such ice parameters as elasticity modulus, shear resistance, etc and those of rock… Therefore it is absurd to presume that glaciers could have destroyed rock, unless one credits them with mythical power."

Now let us have a closer look at the moraine-containing stratum of ice (basal moraine) assumed to be 40, and even 100 m, in depth (Yevteev). Further research will, logically, be based on information about its lithological structure, mechanical and mineralogical composition, the petrographic composition of blocks and boulders, and quantitative analysis. No such data are given in either Yevteev's papers and monographs, or in any other authors', although the work was carried out under the aegis of such a respectable project as MGY**!** Information is also zero concerning the percentage of volcanic ash and terrigene impurities. It is only explicit regarding the petrographic characterization of blocks and boulders – no boulders, no petrographic analysis.

Other researchers of Quaternary sediments and moraine-containing ice of the Antarctic N.F.Grigoriev (1962), G.V.Konovalov (1971), I.M.Simonov (1971) are also reluctant to disclose the grain size of moraine substance using only the terms "dirty ice' and "soiled glacier parts", but feeling much freer with other sediments –

down to contemporary lake sediments. There seems to be a veil shrouding the data on the grain size of moraine substance in glaciers in the Antarctic (and Greenland) precluding an explicit determination of “dirty ice”. Putting aside the scientists’ obvious embarrassment at the lack of boulders in both continental and outlet glaciers, they ought to perform the task of analyzing the mineralogical and grain-size compositions of dust and fine earth, if there are any.

It was only forty years later that light was shed on the Bunger oasis moraine, after the geological-glaciological research of D.Yu.Bolshiyanov (Research Institute of the Arctic and Antarctic, Russia). According to his both published and privately disclosed information, the “morainic breccias” stratum is represented by ice containing mineral particles of the sand-clay-dust size. Besides, the amount of the substance in the Bunger oasis ice, reported by Yevteev, has been overrated by an order of magnitude.

Facts about the absence of boulders and blocks in ice sheet moraines have been concealed for a long time. Everybody relied on assertions pronounced with authority. All textbooks carried cross sections and schemes of ice sheets interspersed with blocks and boulders. With no access to facts, they had to be taken at face value.

I dare suggest this situation parallels one described in the tale of H.C.Andersen “The Emperor’s New Clothes” (1843), with Emperor sporting ever so importantly the supposedly gold-clad, but actually non-existent, clothes, both the fawning courtiers and commoners not daring to admit His Majesty’s nakedness. In our case, respectability now demands to stick to what has not once been proclaimed and petrified as the ultimate truth!

One may say that there is too much controversial ardor of this passage. That there are, somewhere, sections of ice sheets with real moraine containing rock fragments and boulders, as is shown in Figures 1 and 2. Indeed, there we are shown thick strata of moraine boulders, but in fact this refers to myth coinage, as N.A.Shilo put it.

We needed reliable, duly recorded field acquisition. Finally, such evidence appeared for the Antarctic ice sheet. The fundamental *Glaciological Glossary* (1984) made public a photograph (photo X.19) with a caption that reads: “Strata of moraine-containing ice in an iceberg off the Wilkes Land”. Indeed, the section of the upside-down iceberg demonstrates bands of black ice smeared with a mineral substance, and bands of clean ice, with a fountain pen put nearby, for scale. But what is the substance composing the moraine? In appearance, it is till with white ice visible in places through it. Such textures are known as ‘dirty ice’, where the moraine substance is represented by argillaceous-aleuritic material. So far, there have not been recorded any inclusions of at least coarse sand or pebble size, to say nothing of boulders. Glaciations proponents, so impressive in numbers, have failed to produce anything more convincing, although they must understand that melting of such ‘moraine-containing” ice would yield a nominal layer of argillaceous-aleuritic deposit.

It is pertinent to turn now to the “glacier-boulder formation” of the Russian Plain supposedly created by the Fennoscandia ice sheet. Its lithology is described in detail in the work of I.I.Krasnov and co-authors (1986): “ A glacial formation is generally characterized by scaly bedding, close affinity to the composition of underlying rock, availability of sheared rock, abundant local breccias including rocks from practically all the lower-lying, pre-Quaternary horizons”. It should be added: including the blocks and boulders from the crystalline base uplifted together with tectonic breccias along the deep-lying faults in the base and sedimentary cover. In point of fact, the “glacial formation” described by Krasnov et al. is fault-tectonic, formed in the seams of dynamic neotectonic faults and adjoining areas. Other natural processes creating boulder deposits will be considered elsewhere.

1.5. Morainic matter in mountain glaciers

Glaciers of the mountain-valley type carry a lot of detrital material brought down from mountain sides overhanging the glacier, or transported by screes, landslides, and avalanches. Some of the rock moves as far as outlet glaciers, if they flow along fjord-like valleys or are obstructed by nunatacs. Valley glaciers are known to be actively forming the relief such as terminal, side and middle moraine ridges, and also ablation moraines. On many glaciers, the surface moraine sinks gradually through the ice, occasionally reaching its bottom. A part of it crumbles into transversal fissures, building the internal and basal moraines.

Our understanding of the transport mechanism of stone material at the glacier bottom became essentially clearer due to a many-year-long research of E.Evenson and M.Clinch (1987) carried out at Alaska with its highly dynamic mountain glaciers. Of the eleven glaciers examined, two (McLaren and Galkan) were studied most thoroughly. Qualitative assessment of material transfer included:

1) Mapping of side and terminal moraine deposits;
2) Tracking the ways of material transport to glacier boundaries;
3) Genetic analyses of supraglacial, englacial, and subglacial till.

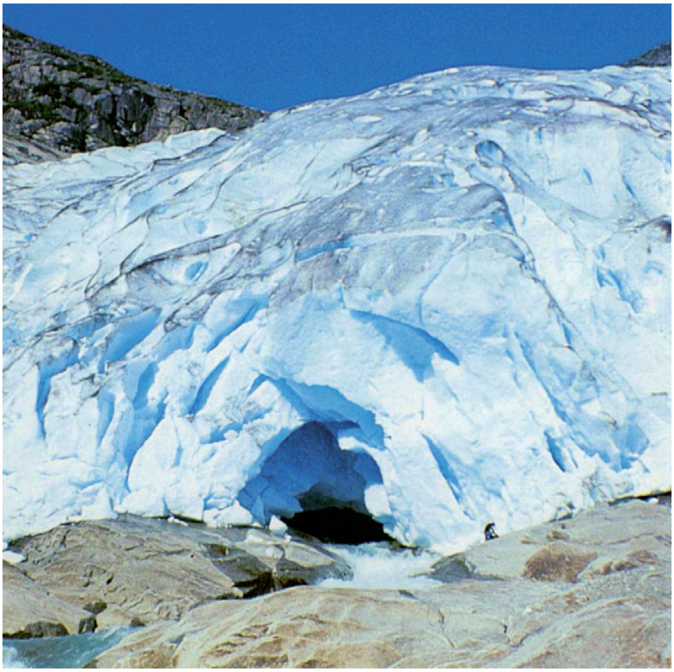

Fig. 5. Mountain-valley glacier (Norway)
Drift along a tectonic rocky bed; no traces of basal moraine
(photo of S.Ehlers, 1983)

E.Evenson and M.Clinch came to the conclusion that fragmentary material is generally transported by supraglacial, superficial processes. In the examined glaciers edges, 90% of sediments have been brought by water gushing from overlying glacier parts and from surrounding sides. About 10% of fragmentary material is contributed by subglacial and englacial moraines, whereas the subglacial contribution (the basal moraine) was negligible.

So, even in mountain-valley glaciers, with their steeply inclined beds, the breccias transport from basal moraine is insignificant, almost 100% of it being transported by other processes. Furthermore, whereas in mountain glaciers the transport is predominantly supraglacial and englacial, ice sheets covering a flat country could not have transported it due to the absence of this material on, or in, it.

In this connection, it is interesting to consider the estimated boundary shear reported by Sh.A.Danielyan (1971):

1) the boundary shear of glaciers has negative values, i.e. glaciers cannot transport boulders at their bottoms;

2) the boundary shear tends to diminish (not to increase) with increasing of glacier thickness;

3) notwithstanding the fact that the boundary shear increases with increasing steepness of slopes, it is still insufficient for shifting subglacial boulders.

Not surprisingly, Dr. Danielyan's findings got no acclaim with glaciationists. Similar findings were earlier reported by D.Dyson (Dyson, 1952) who observed that dynamic alpine glaciers of the Snerry and Grinnell type (Rocky Mountains, Montana) could not transport even small boulders, either lying on the glacier beds or half-protruding from the ground. Besides, no boulders have been found at the bottom of even the largest mountain-valley glaciers in Scandinavia.

1.6. On glacial erosion

Let us turn to direct observations casting doubt upon the glaciers' ability to plough land. More than a hundred years ago, T.Chamberlain and R.Salisbury pointed out the insignificance of glacier-related erosion. According to their observations, the soil emerging from under glaciers drifting along a flat country was little disturbed and even preserved grassy vegetation.

This is confirmed by a many-year-long research of M.I.Iveronova (1952) in the Tien Shan, who discovered that drifting glaciers did not disturb either the underlying sediments or soil, including herbaceous vegetation.

As reported in K.K.Markov's Pamir studies (1946, 1986), glacial erosion there is weak and, consequently, could hardly have produced the so-called "basal moraine". Studying of uncrumpled and uneroded cobble and clay deposits has led K.K. Markov to a conclusion the logic of which is yet to be refuted by glaciations advocates: "If the glacier has not eroded loose deposits, it cannot be expected to have eroded harder rocks" (1986).

Traces of exaration are lacking on the subglacier floor in Scandinavia, which has been demonstrated by melting out soil polygons and ancient deltic sand deposits with remaining sand waves (Whalley, 1981; Harris, 1984). The emergence of well-preserved Roman fortifications from under melting alpine glaciers, or ancient Norman settlements from under outlet glaciers in Greenland, has been reported not once (Shilo, Danilov, 1984; Chizhov, 1976).

Critical data have been obtained from the subglacier floor of Twin Glacier in Elsmere. During the Little Ice Age, this glacier protruded far down a graben. Having receded now, it has exposed a valley with tundra vegetation of the day and a soil cover, all this contrary to the glacial theory (Bergsma, Sloboda, Freedman, 1984). Absence of morainic formations on the soil cover suggests that Twin not only has preserved the valley with its soil layer from erosion but also has left the moraine intact. Studies at other glaciers in the Canadian Arctic have also revealed that their impact on relief was insignificant. Writes G.England (1986): "One cannot but question the essentiality of glacial erosion contribution to the fundamental process of landscape transformation".

A good state of preservation of preglacial drifts, including auriferous ones, located in grabens and circuses of Central Tien Shan has been reported by

Yu.P.Seliverstov (1999) who also attributes it to glacial conservation. It follows thence that mountain-valley glaciers prevented the bed from denudation rather than gouged it and that, most likely, the grabens have originated through tectonic erosion.

Somehow, the hypotheses of a titanic glacial activity are fading into insignificance when faced with the following facts. It was in 1968 that D.Hooke noted a peculiar behaviour of the Greenland ice sheet which margin overlaps snow fields further drifting over them, instead of plowing them. In Iceland, it has been noted that even the fastest-moving, "surging" glaciers fail to produce any exaration in the bed. A description of Bruar (an outlet glacier of the Vatnajökull massif) surging in 1964, has been provided by V.S.Koryakin (1988). Forging ahead, the glacier "was crumpling the snow in folds of 2-3 m in height". It may be argued that the glacier bed was protected by a snow cover. In reply, one may wonder how little a glacier bed needs to be protected from exaration.

It may be bewildering how can direct observations, properly recorded and duly brought to public notice, have been so long disregarded by Quaternary geologists and paleographers. The answer appears simple, but far-reaching. What would befall the glacial theory if it discarded the premise of a large-scale glacial erosion? Inevitably, that would make redundant the ideas of shearing of crystalline rock on the Baltic and Canadian shields, plowing of fjords and lake hollows, and transporting of boulders and erratic rocks to thousands of kilometers. Making redundant the theory as well.

The extent of glacial erosion has been discussed for already 150 years. According to the French geographer E.Martonne (1945), "those deeply involved in alpine glacier studies are skeptical about glacial erosion. Others are inordinately hyperbolizing it".

It so happened that "those deeply involved" founded the Alpine school of glaciology headed by A.Heim. The others, furthering the glaciers' inordinate might, congregated with H.Hess. A.Heim denied glaciers the ability to form grabens, lake beds and valleys in the Alps referring them to a tectonic form of relief. At the same time, he considered the rock polishing found in melting glaciers a result of glacial activity. Inevitably, the compromise brought the problem to a blind alley: slikensides which are, in fact, a product of fault tectonic polish, a striated tectonic bed over which a glacier glides, preventing the slickensides from weathering and erosion, have been mistaken for glacial erosion. (The origin of striation, polishing on massive rock, and other types of exaration relief will be dealt with specifically in this book). Apparently, some of the problems related to relief exaration could be solved by comparing the physical-mechanical properties of ice and those of rocks underlying the glacier drift.

The nature of processes allegedly enabling glaciers to plough and wrench out rock blocks can be approached by researching such ice properties as cleavage and shear strengths. Shear strength has long been brought into play to account for the glaciers' ability to plough, cleave and shift rocks. However, in terms of resistance to cleavage and shearing, ice is 10-20 times weaker than rock. Similarly impressive are compared compression and tensile strengths: 25-59 and 5-10 times as little as those of rock, respectively. This signifies that ice cannot ruin the underlying bedrock. Nor can it plough or abrade it.

Moreover, low cleavage strength prevents the accumulation of substantial tangential stresses in the ice body since critical stresses are easily achieved, each time resulting in cleavage. Hence is the characteristic drifting of ice along the internal cleavage facets in glaciers.

1.7. Boulder material into shore (fast) marine ice. Ice marine drift and rafting phenomena

The so-called aquatic moraines contain much erratically scattered boulder material, sometimes transported from afar as, for instance, small boulders transferred from the Khibiny Mountains to the White Sea neck to as far as 250 km. Some erratic material is also found in "basal moraines".

This is hardly surprising considering that lowlands on the Kola Peninsula used to be submerged under sea-level transgressions during the Quaternary. Marine deposits, or fragments thereof, have been discovered at elevations of 150-170 m, and even higher, on tectonically lifted areas – at 260-300 m (Lavrova, 1960; Chuvardinsky, 1982, 1985).

Thick strata of clay loam with boulders are known in Russia's European part, in Western Siberia, and on the bottom of Arctic seas. Commonly, they are believed to be of glacial origin, but many regard them as ice-marine deposits. Boulders have been transferred there by shore ice and, partly, by icebergs. Sea-level transgressions have contributed not only to accumulation of marine and ice-marine deposits but also to vigorous washing-out of continental sediments and their re-deposition as outwash moraines. Wave abrasion has created vast boulder fields by washing fine earth from upper levels of boulder-block deposits. These formations, the so-called "abraded moraines", are frequently encountered in Karelia and southwest Kola Peninsula up to the altitude of 120-140 m. They have been recorded (*Sevzapgeologiya*) on Quaternary deposit maps (1:1000000 and 1:2500000) published in 1962 and in 1967.

So, by studying the processes of boulder transfer with fast shore ice it is possible both to understand the nature of boulder deposits (ice-marine, according to some; glacial – according to others) and improve the boulder surveying techniques.

It has taken the author several years to research the drift phenomena in the Kandalaksha Bay of the White Sea to penetrate into the mechanism and scale of these processes (Chuvardinsky, 1966, 1985). The findings are summarized below.

Littoral structure and shore (fast) ice dynamics

Tidal fluctuations in the Kandalaksha Bay (2 – 3.5 m) have produced littoral zones along both the bay and islands shores. The littoral is clearly divided into the following zones (starting from outshore littoral): a) a 2 – 2.5 m high boulder ridge; b) a flat-bottom depression built by boulder debris, both sand and loam; c) a coastal strip strewn with pebble and rubble. The first two zones are completely flooded, whereas the third is characterized by positive and negative setup phenomena. The width of the tidal zone depends on the shore geomorphology varying between the first meters to 2 km.

A fast ice strip runs uninterrupted along the coast, islands, and sand bars. The ice is 1-5 m deep (as of the high tide level), with areas 7-8 m thicker, where ice shoves from below. Fast shore ice forms both within the tidal and upper subtidal zones. The widths of the ice strip and tidal zone vary between several meters to 2 km.

Tidal phenomena have divided the fast ice into distinct zones, namely: the foot (an ice strip occupying the littoral between the boulder ridge and the shore); the outer (seaward) part stretching from the boulder ridge to a part of the adjacent sublittoral to the depth of 5 m. Owing to tide-related strains, the fast ice is split into 0.5–1 m thick blocks of about 10x30 m by a network of longitudinal and transversal cracks.

Processes of coarse block fragment capturing by fast ice

Coarse rock fragments get stuck into fast ice throughout the entire freezing period, starting from the foot and spreading to the offshore area. The positions of boulders and other rocks found in fast ice are different due to dissimilar mechanisms of their capturing, i.e. on the ice surface (1), at the ice bottom (2), and inside the ice (3).

Most of the boulder material accumulates on the fast ice surface. Both in Russia and abroad it is believed that shore cliffs are the only source of rock fragments in ice. According to our observations, the mechanism whereby fragments are raised from the littoral and upper sublittoral beds are the following. When fast ice gets stranded, boulders and rock fragments, both large and small, lying on the littoral bed, are transferred to the band of ice cracks. Next, during compression and hummocking, the material is extruded along the cracks to the ice surface. Extrusion of terrigenic material is most intensive in February-March, although it occurs throughout the freezing period. During further hummocking, some of the extruded rock fragments are shoved away from the crack lines to the ice interior. This mechanism has been observed by us more than once in natural conditions and is also confirmed by the following data (Fig. 6,7,8):

a) Boulder-fragment material is usually huddled near cracks on the fast ice surface, visibly concentrating along the greatest strain zone, i.e. a crack between the foot and the sea floor.

b) Boulders are frequently found in cracks between fast ice floes demonstrating partial extrusion of rocks from the littoral bed. At the same time, one can see depressions previously occupied by the boulders.

c) Depressions, previously occupied by boulders, are located along a boulder ridge, the boundary of greatest-stressed fast-ice areas.

Both boulders, blocks, pebble and detritus lying on the ice surface exhibit traces of previously staying in sea water, such as colonies of acorn barnacles and attached seaweed and mussel shells.

Extrusion of rock fragments onto the ice surface can also be proved by ramparts of bottom sediments running along both the principal and secondary ice cracks. Bottom sediments (loam and sand) are also extruded onto the ice surface.

As to rock fragments sliding down onto ice from shore cliffs, this does happen, although on a small scale. We have noted only individual fragments fallen from 50-90 m high cliffs. Their origin was unmistakably terrestrial due to the presence of lichen and plant roots (the latter in fragment cracks). However, most of the rock fragments in the cadder bore the traces of immersion in sea water.

Fig. 6. Boulders and other rock fragments on the fast ice surface. It can be seen that the material is clearly confined to the principal crack, Kandalaksha Bay (photo of the author)

Freezing of boulders, detritus, sand, and other material to the fast ice bottom occurs in littoral and sublittoral zones. This process is widely spread to the depth of 2-4 m of the high-tide level. Ice bottoms often reveal frozen layers of sandy-pebble and clayey-rubble soil. Not infrequently, the terrigene sediments are interstratified due to freezing of rock fragments while the ice regularly strikes the ground during low tide. Emerging again during the high tide and subcooled in subaerial conditions, fast ice gathers more ice from beneath (Fig. 9,12).

Stratified fast ice is commonly observed in the Kandalaksha Bay. It demonstrates the parallel processes of ice increment from beneath and from above, with detritus caught in between. Both the ice increment on the surface and burying of detritus from beneath occur during the surging and tidal phenomena, when sea water rises through cracks to the ice surface. Frozen with snow, it forms aufeis ice. Depending on the aufeis thickness and detritus size, the latter gets buried either entirely or partly. These cycles create a multilayered structure of fast ice in its upper section (Fig. 10).

As noted above, detritus also penetrates into the ice on freezing from beneath. If freezing of detritus to the ice bottom occurs repeatedly, boulders and other material of the initial freezing cycle often appear in the floe's middle part. One and the same floe may be carrying overlapping layers of detritus frozen both from above and from below.

Together with terrigene material, both the upper, middle and bottom parts of fast ice abound in seashells (mussel and gaper), acorn barnacles, rockweed, eelgrass, and ahnfeltia. The mechanism of biogenic material penetration into the ice is the same as described for terrigine material. Also, seaweed may be entrained onto ice during surges and initial cycle of ice formation.

In terms of mechanical composition, the frozen material varies over a wide range between clay particles to boulders and blocks. The largest boulders and blocks (up to 2 m across) are extruded to the ice surface, whereas smaller ones freeze into the bottom. The level of rounding differs over a wide range, from practically untouched blocks and detritus to fairly rounded boulders and cobble. The shape of boulders does not depend on their petrographic composition varying from subangular and brick-like to smoothing iron-shaped to rounded. The material composition is the same as that of local and underlying rock including gneiss, composite gneiss, amphibolites, granite, anortisite, and gabbronorite. The boulder-block material is transported from broken bedrock in the tidal zone and from rock outcrops on the coastal area, and also from wave-cut boulder-containing Quaternary deposits.

Fig. 7. Gneiss and migmatite boulders extruded along cracks to fast ice surface. The gauging rod is 0.9 m.
The Kandalaksha Bay (photo of the author)

Fig. 8. Migmatite boulder of protruded onto the fast ice during ice hummocking (photo of the author)

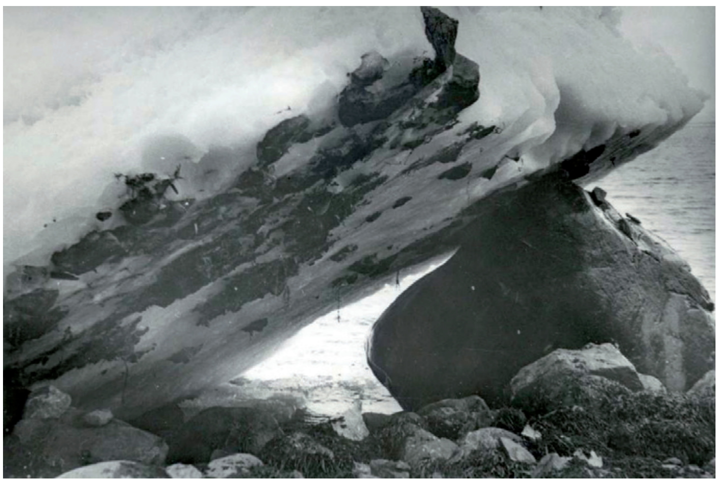

Fig. 9. Boulder material frozen into an ice floe bottom. The Kandalaksha Bay (photo of the author)

Fig. 10. Gneiss boulders in the ice section (ice foot and interior). The Kandalaksha Bay (photo of the author).

It is customarily assumed that breaking of bedrock outcrops is caused by weathering. This is true, but to a certain extent. The principal activator in this case is diastrophic movement along faults. The main source of block material is disturbed, seamy rock blocks displaying traces of tectonic dislocations such as slickensides with striated planes and traces of shearing. Paraclase tectonic dislocations are still occurring in the Kandalaksha Bay which is evidenced by the fairly high seismicity of the Kandalaksha graben fault.

Scattering of boulder material by fast marine ice (rafting)

Erosion of sea ice starts in the skerry part of the bay characterized by strong reversing tidal currents. Broken ice on this area drifts either immediately after, or simultaneously with, breaking and drifting of sea ice. On areas with lower hydrodynamic activity, breaking of both sea and fast shore ice sets in much later.

The first to be carried into sea is the outshore ice; next the ice from the foot, which is subjected to heaving oscillations accompanying the tidal phenomena. This ice is carried away by tidal currents, including in calm weather. Some of the cadder, attached to the ripple, is carried away at syzygial tides concurring with rundown winds. As for the bay-head beaches, cobble and boulders are practically not entrained from them since ice there thaws on site.

The author has estimated the amounts of boulder material, captured ice and drift at different sites of both the bay coast and the islands. The data acquisition techniques and analysis have been reported (Chuvardinsky, 1973, 1985). Here are presented the principal results.

Every season, each linear kilometer of fast shore ice, both surface, interior and foot, contains 45 m^3 of detritus, mostly boulders. The volume of detritus carried seaward with fast shore is about 40% of that scattered over the floes which are partly destroyed and partly melt down without shifting. The amount of stone material, generally boulder-size, annually carried to the sea from 1 linear km of fast ice, is about 16-18 m^3. The size of larger boulders found on drifting ice of the Kandalaksha Bay was 1.5-2 m in diameter (Fig. 11, 12).

Fig. 11. Breaking and drifting ice in the Kandalaksha Bay. One of the floes is seen to be carrying an amphibolite boulder of about 1 m across. Smaller rock fragments on other floes (photo of the author).

Fig. 12. Boulders on fast ice surface. Other floes brought onto fast ice by tide, a part of them containing boulders and rock fragments frozen into floe bottoms (photo of the author).

Being affected by discharge and ebb currents, floes with boulder material mainly drift southeast. However, the drift direction may be changed by winds and incoming tides up to northwest. Boulders are transferred to as far as several tens of kilometers.

It should be noted that in the White Sea, known for its mild winters and rather thin shore ice, conditions for boulder transfer are far from being favourable. Comparable data reported from the Okhotskoye Sea are much more illustrative. Thus, according to L.E.Stepanova (1985), the amount of rock fragments carried into the sea from each kilometer of the shoreline equals many tens of m^3.

Thus, boulder material is scattered by fast ice all over freezing seas, sinking gradually to form bottom deposits and, finally, glacial debris. This should be taken into account in paleographic reconstructions.

Compared to dust-like particles in ice sheets, it is a substantial, but not the main, means of boulder transfer. The main driving force here has been the neotectonic cleavage fracturing of crystalline rock into coarse fragments and boulders subsequently dislocated inside the faults along with breccias.

1.8. Mud torrents

Mud torrents are destructive flows burdened with rock fragments, leaving behind muddled loam, cobble, boulders and blocks, some of which are as large as tens of cubic meters, often building ridge-undulating relief.

Mud torrents are often actuated by heavy rainfalls, sometimes by precipitous melting of snow and glaciers in the mountains. Boulders and blocks in mountainous regions and foothills are transferred as far as several dozens of kilometers. The remains of mud torrents, gushing into foothills and strewing them with boulders, are often mistakenly regarded as glacial-related. But in case of mud torrents, which are not infrequent and always disastrous, there has been careful recording that deprives the glacial theory of a substantial part of its argumentation.

By way of example, let us consider the powerful shower torrent that flooded the city of Alma Ata (the capital of Kazakhstan) on 8 June, 1921. The mass of mud and stone was estimated as 4 million tons, with erratic blocks of 60 m^3 weighing dozens of tons (Pidoplichko, 1956). A postcard in I.G.Pidoplichko's book provides a clear view of Karl Marx Street in Alma Ata totally obstructed by large boulders making the street impassable for cartage and motor transport. As reported by S.M.Fleishman and V.M. Perov in their book "Mud Torrents" published in 1986, some of the huge boulders remained lying in the streets of Alma-Ata in commemoration of the torrent of 1921.

This suggests that whenever one comes across debris on mountain foothills, he should not necessarily regard it as glacial heritage, the more so that mud torrents are, undoubtedly, a by far more powerful and more frequent natural process of boulder transfer than mountain glaciers.

1.9. Iceberg deposits

As it has been pointed out, mountain-valley glaciers transport a good deal of large rock fragments. If such glaciers glide or collapse straight into the sea (thus turning into icebergs), they preserve some of the fragments on the surface. On melting, disintegrating, or capsizing, this material collapses onto the seabed, forming in places iceberg-marine deposits. Areas of active iceberg-related deposition include the Western Spitzbergen, Alaska Bay, Melville Bay off the Greenland coast, and a section of the Pacific Ocean adjoining the mountain glaciers of South Patagonia (Chili). In the Ross Sea, large stone blocks are delivered by icebergs produced by mountain glaciers of Victoria Land.

On the other hand, continental glaciers, unlike their mountain counterparts, do not contain coarse rock fragment, only fine earth (mostly volcanic ash) as particles and aggregates. The same refers to shelf ice of the Antarctic, the greatest producer of large, and huge icebergs, some comparable in area with Luxemburg.

Concerning the contribution of fine-earth-dusty incrustations entrained by icebergs from ice sheets and shelf ice to form marine deposits, it is too small to identify due to irregular, but persistent, precipitation of volcanic ash and space dust.

1.10. The origin of stratified ice in perpetually frozen soil

For glaciations advocates, the presence of buried ice strata in perpetually frozen Cenozoic sediments serves as irrefutable evidence of erstwhile existence of a continental ice sheet in Western Siberia. They are considered “to have remained there since the great glaciations” (V.I.Astakhov, M.V.Grosswald, and many others).

Thus asserting, they disregard the permafrost and cryolith studies, both field and laboratory, indicating that their origin was cryogenic, not glacial. These findings are available in performance reports and in publications, particularly in cryogenic-hydrogeological researches of L.N.Kritsuk et al. (1985, 1988, 1990). There it is convincingly shown that embedded ice was produced on crystallizing of free underground water injected into the ground under external pressure. As the soil was perpetually freezing, water in cracks and edges also froze. When frosts became more severe, there also froze out the interstitial and pressure water from cracks. In particular, the embedded ice of the well-known Ice Mount in the lower reaches of the Yenissei

River was found to have been formed by freezing pressure water (Kritsuk, Anissimova, 1985). This inference has been supported by hydrochemical and isotope studies.

As was reported by M.A.Velikotsky and Yu.V.Mudrov in 1985, embedded ice on the Yamal Peninsula was also built by freezing interstitial sea water during sea-level regressions (this was proved by hydrochemical analyses) and by cryogenic segregations.

Studies of V.F.Bolikhovsky on the Yamal and Gydan Peninsulas (1990) have revealed a paragenetic association between the embedded ice and saline marine deposits containing sodium chloride and fragments of shells and foraminifers. According to Bolikhovsky, embedded ice represents subnormal syncryogenic formations having no relation to glaciations.

An invaluable contribution to establishing of the origin of interstitial ice was made by I.D.Danilov (1983, 1990) who came to a conclusion that this ice emerged as the result of freezing of water-saturated deposits, of underground and pressure water.

Cryogenic origin of embedded ice has also been proved by N.A.Shpolyanskaya and N.D.Streletskaya (2004), who have drawn up a genetic classification of embedded and cavern lode ice on Siberian plains. In their opinion, the wide-spread occurrence of underground ice rules out their glacial origin.

Recently reported chemical trace analyses of embedded ice in Siberia, including in the Ice Mount from the lower reaches of the Yenissei River (Yu.K.Vasilchuk and V.M.Kotlyakov (2000)) have confirmed the cryogenic nature of the processes. It is now known that the ice embedded in Ice Mount has been created by underground pressure water.

Obviously, this evidence rejects the hypothesis of the glacial origin of embedded ice in the Arctic plains; using the same in support of it is incorrect. “What, then, remains of the seemingly solid structure of the glacial theory?” – queries I.D.Danilov (Danilov, 1990, p.82). Other researchers (Lovchuk and Krass, 1987, p.102) also emphasize that the body of available evidence on the structure of frozen earth and embedded ice “invalidates the hypothesis of glacial diapirism and burying of glacial ice”.

Chapter 2.
Fault tectonics and geomorphogenesis on the Baltic shield

Neotectonics as a science emerged early in the XIX century, when it was established (by W.Hobbs and I. Sederholm) that the crystalline basement of the southern part of the Baltic Shield was split by a dense network of diaclases forming distinct systems of linear disruptions. Diaclases had a vertical dip and crossed at right, or almost right, angles, cleaving the crust into various size blocks (Fig. 13, 14). Diaclase systems were found to have longitudinal, latitudinal, north-eastward and north-westward strikes. A more detailed study of R. Sonder (1938) has revealed two main types of regional fissures: those genetically associated with tectonic processes and the so-called lineament jointing, or 'lineaments'. According to Sonder, the lineaments are responsible for the geometrically correct fault network, subsequently causing tectonic displacements, and the block structure of the crust. The origin of the lineaments was outside the scope of Sonder's work.

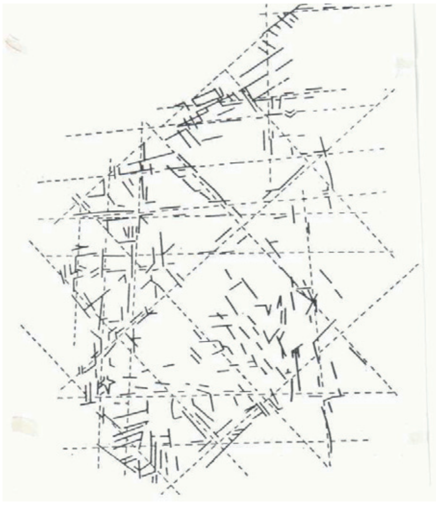

Fig. 13. A system of deep-seated faults in South Norway (according to Hobbs, 1913). The dotted line shows large blocks of the Earth's crust.

Fig. 14. Fracture systems in Precambrian rock of South Norway (from aerial photographs) (according to O.Holtedahl, 1958).

For about 50 years afterwards, no fault tectonic studies, lineament tectonics in particular, of the Baltic Shield were carried out. Moreover, faults, including ruptures and diaclases, were almost entirely ignored on geological maps of the time.

But time went on, and geological surveying got a powerful support from remote surveying (interpretation of aerial and satellite photographs in the first place) making visible the fault tectonic elements on maps. Interpreted air photographs and on-land studies were employed to construct numerous patterns of the Baltic Shield fault tectonics (in the contours of geological-surveying sheets and areas, and larger regions such as the Kola Peninsula, Finland and Karelia). This brought back to life the almost forgotten Hobbs-Sonder lineament hypothesis launching debates on the lineament tectonics and planetary jointing and giving rise to new interpretations of the notion 'lineament' and such new terms as 'planetary jointing' and 'regmatic rupture network'. There emerged concepts of a rotational origin of the Earth's lineaments. However, the new definitions were vague and cumbersome. We even find them all meddled up, since are not faults the diaclase lineaments of Hobbs and Sonder's or do they include only deep-seated faults? As the result, the Russian

Geological Glossary gives the following definition: “A lineament (line) is linear or arched elements of a planetary scale associated with deeply-seated faults...”

No satisfactory treatment of lineaments can be found in the fundamental work *Space Information in Geology* (1983), although it is essentially based on lineament tectonics.

The lineament classification presented in *The Fundamentals* of *Linear Tectonics* (1986) is too unwieldy to be satisfactory. The classification includes: 1) lineaments of geographic environment (topolineaments, batilileaments, photolineaments and kosmolineaments); 2) lineaments of the geological structure (geolineaments, tectolineaments, metallolineaments and hydrolineaments); 3) lineaments of geophysical fields (magnetolineaments, gravilineaments and thermolineaments).

It is evident that much of the initial sense of the term ‘lineament’, jointing of the Earth’s crust, a diaclase in Hobbs-Sonder’s definition, has been lost.

Note also that the lineament theory disregards an essential component of disjunctive tectonics, namely, the horizontal and gently sloping crustal fractures. Focusing solely on the vertical fractures (lineaments) can hardly give insights into the complicated dislocation process in its entirety.

Factual evidence obtained by the author during geological surveying, combined with interpreted air-, and later satellite, photographs (Chuvardinsky 1998, 2000) has revealed abundant steeply dipping discontinuities (regional fractures and faults) in the eastern part of the Baltic Shield. Not infrequently, they form readily interpretable systems either in air photographs or – the largest of them – in satellite photographs (Fig.15, 16). The faults are normally visible as gorges, series of linear depressions, rectilinear river valleys and fjords. They cut the Archean, Proterozoic and Paleozoic crystalline rocks having no relation to ancient fold structures or crystalline banding and gneissoids. From these data it can be suggested that:

1. The so-called lineament (planetary) jointing is fairly heterogeneous at the Baltic Shield and has no regular fault systems, as is asserted by the ‘rotogenesis’ theory. Even within the geoblocks composed by lithologically homogeneous and

coeval crystalline rocks (for instance, the Murmansk granitoid geoblock) the fracture network is autonomous in each block. At the same time, some of the blocks feature not only linear but arcuate fractures as well.

2. Generalized rose diagrams of macro-jointing of major areas, such as the Kola Peninsula, with a number of geometrically correct fracture systems varying with researchers between 8 to 18, seem to be ignoring the independence of faulting fractures in even small blocks and the mosaic pattern of the entire fracture network. At the same time, when statistically generalized in rose diagrams (figuratively speaking, cast into the gigantic tectonic cauldron), the fractures yield an artificially averaged, geometrically correct fracture network with a stable azimuth location on vast areas.

3. For the 18 isolated, geometrically correct systems, a part of the fractures is bound to coincide with the strike of an individual system, seemingly proving the correctness of regmatic systems in the Shield macro-jointing. But this artificial approach to the planetary jointing is unlikely to shed much light on the problem.

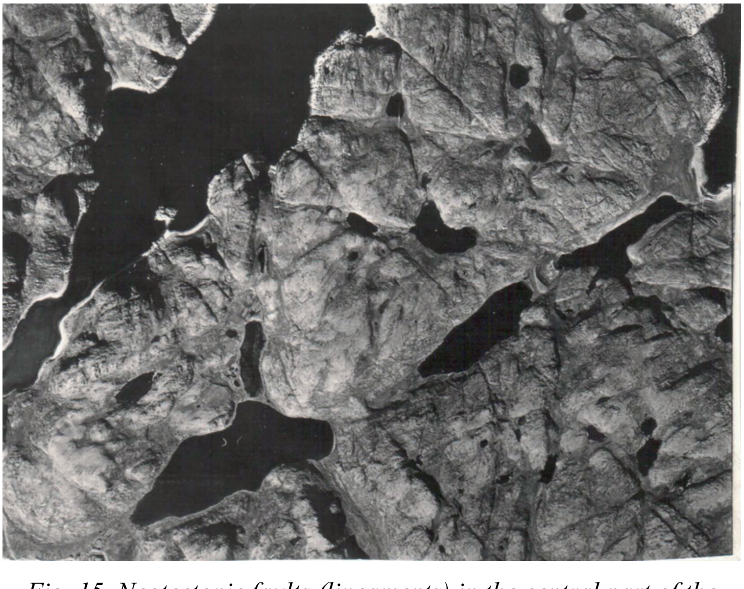

Fig. 15. Neotectonic faults (lineaments) in the central part of the Murmansk geoblock: Archean granitoids (aerial photographs).

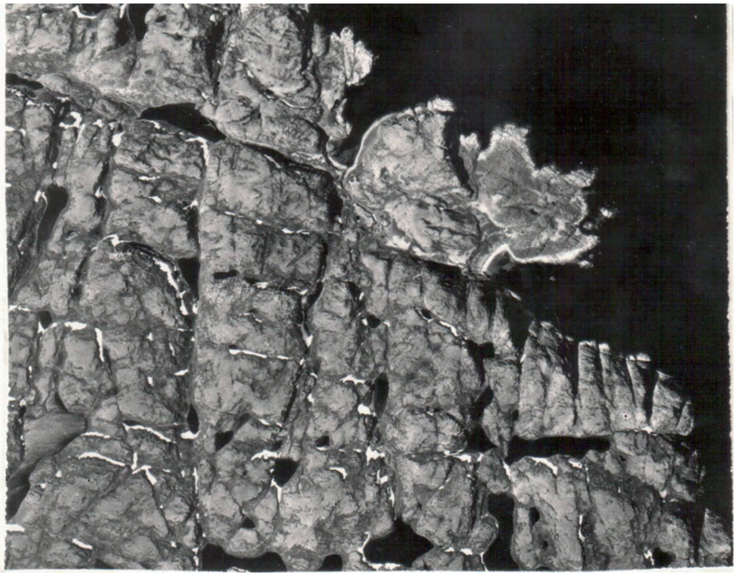

Fig.16. A system of neotectonic faults (lineaments) on Archean granitoids. The Barents Sea shore (aerial photographs).

2.1. Fault tectonics and the age of faults

Most of the dislocations with a break in continuity at the eastern part of the Baltic Shield were mapped by interpreting air and satellite photographs, and partly verified by land survey. Geological surveying focused on land studies, although Precambrian faults were mapped using aerial data. Throughout the Shield's fault tectonic studies there has been no answer whether Precambrian faults and Precambrian regional fractures can be revealed by remote or geomorphological methods. The sole reason why a fault or a major fracture are distinctly seen in an aerial or space photograph is their pronouncement in the relief. The issue is crucial for fault tectonics, but it has been commonly approached following a simplified scheme: both the Archean, Proterozoic, and all faults in general, were rejuvenated and inherited by neotectonic movements, hence their conspicuousness both in relief and photographs. These statements have not been proved but taken for granted and operated with for decades.

Assuming of a Cenozoic rejuvenation of ancient Precambrian faultshas allowed to use remote methods in constructing of maps of Precambrian formations. It goes without saying that this situation made it impossible to accept the concept of neotectonic genesis, Cenozoic age, and posteriority of the Shield fracture network (the part of the fractures unambiguously interpreted in remote data). Such projects were unfeasible then, but reliable neotectonic maps did emerge, though unintentionally.

The genetic and age relation between faults and neotectonic (Cenozoic) movements can be determined using the following criteria:

1. Distinct expressing of faults (and lineaments on the whole) both in topography and aerial-satellite photographs as linear depressions, gorges, linearly extended lake hollows, fjords, etc.

2. The presence on fault walls of numerous slickensides with striae and polishing. Slickensides are subject to rapid weathering, being therefore geologically short-lived.

3. Fault dislocations disrupt the Quaternary deposits, displacing and folding them.

4. Fault dislocations are mostly near-surface faults, upthrusts-overthrusts, wrench and normal faults with destroyed displaced elements (blocks and scales). These have produced a mass of unweathered material incorporated in Quaternary boulder-block deposits.

This is normally sufficient to justify the neotectonic age of faults. As says P.S. Voronov (1968): “Since the lineaments are expressed in modern relief, they are undoubtedly young and connected with neotectonic movements in the crust”.

2.2. Faults and their characterization

The types of faults observed at the eastern part of the Baltic Shield are the following: wrench faults (including upthrust-wrench and normal-wrench faults), overthrusts and upthrusts, extensional faults and normal faults. Seismically, many of the faults appear as deep-seated, penetrating into the crust down to the "M" surface, some of them plunging into the upper mantle. In the present situation, with an inadequately studied kinematics, all deeply seated faults are indiscriminately termed as 'faults', without subdivision into wrench, upthrust, or normal faults. Near-surface faults are likewise poorly understood. Their types are arbitrarily defined, and for only a few of them there is geological evidence of displacement, to say nothing of their apparent slip.

Here the author presents his own field research revealing the structural peculiarities of several wrench faults in the Eastern Baltic Shield.

2.2.1. Startsevsky wrench fault

The fault is located in the south of the Murmansk region bordering Karelia, in the vicinity of Startsev Lake and namesake bay. Studies were carried out in 1986-1987 and 1999. The fault cleaves the rocks of the Belomory Archean gneiss series and small basite-hyperbasite massifs. In its center, the fault is built up by uranium-bearing metasomatite strata forming the marking horizon. The width of the metasomatite band is 500-700 m, and its strike has been followed to 6 km.

The gabbro-norite and peridotite bodies enclosing gneisses and metasomatites carry an impregnated copper-nickel mineralization (Chuvardinsky, 1998). The fault has a south-eastward strike deviating east-south-eastwards in the Startsev Bay.

The scale of horizontal displacement along the Starstev wrench fault can be determined from displacement of a marking geological body, in this case, uranium-bearing metasomatite strata, which was shorn by the fault and displaced along it in the horizontal plan. Horizontal displacement of the fault walls relatively its northern and southern walls is 1.9 km. Moreover, the northern wall within the metasomatite strata contour is split into blocks by subsidiary wrench faults, nearly parallel to the axial wrench fault. The rock blocks have been shifted in the horizontal plan by several hundred meters. The metasomatite strata of the southern wall are torn off by a near-latitudinal fault.

2.2.2. Wrench faults of Ovechy Island

Ovechy Island also contains a set of wrench faults mapped and explored by the author. The island is situated in the Kovda Bay in the conjunction zone of the Startsevsky wrench fault and Karelian regional wrench fault running along the western edge of the Kandalaksha graben. Composed of gabbronorites in the west and granite-gneisses, it is crossed by two near-parallel wrench faults of south-eastward (100-105^{o}) strike. The faults are 0.8 and 0.65 km long, running south-eastward and north-westward under the Kovda Bay water. The faults are clearly visible in the relief. The seam zones in the western part of the island, composed of gabbronorites, represent gorges with steep, 10-12 m high rims. The amplitude of horizontal displacement along the wrench faults is established by a marking body – an impressive, 10 m thick, quartz-pegmatite vein crossing the wrench faults nearly across (the vein strike is NE 10^{o}). The vein is shorn by two wrench faults and displaced (together with enclosing rocks) south-eastward by 150 m. Thus, the horizontal displacement of the rock block, compressed between the two wrench faults, is 150 m.

The fault seam zones, superficially expressed as 30-50 m wide gorges, are filled with boulder-block material of granite-gneiss and gabbro-norite, i.e. products of tectonic crushing of the rock in the wrench fault zone. The boulder-block breccias are for the most part overlain by contemporary marine shingle.

The tectonic sculpture in the wrench fault zone is peculiar. The vertical fault rims exhibit slickensides with subhorizontal striae and shear scarps (scarp benches facing SE, i.e. along the fault fissure). The slickensides are covered with tectonite gouge – mylonitized gabbroids. The zone of geodynamic impact of axial wrench faults displays lower-order subsidiary wrench faults and upthrusts, among which is an impressive arched wrench fault displacing gabbronorites. It is peculiar that arched fissure plane of this upthrust-wrench fault clearly protrudes into gabbro-norite blocks (Fig. 17, 18). So, the displaced southern wall is ruined into blocks, whereas the northern wall is a tectonic fault fissure with a polished vertical surface of slickensides, their subhorizontal and subvertical striae, and mylonite gouge. Though the striae and furrows on the fault fissure surfaces are partially intercrossing, they are mostly near-parallel, obviously tending to subvertical rising in the upper, south-eastern, part of the visible fault fissure. This suggests an upthrust-wrench fault displacement of rock blocks in the southeastward and eastward directions. The strike of striae and furrows on the fault fissure slickenside changes, conforming to the arching fault fissure line – from 120^o south-east to 80^o north-east.

Fig.17. General view of an arched wrench fault and an area of tectonic crashing. Gabbro-norite, Ovechy Insland in the Kandalaksha Bay (photo of the author).

Fig. 18. A part of the wrench fault slickenside structure: Ovechy Island. A set of subvertical, intercrossing striae on the polished vertical fault fissure surface. The slickenside is seen to be plunging under displaced rock (photo of the author).

2.2.3. Wrench faults of the Dolgaya Shchel fjord

The Dolgaya Shchel fjord (bay) is located in the Northwest Kola Peninsula bordering Norway. It is a narrow bay of a near-meridian strike thrusting into gneiss strata of the Barents Sea southern shore. The fjord is 4.5 km long, 0.6-0.7 km wide and about 45 m deep, its steep cliffs towering to a high of 50-250 m above the water. Its sea-facing part is dammed by a block-boulder bar, the sea bottom rising abruptly to 1-2 m deep and forming several sills.

The fjord shores are built of Archean gneisses, granite-gneisses, and amphibolites torn by Paleozoic dykes of gabbro-diabase and hydrothermal quartz-barite veins. Its southern extension represents a through valley filled with Holocene marine sands and shingle up to 30-40 m deep. The steep valley slopes are up to 150-200 m high and are composed of the same gneiss complex as the Dolgaya Shchel borders. The valley runs 12 km southward, across Trifonoyarvi Lake, finally joining the southern part of the Pechenga Bay.

Both the fjord and its southern extension have been formed by fault tectonic processes, predominantly by submeridian wrench faults, conforming to the fjord strike. In the course of geological surveying of 1997, the author discovered the following:

1. In many places, particularly in its western shore, the Dolgaya Shchel borders are actually fissures of the wrench fault type. Their vertical surfaces carry horizontal striae and furrows oriented along the fjord borders and following their configuration, namely, 340^o NNW and 15^o NNE.

2. Gabbro-diabase dykes, cleaving the gneiss complex rocks have exposed a horizontal displacement relatively the western and eastern fjord borders. The dyke location demonstrates a 100-250 m horizontal displacement of the western border relatively the eastern one.

3. Observations have revealed two wrench faults of a north-west (340^o) strike, following the Dolgaya Shchel hollow and shaping the fjord's morphological structure. The fjord borders, especially in their upper parts, are complicated by numerous gravity faults.

4. Notwithstanding the rather modest scale of research of horizontal displacements along wrench faults (0.1-0.25 km), it is apparent that the fjord once hosted near-fault and 'inter-wrench fault' displacements of tectonic wedges and rock blocks. It was these dislocation processes that shaped the fjord hollow and piled up boulder-block material in the fjord's mouth – the so-called rock bar.

2.3. Low-order wrench faults

Modeling of tectonic processes has been carried out in geodynamic and tectonic-physics laboratories both in Russia and abroad for several decades. Some of laboratory patterns of fault zone development, chiefly of wrench fault zones, are cited in this work. Giving due credit to laboratory tectonic modeling, we should not disregard another method of fault-dislocation exploration, fairly accessible and by far less costly, namely, a natural observation of low-order faults. In the latter case, one needs totally exposed areas. Low-order faults have this advantage over major ones, usually exposed weakly and irregularly.

Another requirement is the availability of marking bodies (veins, dykes, etc.) cutting the wrench faults; their displacement may be indicative of the scale of tectonic displacements. It is also important that such fully exposed areas should have numerous tectonic slickensides and various tectoglyphs offering a clear view of kinematic types of fault disruptions and features of their dynamics.

The author has encountered a combination of these factors at tectonically active zones of the Shield: the Barents Sea fjord coast, Northern Ladoga Lake and Northern Onega Lake regions, shores and islands of the Kandalaksha graben, and some of the White Sea islands adjoining Karelia and Pomory. We have closely studied the structure of low-order wrench faults in the southeastern Kandalaksha graben and the Pentelsky - Kochinny Promontories. The wrench fault structures were the most revealing at the following four sites: 1) Izbyanoy, 2) Ruchey, 3) Kochinny Promontory, and 4) Kochinny Island. The four sites, located in the band of development of Archean rocks of granulite formation, extend into one another, sometimes with a break in continuity. These wrench faults are tens- to hundreds of meters long. Their horizontal displacement amplitudes, demonstrated by displaced granite pegmatite veins, are 0.5-2 m. The faults are parallel to a system of regional wrench faults running along the Kandalaksha Bay bottom, which suggests that the structures, both small and large, have been created in a single field of regional tectonic stresses.

Some inference regarding the structure of low-order wrench faults is the following. The dynamic impact of low-order wrench faults on forming subsidiary structures is limited by the seam zone and a relatively narrow near-fault zone. Not infrequently, the latter exhibits small shear dislocations of the overthrust type on one of the walls, the opposite wall having cracks and extensions.

Characteristically, these wrench faults have adjoining areas of compression and extension. Both are clearly seen on the fault plane, alternating along its strike. The extension areas are open fractures with ragged edges; the compressed areas are narrow, near-fault grabens (or ‘baths’) with traces of block-wedge extrusion. The edges of these grabens are polished and have developed striae sets directed along the fault up the ascending subhorizontal line. It must be emphasized that both near-fault extrusion of blocks and their displacement by the upthrust-wrench fault type occurred only in the upper part of the wrench faults. This is suggested by the graben depths of not more than 2 – 4 m, mostly 0.5 – 1 m.

Both extrusion of near-fault lenses and graben formation may have occurred without displacing of walls, since excessive strains in rock mass can be realized in surface shearing and extruding of tectonic wedges.

The wrench fault surfaces are often buffed. Rocks of the fault seam zone (amphibolites, schist, gabbro-norite, granite pegmatite) are at places crushed, ground and compressed by tectonic processes to cataclasites and mylonites. The layer of cataclasites and mylonites in the low-order wrench fault seam zones does not exceed 0.5 m, and sometimes they pass to friction breccias along the strike.

Consider also another aspect of our low-order fault zone studies, namely the three types of small, shallow lake basins. Lakes of type I, occupying the extension fractures and areas of wrench fault extension, have elongated basins and steep edges. The type-II lakes accommodate the intersection lines of dissimilarly oriented faults, including wrench faults. A fault intersection is frequently an area of crushing and subsidence of small blocks. Configurations of the lake basins are the most complex of all – from crucifix to graben-shaped. Lakes of type III are also abundant. They accommodate shallow upthrust-overthrust sheared grabens and have a patelloid shape and flattened bottom. There are lake basins genetically close to them and accommodating areas of tectonic wedge extrusion in wrench fault compression zones.

2.3.1. Upthrusts and overthrusts

Upthrusts and overthrusts are tectonically related, since both represent a thrusting, either gentle or steep, of one rock block over another. These structures are distinguished by the thrust angles of their walls. According to the *Geological Glossary* (1973), an overthrust is a fault disruption with a gentle (up to 45°, or not more than 60°) tilt of the fault fissure plane, whereas an upthrust has a thrust angle varying with authors between 45° and over 60°. Naturally, overthrusts tend to increase the gentle displacement angle to steeper one gradually transforming to upthrusts.

In emerging overthrusts and upthrusts, the axis of maximum tectonic pressure is located on the horizontal plane, whereas the axis of minimal stress (the gravitation load) is vertical. Characteristically, the crust during the upthrust-overthrust formation is under a total, predominantly horizontal, tectonic compression. The tectonic stresses are discharged by shearing and displacing of blocks and plates of rock towards the day surface. This accounts for the abundance of overthrusts and upthrusts on areas with a high tectonic activity in the ground plan, i.e. under conditions of horizontal tectonic contraction.

Allochthonous blocks of small, near-surface overthrusts and upthrusts are usually ruined, with block-boulder material and numerous slickensides on the fault fissure plane (autochthon). The over-upthrust slickensides feature tectonic striae and furrows, practically always oriented along the rock block displacement. The steep scarps of transversal shears at various upthrust sections may either be facing or following the block movement. Most of the near-surface upthrusts-overthrusts on the Baltic Shield are ‘adaptive’; their displacement proceeds along the ready surfaces of tectonic parting, such as various, specifically, horizontal and near-horizontal fractures. This relationship is particularly evident in intrusive rocks (granites, gabbroids, peridotites, pyroxenites) which are split into blocks by a set of partings. In such massifs one observes displacement of both single blocks and series of adjacent blocks along an even, or hummocky, fissure plane with a surface imitating that of the lying wall. Apart from upthrusts and overthrusts, plentiful in Precambrian crystalline rocks of the Shield’s East, the Quaternary deposits contain numerous overthrusts.

2.3.2. Low-order overthrusts

Since fissures of large overthrust faults are normally hidden by walls and blocks, they can be revealed only by drilling. Access to their outcrop lines is also hindered because the fronts of major overthrusts are commonly overlain by boulder material from fallen debris.

Unlike larger structures, fissures of low-order wrench faults are often exposed and readily examined. Low-order overthrusts are shear structures normally conjugated with wrench faults and formed in the area of their dynamic impact. Actually, they have been formed by wrench faults, due to tectonic strains emerging during dislocations of the wrench-fault type.

The examined overthrusts are superficial structures formed at a low depth, with a rather thin hanging wall. The thin wall had been destroyed into smaller blocks and boulders piled up in places of dislocation decay. This explains the fact why low-order overthrusts of the Kola-Karelia region are mainly represented in outcropping crystalline rocks as lying wall fissure planes. Protruding of an overthrust fissure plane under an unbroken hanging wall is a rare occurrence. Nonetheless, the author did observe overthrust slickensides protruding under hanging rock walls and managed to map the structure of the wall bottom with tectonic slickensides and furrows. Not infrequently, the overthrust fissure plane is found under allochthonous boulders of a displaced block, whereas at a small apparent slip, the rock of the upper wall is only cracked into blocks subsequently displaced under gravity. The contact of lying and hanging overthrust slickensides is represented by a thin horizontal, or gently dipping, fracture running under the upper block. To follow the slickenside's extension, one has to remove a part of the overhanging block, either by blasting or hammering it. When the fault fissure surface contact contains gouge, readily washed out in the littoral zone, the slickenside is either visible or can be traced manually. Contact areas of fault fissures often contain thin layers and lenses (up to 0.5 m) of cataclasites or mylonites. Fissure surfaces can also be observed (or felt) on contact of lying and hanging walls with partly detached crushed tectonite.

2.3.3. Conjugated sets of overthrusts and wrench faults

Lower-order overthrusts in the eastern part of the Baltic Shield are normally conjugated with wrench faults being derivatives of the former. The author has examined the conjugated overthrust-wrench fault systems on well exposed areas of the Shield areas, at the Kandalaksha and Ladoga grabens, northwestern Murmansk block and Karelian shore of the White Sea (Fig. 19, 20).

Fig.19. Overthrusts conjugated with wrench faults on gabbro-norites of Vysoky Island (Northern Karelia, Rugozero Bay) – general view (photo of the author).

Fig.20. A part of an overthrust slickenside structure of Vysiky Island. Subparallel striae and furrows (grooves) are developed on the vertical and horizontal fault fissure surfaces (photo of the author).

The overthrusts there can be subdivided into two types: a) those with fissure strikes oriented at an angle of 30-60^{o} relatively the axial wrench fault strikes; b) those with strikes subconforming, or conforming, with the axial wrench fault strikes. So, rock block displacing in type-I overthrusts occurs in the direction of wrench faults at 30-60^{o}, whereas in type-II overthrusts the hanging wall blocks have been shifted in the direction of general wrench fault displacement. Striae, furrows and other tectoglyphs, indicating the direction of overthrust wall displacement, are oriented accordingly (either at an angle to the wrench fault or parallel to it). Type-I overthrusts, whose fault fissures are oriented at 30-60^{o} to the axial wrench fault, are frequently encountered in the Kandalaksha graben.

One important peculiarity of overthrusts is a parallel-wavy pattern of their fissure surfaces, known as structural waves. These are parallel, alternating concave and convex, polished, shingle-like rock surfaces, with convex and concave elements more flattened and broader than in normal roofing shingle. The planes of structural waves, both their crests and sunken parts, carry striae and furrows oriented along the general wave strike. The slickensides carry mylonite, transversal scarps and crescent-shaped hollows oriented across the striae and furrows. The width of the structural waves varies between first meters to several meters. They are tens of meters in length and parts of meters to 0.5-0.7 m in depth. The structures are gently sloping.

As asserted in manuals on structural geology, such parallel-wavy surfaces suggest tectonic displacements. This is particularly true of overthrusts (*A Study of Tectonic...,* 1984). Apparently, structural waves developed on overthrust slickensides are the initial stage of fold formation in hard crystalline rocks.

Type-II overthrusts are predominant in the Ladoga graben. The strike of fault fissures here is conforming, or subconforming, relatively the axial wrench faults. Therefore the tectonic slickensides with striae and furrow sets are oriented either along the strike of wrench fault zones or at small angles to them. Such conforming overthrust and wrench fault structures can be observed in a system of proximate wrench faults. They are controlled by a two-axial horizontal contraction emerging in the zone of dynamic impact of proximate, near-parallel wrench faults. A system of this type creates a single dislocation field where shifting of overthrust blocks and plates occurs in the same direction with the general wrench fault displacement.

2.4. The structure of tectonic fault fissure planes and slickensides

Slickensides, their tectoglyphs and low-order rupture dislocations can be easily studied in the Baltic Shield East with its well-exposed areas of neotectonic activation. However, they are ignored by geologists and tectonic specialists, and it is evident why. It is already a hundred years that all slickensides, striae, furrows, crescent signs, and chevrons observable on crystalline rocks have been called upon to support the glacial theory as traces left by receding continental glaciers. As the result, numerous traces of tectonic dynamics have been ousted from structural geology.

2.4.1. Fault fissures and slickensides of overthrusts and upthrusts

Fault fissures and slickensides of overthrusts and upthrusts are the most revealing and easiest to observe. It is true that this mostly refers to low-order faults whose displaced (hanging) thin walls are usually crushed into blocks, denuding the autochthonous fissure plane.

According to a ten-order classification of L.M. Rastsvetayev (1987), the first-order slickensides are over 100 cm^2 in size; those of the second, third, fourth, and fifth order vary between100-10000 cm^2, 1-10 m^2, 10-100 m^2, and 100 m^2, respectively. Following this classification, the overthrust slickensides now in question can be referred to the 4-5th orders. This means that they are quite representative for obtaining reliable results. The same refers to fault fissure planes of overthrusts and upthrusts. In relation to these structures, 'slickenside' is the same as 'tectonic fault fissure plane' because tectonic displacement there, realized as gliding of the upper wall over the underlying wall, was occurring over the entire fissure plane and producing sets of slickensides on it.

Morphologically, the overthrust fissure planes are expressed as convex or concave surfaces of crystalline rocks having a near-horizontal or gently sloping (up to 45^o) dip. The overthrust fissure planes are often wavy. Upthrust fissure planes may also be flattened or convex, spherical, but their dip angle is greater than 45^o. It is a peculiarity of upthrust-overthrust fissure planes that all the rock-forming minerals and vein-lens-shaped intrusions, irrespective of their composition, are cut to one level. The same happened to monomineral quartz veins cut to one level with enclosing crystalline rocks, although in hardness quartz ranks below only the rare topaz, corundum, and diamond. No geological processes, other than tectonic shearing, could have resulted in such surfaces. If we persist on glacial planation of heterogeneous rock, we are to understand that due to the low hardness of glacial ice the leveling of surface could have been only selective. Otherwise, hard mineral inclusions, quartz veins and lenses in particular, would appear as protrusions, ribs and ridges, and the rock surface would be generally rough. The same would have been happening during water-abrasion of cliffs; moreover, the rocks then would contain singular potholes abraded by water. These indications missing, the only explanation is shear fracturing, leveling of all the rock-forming minerals and mineral inclusions.

A many year-long research of upthrusts and overthrusts has allowed the author to distinguish their common features: a) availability of slickensides discernible, in their uncomplicated form, as ground or polished rock surfaces; b) tectoglyphs (on slickensides), i.e. striae, furrows, scars, crescent-shaped signs, transversal scarps, and chevrons; c) cemented or layered of tectonites; d) structural waves. The structure and mechanism of these formations will be discussed below.

Polishing on slickensides

An upthrust-overthrust displacement results not only in the leveling (shearing) of fault plane rock. The emerging subsidiary mechanical and tectonic stresses grind and polish the crystalline rocks producing superficial mylonitization. Generally speaking, the level of grinding and polishing depends on the lithological-textural features of fault planes and slickenside rock. On fine-grained rocks (diabases, amphibolites, crystalline schist, fine-grained granites or gabbroids) grinding and polishing may be almost perfect, up to a mirror glance. On coarse or dissimilarly-grained rocks, such as granites, gneisses, gneiss-granites, and pegmatites, it is rougher and only occasionally polished.

As has been generally observed, polishing on fine and coarse-grained rocks of fault planes is present on the front parts of lying overthrust blocks and at junctures of adjacent blocks, i.e. on areas of greatest tectonic pressure. Rock surface at these stressed, buffed areas appears as a fine mylonite film. Mylonitized rocks are both fine- and coarse-grained. Fine-grained mylonitized rocks are also found in cross sections, where the film thickness is typically the first millimeters, sometimes 0.5-1 cm.

It is clear that polishing of tectonic fault planes in overthrusts and upthrusts is similar both in character and in mechanical origin. It was created while the displaced rock blocks were rubbing the tectonic bed (autochthon), at the same time grinding and polishing the fluccan compressed in fault planes. This is how an almost mirror glance is achieved on fine or aphanite rocks. Polishing is also created by the powerful tectonic pressure exerted on sundry areas of overthrust fault planes, leaving a film or thicker mylonite layers on their surfaces. So, it is rubbing and recrystallizing of rock surfaces converted into mylonite, combined with syntectonic friction (with participating fluccan), that produces polished, almost buffed, surfaces on originally coarse-grained rocks.

Furrows (grooves) striae and scars

It is not infrequently that flattened, ground or polished fault planes display furrow, striae and scar sets. Combined with other criteria, these impressive microforms quite reliably indicate the direction of tectonic displacements. However, their origin on the Baltic Shield is still disputed.

Striae in the *Geological Glossary* (1973) are treated as 'hollows in the form of scratches and small parallel grooves produced on the fault plane by gliding of one layer over another. Hollows are scratched by protruding plane parts'. Larger striae analogues (furrows) are described in the *Glossary* thus: 'Furrows are the result of rock friction against the surface of ruptures emerging during tectonic displacements, i.e. overthrusts, wrench and normal faults. These are manifest as narrow furrows, grabens, and striae separated by low fillets and mounds often observable on friction-polished surfaces called slickensides' (1973, p. 84).

Curiously, these tectonic criteria are used for substantiating the glacial origin of the same furrows and striae (see, for instance, the *Field Geology* of F. Lakhy (1966). According to some researchers, there is a difference between tectonic and glacial furrows and striae, although no one specifies the difference, including the *Glaciological Glossary* (1984). A brief description of these criteria can be found only in M.G. Leonov's monograph (1981). According to Leonov, the surface of tectonic striae and furrows is more splintery or imbricate. More details are provided in a later work of M.G. Leonov, D.S. Zykov and S.Yu. Kolodyazhny (1998) enumerating the following traces of glacial exaration of furrows and striae: a) their superimposition on a flattened, polished and gently curving surface; b) lacking rear parting zones, splinters, notches or mineralization pertaining to tectonic slickensides; c) symmetrical longitudinal profile of furrows (1998, p. 75). The author will try to demonstrate to what extent these signs are applicable to the furrows and striae of the Baltic Shield rocks.

Furrows (grooves) and striae of fault fissure planes and slickensides on overthrusts and upthrusts are variously assembled. They are usually parallel or subparallel with a stable strike continuing well beyond the fault fissure plane. The tectoglyphs have the following parameters: the length of furrows varies between 0.2-0.5 to 2.5-10 cm, rarely more; the width – between several millimeters to 1-4 cm (Fig. 21). The cross section of a furrow is typically conical; it converges as it protrudes inwards the rock. There are also furrows with a trapezoid section. The lengths of furrows inside the slickenside vary between several centimeters and 1-2.5 m; an interrupted furrow is superseded by another one of the same strike. Furrow networks are different in density, sometimes carrying only rare or single furrows, sometimes uninterrupted. Typically, there is an alteration of furrows and fillets in bedrock. It is interesting that furrows are markedly different in width and depth within one and the same fault fissure plane.

Fig. 21. Furrowed (grooved) surface of an overthrust lying wall. Alternating splintery and evened-out furrows. Northern part of the Ladoga graben, gabbro-norite skerries in the vicinity of Palosaari Island (photo of the author).

Striae are smaller by an order of magnitude; still, they preserve a generally parallel pattern. Furrowed and striated rock surfaces are the first meters to tens of meters long and up to several tens of meters wide.

A furrowed plane is normally split into sections by transversal stairs (shears). Besides, the furrow and striae sets contain crescent-shaped hollows and carved shears. Striae and furrow sets on areas of young tectonic dislocations, where the crystalline basement is well-exposed, have been traced to as far as hundreds of meters. They are intermittent but generally preserve their strikes.

There have been found slickensides with striae and furrows of dissimilar, sometimes intercrossing, directions. This was caused by changing direction of displaced and turning rock blocks during dislocation. Also, the type of displacement along the fault may have been changing: “Within one and the same fault, there may be an alternation of wrench fault and normal or extension fault, upthrust or overthrust areas” (Burtman et al., 1963).

Furrow and striae sets in question are easily mapped on the surface of allochthonous blocks of upthrusts and overthrusts because, being on the surface, the displaced upper wall is ruined to blocks retaining the tectonic polishing, striae and furrows.

Sometimes it is possible to trace the structure of the foot of an overthrust hanging wall. Similarly to the lying wall, it is polished and carries sets of parallel furrows.

Although plunging of striae and furrows under overthrusts and upthrusts is rare, we have established exposures with furrows and striae plunging under the thrust’s allochthonous rock. More often, we observed extending under the bedrock of polished planes on the hanging walls of overthrusts and normal faults. This was observed within the Kandalaksha and Ladoga grabens in the west of the Murmansk block and on islands of the Pomory shore of the White Sea.

What is the mechanism generating furrows and striae? Basically, we rely on explanation provided in the *Geological Glossary*: the fault fissure surface is furrowed by the hummocky foot of displaced rock blocks. However, it is not as simple as that. Furrows are mainly scratched by coarse breccias fragments compressed between fault walls so that the harder the breccia fragments, the longer and deeper the furrows. Most furrowing is produced by quartz as the hardest and widest spread mineral.

Unlike furrows, striae are produced by smaller breccias fragments, including quartz grains. Striae and furrows often co-exist on large slickensides, forming single furrowed surfaces. Some of the slickensides carry only fine striae as, for instance, on amphibolites of Kochinny Island.

Obviously, the above criteria for differentiating the tectonic and glacial striae and furrows have been derived from inadequate study of the problem, including insufficient field studies. Note that the slickensides of both overthrusts, upthrusts and wrench faults display furrows with burrs and notches (allegedly, purely tectonic indicators) and furrows with smooth, polished surfaces (allegedly, glacial indicators).

Moreover, both furrow types are often found on one and the same slickenside, alternating in type and strike. It seems unlikely that a selective tectonic furrowing was later superimposed by glacial furrowing (or the other way round) so that the strikes of both coincided. The same refers to furrow's symmetrical cross section: it rarely changes even within one fault fissure plane depending on the surface dip and varying lithologo-textural structure of rocks. Another interesting fact is that the overthrust fissure planes may feature alternating 'unsymmetrical' and 'symmetrical' furrows.

All this will not be so puzzling if we admit that both furrows with burrs and notches and 'unsymmetrical' furrows have resulted from furrowing of the rock surface by angular, unrolled material of friction breccias, while the furrows with correct cross sections were cut by tectonic pebble, and also ground and polished by fluccan during dislocation.

Ground and polished fault surfaces are remarkably dissimilar. Sometimes the already polished surfaces were striated as the result of further dislocating along the same fault surface. Or, the already striated slickensides were subjected to tectonic grinding and polishing.

We have observed combinations of furrow sets with evened-out, polished surfaces and symmetrical cross sections (glacial indicator), and splintered and notched furrows with uneven, rugged cross sections - all this on limestone of the Crimea Peninsula, on normal fault planes, in a region regarded as unaffected by glaciation.

Nor can it be agreed that "superimposition of furrows on smooth, gently curving surfaces" has been produced by glaciers. Superimposition is a purely tectonic feature, and this is extensively discussed in the section dealing with polishing and striation on crystalline rock. Moreover, as pointed out in the *Geological Glossary* (1973), furrows and striae are developed on slickensides representing smooth rock surfaces polished by displaced rock blocks. Besides, slickensides, i.e. domed and evened-out surfaces, are often covered with mylonite films, evidently suggesting tectonic processes.

The tectonic genesis of furrows and striae is also evidenced by their occurrence on ground rock blocks uncovered in facing stone quarries on the Kola Peninsula, as well as on sides of intrusive rock blocks mined on the Ukranian Shield (Koshik et al., 1976; Sapfirov, 1982; Belyaev and Petrov 1977).

There has been mapped and reported a large body of evidence on fault-related origin of striae and furrows on crystalline rock surfaces. Still, the concept of the glacial origin of these formations is prevailing. The glacier is believed to have furrowed the rocky basement by its bottom part, with rock fragments frozen into the bottom. However, according to recent findings, the lower horizons of continental glaciers in Greenland and Antarctica are immobile, all motion occurring along interglacier shearing zones, or by flowing around smaller irregularities in the rocky basement. In either case, the rocky basement is protected from either exaration or striation.

Another important fact to be remembered is that striae and furrows have developed on evened-out (convexo-plane), solid rocky surfaces, i.e. slickensides. Therefore, prior to producing parallel striae and furrows, the glacier should have treated these planes, which included cutting of the rock-forming minerals to one level, polishing, cataclasing, and mylonitizing them. Furrowing of the set of parallel striae came as a next stage.

It may be argued that thawed out, furrowed and polished solid rock surfaces are the proof of the glaciers' ability to striate their rocky basements. But actually, the glacier overlapped the earlier formed tectonic slickensides, thus accommodating itself in the tectonic bed and protecting the slickensides from weathering.

Transverse faults, crescent-shaped hollows and other tectoglyphs

Apart from striae and furrows, the upthrust-and-overthrust fault slickensides and planes display transverse stair-shaped shears, crescent-shaped and carved signs and hollows. Since we have examined transverse fractures predominantly in low- and intermediate-order fault zones, characterization here is limited by these structures only.

In addition to stair-shaped shears, the upthrust-overthrust fault planes carry all microforms enumerated in the subtitle. These tectoglyphs are often invoked to illustrate the plucking ability of glaciers (*Glaciological Glossary*, 1984; R.F. Flint (1963)).

Here is a classification of these microforms proposed by R.Flint (1963):

1. Sickle-shaped hollows (or signs) facing with their dented (concave) side the glacier movement.
2. Carved signs resembling the sickle-shaped hollows but facing the glacier movement with their convex sides.
3. Sickle-shaped hollows following with their concave sides down the ice movement. In appearance, they are cracks bearing no traces of rock removal.

Both the above microforms and transverse shears and stairs are oriented transversally to slickenside strikes (at a right angle to striae and furrows). They are abundant in zones of juvenile faults (the Kandalaksha and Ladoga grabens, and the fjord-indented Murman shore). They may be either isolated or clustered, with or without striae and furrows. Normally, they are 5-10 to 50-70 cm in diameter and 1-5 cm in depth, stretching as long as several meters, depending on the slickenside size.

We believe that both sickle-shaped and other similar signs testify to the initial stage of shear and extension joints. The entire cycle is traceable in nature – from incipient single microcracks (sickle- and geometrically similarly shaped signs and hollows) to transverse benches and shear joints.

Sickle-shaped cracks and hollows are mostly characteristic of upthrust-overthrusts fault slickensides, but can be found on normal fault surfaces as well. Both sickle-shaped and similar formations can be seen on slickensides extending under bedrock blocks. They are also plentiful in zones of lower-order wrench fault dynamic impact. The author has also observed them on areas never claimed as glacier-affected, namely, on granites of Lake Balkhash.

Overthrust fault planes also exhibit the so-called structural waves imparting a corrugated appearance to the polished rock.

2.4.2. Fault fissure surfaces and slickensides of wrench faults

In the Karelia-Kola region, fault fissure surfaces of neotectonic wrench faults are steeply dipping, less frequently inclined, with scarps or joints separating the adjacent blocks of the Earth's crust. In topography, wrench faults fissures are expressed as long, rectilinear, curved or arched fractures. Deep-seated or regional faults normally consist of several proximate, near-parallel fault fissures, but they are poorly studied due to insufficient or irregular exposure. Low- and medium-order faults can be examined much easier.

Unlike other steeply dipping fault structures, wrench faults were horizontally displaced along near-vertical fault surfaces. This affected the structure of both the fault proper and slickenside surfaces. Like in shear structures, the wrench fault surfaces are evened-out or undulating, with leveled rock-forming minerals and vein-dyke formations. At the same time, wrench fault surfaces have a heterogeneous structure. They carry domains with either numerous slickensides (ground and polished, with sets of striae and furrows) or with shears and partings. Notably, this regularity can be observed both along the fault plane strike and dip, which may suggest alternation of compressed and extended sections in suture zones, the former sections being upthrust-wrench faults and the latter – normal wrench faults.

This alternation of compressed and extended areas along the fault plane strike and dip should result in emerging in the suture zones of wedging out lenses and blocks displaced either along the wrench fault strike direction or upwards, in this case extruded to the surface. As was pointed out above, extruded near-surface wedges and blocks in low-order wrench fault suture zones are observed everywhere.

The aforementioned processes are also responsible for the fact that wrench fault slickensides, striae and furrows are sometimes located horizontally or, most often, near-horizontally. In other cases they are subhorizontal or subvertical, thrusting towards the surface. Or, less frequently, they are inclined with a trend to dipping. The parameters of striae and furrows on wrench fault slickensides are approximately the same as those on upthrusts-overthrusts. These are usually sets of parallel and near-parallel furrows and striae developed on steeply dipping blocks (fault planes). Striated surfaces may be as large as tens to first hundreds of square meters, with strike directions traceable for many tens of meters. Similarly to overthrust-related furrow sets, the surfaces of wrench fault furrows vary from smoothed, polished, to splintered, jagged. Both types alternate in strike and often co-exist on the same fault fissure plane. Both slickensides and fault fissure surfaces carry transverse scarp-shaped fractures and thresholds, as well as carved and sickle-shaped fractures and joints. These tectoglyphs may be indicators of horizontal displacement along wrench faults but, as is the case with overthrust structures, it is necessary to differentiate between shear stairs, whose thresholds face the displaced block, and downfall stairs, whose back suture seams are arranged along the block displacement. The same refers to various carved and sickle-shaped signs.

Wrench fault slickensides carry films and hardened mylonite. The seam zones of low-order wrench faults are filled with mylonites (or friction breccias).

2.4.3. Normal fault fissure surfaces and slickensides

Normal faults of the Karelia-Kola region can be subdivided into steeply-dipping (including vertical) and gently dipping ones. From the methodological point of view, it is important here to clarify the following.

1. The surfaces of steeply dipping normal faults were predominantly formed by near-vertical extension and parting joints, less frequently – by shear joints. As a result, the major normal fault planes have stair-shaped, uneven surfaces, whereas lower-order faults carry slickensides, owing their origin to rock shearing, and slickensides representing surfaces of (frequently polished) parting joints.

Among the indications of a normal-fault downward displacement of rock blocks in steeply dipping faults are transverse shear stairs with steep scarps often facing downwards, along the fault plane strike (Fig. 22).

2. Normal faults of the second type, that is, the gently dipping ones, move due to diagonal and gently sloping (sometimes near-horizontal) fractures. Gliding of the

upper wall of a normal fault along the lower one produces a flattened surface, often with leveled rock-forming minerals and abundant transverse shear and extension scarps, as well as sickle- shaped and carved microstructures of shearing and extension. The gliding of one block over another polishes the rock, and it is only in individual cases that striae and furrows are formed. The direction of a normal fault displacement can be determined from orientation of furrows and transverse downfall stairs whose steep thresholds are turned to gravitational sliding of blocks.

Fig.22. Vertical normal fault in granitoids. Ladoga skerries off Lauttasaari Island (photo of the author).

2.5. What caused near-surface tectonic dislocations

The fault dislocations considered above, i.e. wrench faults, upthrusts, overthrusts and normal faults, which have produced diverse exaration relief, are predominantly near-surface structures. Although this contradicts the current hypothesis of the in-depth origin of tectonic movements, it agrees with the present-day concept of upthrusts and overthrusts forming directly under the Earth's surface, where rock blocks and scales have enough space to freely move upwards (*A Study of Tectonic Structures,* 1984).

In the past 30 years, the geotectonic science has reconsidered its views on the principal importance of vertical movements in the Earth's crust. It has been recognized that the crucial role in fault formation belongs to horizontal stresses; and numerous faults with horizontal displacement have been discovered. The ideas the lithosphere being horizontally stratified, including in its uppermost part, have been corroborated.

Insight into the causes and mechanisms of near-surface displacements can be gained by researching the modern tectonic stresses in the Earth's crust. Evidence accumulated for the Baltic Shield and other platform regions suggests that horizontal compressing stresses in the upper part of the crust's granite layer are several times higher than vertical geostatic pressures. It is essential that high horizontal stresses are recorded in crystalline rocks at small depths, as is in Sweden, at a depth of 10-20 m (Kropotkin, 1971). P.N. Kropotkin reported (1971, 1987) of high horizontal compressing stresses of 150-200 to 500-600 kg/cm^2 (up to 50-40 MPa) in the Baltic Shield rock recorded at 10-20 to 200 m from the surface.

With established existence of high horizontal stresses in near-surface granite-gneiss crustal layer, there has been found an explanation for the abundance of minor shear upthrust-overthrust and wrench-fault dislocations which formed roches mountonnées, numerous tectonic slickensides with striae and scars, and other types of 'exaration' relief.

Chapter 3.
The tectonic genesis of "glacial" erosion (exaration) and other types of "glacier-related" relief

The issues of fault tectonics, major and minor tectonic displacements and traces left by them, have a direct bearing on the genesis and mechanism of formation of many relief types commonly termed as 'glacial-exaration' relief. These form a single paragenetic series with fault zones of compression and displacement.

This relief is well-known to geologists studying the eastern part of the Baltic Shield, including the Ladoga and Kandalaksha grabens. It is considered that glacial ploughing and polishing is manifest in the following groups of "exaration" relief: roches moutonnées, sheepback rocks, lake basins, fjords, skerries, polished and striated rock surfaces. The same areas also accommodate eskers, kames, and 'hilly morainic' relief.

In this chapter, the author undertakes to prove the tectonic genesis of fjords and skerry relief, roches moutonnées, sheepback rocks, and eskers. The formation of eskers, 'hilly morainic' relief, drumlins, and "moraine bars" is also discussed.

3.1. Roches moutonnées and sheepback rocks

The history of relief formation can be traced at major fault zones still active nowadays. On the Baltic Shield, these are the Kandalaksha and Ladoga grabens, fjord shore of the Murmansk block, and others. Here one can observe the entire set of "glacier-eroded" objects, with roches moutonnées and sheepback rocks as the most striking (Fig.23).

Fig.23. General view of a wrench fault area with pronounced structural waves represented by a surface of gently sloping overthrusts. Eastern part of the Kandalaksha graben (photo of the author).

The *Glaciological Glossary* (1984) defines roches mountonnées as oblong, asymmetric hills and ridges, with heights ranging from several meters to tens of meters, and composed of crystalline rock. Some of their slopes (facing the glacier's advance) are polished and striated; others are steeper and confined by fractures. Roche mountonnée clusters form a sheepback relief. In the broad sense, the geological-geomorphological literature assigns to these types of relief any polished and striated, or only smoothed out, solid rock surfaces regardless of their shape (see, for instance, the numerous photographs of roches moutonnées and sheepback rocks in G.S. Biske's *Quaternary Deposits and Geomorphology of Karelia* (1959).

It is curious how the terms fail to fit the real object they describe. Roches moutonnées and sheepback rocks are actually flattened, polished rocks. There is none of the curly fleeciness of a sheep about them - they are totally bald. Moreover, they have been 'scalped' not by the glacier but by fault dislocation processes.

Roches moutonnées and sheepback rocks are abundant in all types of Archean, Proterozoic and Paleozoic crystalline rocks: both metamorphic, volcanogenic-sedimentary, and intrusive. Commonly, they are observed on intrusive massive-crystalline rocks, i.e. granites, gabbroids and peridotites. They are particularly abundant on areas dynamically affected by regional wrench faults and overthrusts.

As has been said, we have revealed a paragenetic relationship between 'exaration' relief and neotectonic faults. Evidence in support of the fault-tectonic genesis of this form of relief is provided in some publications of the author (Chuvardinsky, 1998, 2000, 2008). New field observations have confirmed our earlier conjectures: both roches moutonnées and sheepback rocks are indicative of tectonic displacement along faults. The polished and striated solid rock surfaces are the surfaces of lying (autochthonous) blocks of tectonic fault planes and slickensides of upthrusts-overthrusts, low-angle normal faults and wrench faults. The mechanism of their formation and factual data substantiating their tectonic genesis have been discussed above.

Let us consider other proofs of their tectonic genesis. Polished and striated rock surfaces in exposed roche moutonnée clusters are thrusting directly under bedrock blocks. The same is observed in fjord and drumlin borders, particularly in the band of skerry relief, which means they are found everywhere on exposed crystalline rock (Fig. 24, 25, 26, 27).

Fig. 24. Overthrust origin of polishing and grooves (furrows) of "exaration" relief. General view of an overthrust structure: gneissose granite on Veliky Island in the White Sea. Polished and furrowed surface of an overthrust plunging under an allochthonous block (photo of the author).

Fig.25. Neotectonic imbricate overthrusts in Proterozoic migmatites. The polished slickensides of the overthrust foot are seen to be plunging under displaced blocks. General view, Putsaari Island (photo of the author).

Fig. 26. Parts of the structure of an overthrust (see Fig. 25). Putsaari Island, northern part of the Ladoga graben (photo of the author).

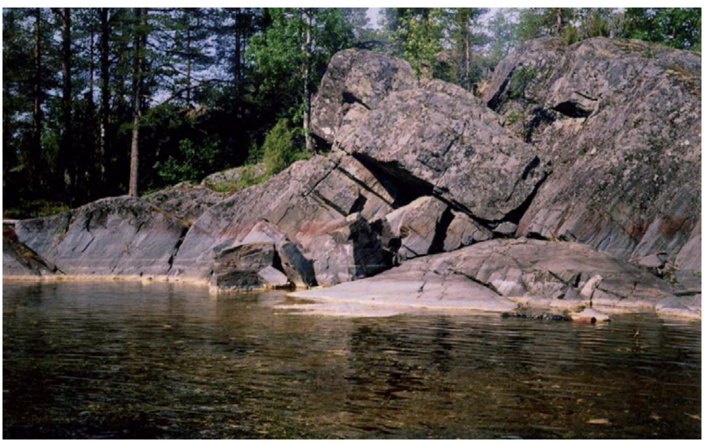

Fig. 27. A roche moutonnee emerging from under a rock massif with a part of the massif broken into blocks. The polished surface of the tectonic roche moutonnee can be traced under the dislocated block. Granitoids. Skerries of the Kulhoniemi Peninsula. Northern Ladoga (photo of the author).

Polished surfaces on the Shield's exposed areas are not only seen to be directly thrusting under bedrock. They can be traced under the bedrock by removing a part of the overlying stratum. Moreover, removing reveals both the polished bed under the allochthon and tectonic gouge.

This structural occurrence of polished and striated rock surfaces suggests that we are dealing with tectonic slickensides. These are known to be created by blocks slipping along fissure lines whereby the fault surfaces are ground and polished with the formation of furrows and striae oriented along the direction of block displacement, which is accompanied by small-scale shearing. Near-fault rock stripping, occurring thereby, provides material for friction breccias and gouge.

Polishing on 'bald' parts of roches moutonnées and sheepback rocks is frequently specular, being in fact a solid mylonite film, i.e. fine, recrystallized rock with parts of a millimeter to 1-2 mm in thickness. In other cases, there are only fragments of mylonite film, sometimes seen as remnants up to 0.5 cm thick. Mylonite on overthrust slickensides, forming the bald roches moutonnées, is visible in both sample sections and cross-sections, irrespective of composition and grain size of mother rock. Different sites of polished and smoothed slopes of roches moutonnées display microclinic, hematized and epidotized rocks, which also suggests their tectonic genesis.

Another proof is the fact that all the rock-forming minerals, lens and vein inclusions (including the veins of monomineralic quartz) are cut to one level, irrespective of rocks composing them. Such surfaces can be created by no other exogenic natural process but tectonic shearing.

As noted in the previous section, fault surfaces of dissimilar dislocations differ both in morphology and other features. The best pronounced, 'reference' relief of roches mountonnées and sheepback rocks is the result of upthust-overthrust faults. The surfaces of upthrusts and overthrusts are usually domed, well polished and practically invariably covered by sets of parallel and near-parallel striae and furrows. They often carry other tectoglyphs such as shear stairs, arched and horseshoe-shaped cavities and chevrons.

Many of the overthrusts are characterized by structural waves complicating the fault surfaces of the autochthonous wall of low-angle overthrusts. Structural waves form a peculiar relief of flattened roches moutonnées, since the crystalline rocks of these structures are not only polished but also carry parallel striae and grooves on both concave and convex elements of the waves.

Polished bedrock with striae and grooves is also inherent in wrench fault surfaces, but only a few of the low-angle wrench fault surfaces can be classed as roches moutonnées (as understood by glaciation proponents). Clearly, the tectonic genesis of polishing, striae, grooves, scars and chevrons in wrench fault structures is more apparent, since they can be traced easier than in overthrusts down the tectonic suture and developed on both fault borders.

Wrench fault displacements produce a roche moutonnée relief with an either steeply dipping, gently sloping, or flattened rock surface. The surface is smoothed out, all rock-forming minerals and vein bodies on it are leveled, but striae, grooves or mylonite remnants are rarely observed. The sole exception is the relatively soft rocks of the Ladoga series schist with polishing and grooves on wrench fault surfaces.

Sites with signs of "exaration" relief exhibit, when reference horizons are available, structural nonconformities, i.e. displacements along faults, most often slips. They are established by the displacement of veins, dikes, distinctive intercalations of rock, and autonomous structure of fault walls. We have established a paragenetic conjugation of all types of exaration relief, including roches moutonnées, sheepback rocks, sets of striae and grooves, and other tectoglyphs with rupture dislocations in virtually all the regions examined by us, which is particularly visible on areas with developed low-order offset structures (Fig. 28).

In intrusive and deeply metamorphosed rocks, the controlling factor in morphology, and even the very way of roche moutonnée and sheepback formation, is splitting of the rock into blocks. Joints form in them mattress- or flat iron (wedge)-shaped and egg-shoped (Fig. 29). Both the bed and parting positions are often imbricate, partly overlying. Cleared from overlying or adjacent blocks, the rocks appear as typical 'bald' roches moutonnées. Similar polished, and even grooved, rocks are also encountered on areas outside the glacier's reach (Fig. 30).

Fig. 28. Tectonic origin of polishing and striae on crystalline rocks; the surface of a major tectonic overthrust in rock of a granulitic formation. Polished and striated fault bed plunging under rock blocks. Eastern border of the Kandalaksha graben (photo of the author).

Fig. 29. Roches moutonnees created by gravitational displacement of rock blocks and plates. Exposed polished spherical surfaces of an inner-block origin. Granodiorites, skerries in proximity of Cape Impiniemi. Ladoga graben (photo of the author).

Fig. 30. "Exaration" relief outside the area allegedly affected by the glacier. Fault-tectonic origin (a result of downhill creeping of layers) of polished surfaces, i.e. roches moutonnees on Jurassic granite in Nigeria, with a hut in the right-hand corner at the bottom for scale (Geomorphology and Climate, 1976).

Blocks limited by rock partings often have polished sides. This inside-the-block polishing emerged due to slight mutual shifting of rock masses undergoing tectonic stresses, thus grinding and polishing the adjacent blocks.

Azimuth orientation of both 'bald' and striated slopes of roches moutonnées and sheepback rocks of the overthrust and upthrust types, and structural waves of low-angle thrusts are also reliable indications of tectonic displacement of rock blocks. Dislocation occurred in the direction of the dip of over- and upthrust lying walls. It is quite certain that both the direction of block displacement and accompanying features are tectonic signs contradicting the universally accepted glacial plucking (this idea was first advanced by A.A. Inostrantsev more than 130 years ago).

Roches moutonnées and sheepback rocks are covered with striae, scars and grooves. A detailed description of their structure and substantiation of their tectonic origin are given in "The structure of tectonic fault fissure surfaces and slickensides'. Here we emphasize the importance of sets of parallel and near-parallel striae and grooves as signs of the tectonic genesis of ''exaration'' relief. Firstly, these tectoglyphs are paragenetically associated with other tectoglyphs – shear stairs, arched cavities and chevrons, and depend on fault structure. Secondly, these polished and striated rock surfaces cannot be attributed to water abrasion, as has been done by the drift theory proponents.

On the one hand, water with suspended and entrained sandy, gravel and pebbly material can grind circumlittoral flattened bedrock, thus likening it to the low-angle wrench fault slickensides. But such abraded surfaces may not, and indeed have not, any sets of near-parallel striae and grooves or other tectoglyphs, or traces of superficial mylonitization. What their surfaces do exhibit instead are various-size, rounded, whirlpool potholes. Such potholes are found on overthrust surfaces as well, though they commonly retain, to some extent, the tectonic grooves, shear stairs, arched cavities, and other tectoglyphs.

3.2. Lake basins

There are two viewpoints on the genesis of lake basins, entrenching crystalline rocks of the Baltic and other Shields. The first view invokes the plucking activity of continental glaciers, whereas the other suggests they have been, generally, formed by tectonic processes.

The fault tectonic genesis is supported by a large body of factual evidence. Thus, both on-land, aerial and satellite surveying on the Baltic Shield have revealed a close relationship between lake basins and neotectonic faults and regmatic (planetary) jointing. Interestingly, the linearly extending lakes are found on areas with linearly oriented faults, whereas the more intricately shaped lakes (cruciform, bent, airplane-like, and even more complicated) were formed at fault junctions. Researchers supporting the glacial origin of lake basins seem to ignore these facts. No attempts have been made to explain how the continental glacier could have ploughed bent or airplane-shaped basins in the bedrock. Because the glacier could not have changed its direction by 90 degrees, and several times so, to create such lake beds (Fig. 31, 32).

Fig. 31. Lake basins located along a set of neotectonic faults of submeridional and sublatitudinal strikes. Archean granitoids, north-eastern part of the Murmansk geoblock (aerial photograph).

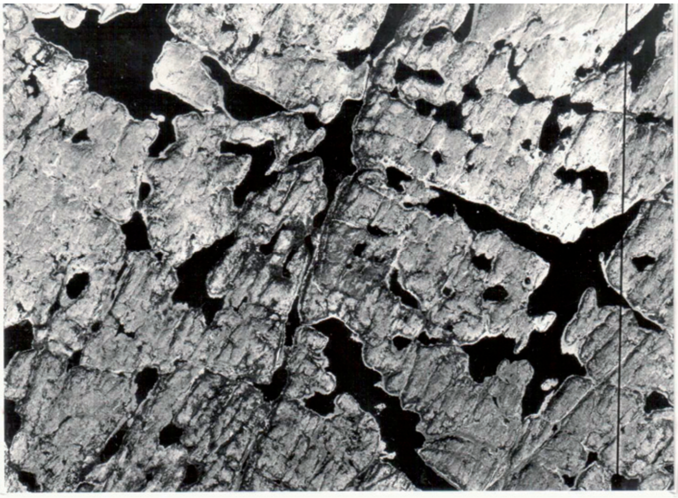

Fig. 32. Lake hollows laid along a set of neotectonic faults of submeridional and sublatitudinal strikes. Archean granitoids, north-eastern part of the Murmansk geoblock (aerial photograph).

On the other hand, we cannot rule out the glacial impact on lake basins in the form of smoothing out, polishing and striating of lakes' bedrock shores. In fact, all crystalline rock, enclosing the lakes, carries striae, polishing, sickle-shaped cavities; all bedrock exposures represent a roche moutonnée relief, while the lake islands are a skerry relief. Nonetheless, these marks are not glacier-related; they are ordinary indications of tectonic displacement of rock blocks in fault zones. The mechanism of this relief formation is considered in the pertinent sections of the book.

Thus, the lake basins on the Shield can be grouped in two main classes:

1. Basins positioned along extensional structures, i.e. normal faults, extensional faults, and regmatic network ruptures (on tectonic blocks at the stage of extension).

2. Basins formed in zones of tectonic compression as the result of overthrust-upthrust and wrench fault dislocations.

The first-type basins do not accommodate any roches moutonnées, striation or polishing, whereas in the second-type basins both slopes and bottoms testify to tectonic displacement represented by slickensides with striae and sickle-shaped cavities and also expressed in relief (roches moutonnées, skerries, etc.).

Rejuvenation of tectonic fractures creating the lake basins is still occurring nowadays. This is evidenced by aligning of earthquake epicenters to several lakes (Ladoga, Panayarvy, Venern, Vettern, Inari, Payyanne, Taryannevesi, Kailavesi).

3.3. Skerry relief

Both the *Glaciological* (1984) and *Geological* (1978) *Glossaries* define this type of relief as a complex of rocky, heavily indented shores and multitudinous islands, representing a system of glacially ploughed valleys and roche moutonnée and sheepback clusters.

But on closer examination, aerial- and satellite data, geological maps, and also field surveying have revealed that the 'glacially ploughed' valleys in the skerry relief are actually tectonic-related. They form a set of linear and transverse faults topographically expressed as linear depressions. In their deepest parts, these depressions happen to coincide with intersection points of dissimilarly oriented faults, and it is here that closed basins are formed. The resulting relief is typically block-tectonic, formed by islands-skerries, dissected shore sections and faults, and partly located under the sea and lake water (Fig. 33).

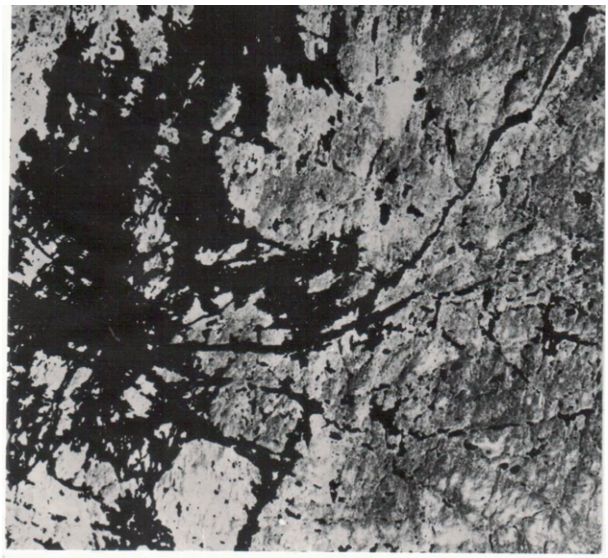

Fig. 33. Skerry relief of Inari Lake (Lapland). The skerry islands are formed by a set of dissimilarly oriented faults (satellite photograph).

The skerry relief has been generated by neotectonic activation of relatively depressed Shield sections. Such enormous fault areas as Kandalaksha and Ladoga are creating, or rejuvenating, regional or local faults, including subsidiary faults. These in turn build up gorges, closed sinks, and promote sharper dissecting of rock massifs into blocks. The relief is further transformed by along-the-fault movements bringing about the shearing of near-surface blocks and creating numerous gliding surfaces, roches moutonnées and sheepback rocks.

The processes occurring in wrench faults represent an extrusion of near-surface blocks in their compressed segments and drawing apart of fault walls at their extension segments, which produces closed grabens and gorges. These processes may occur both under water and on land, including the littoral zone. In the first case, parts of the sea bottom sink, differentiating the relief, whereas in the second case, major fault zones are transformed into lake skerry landscapes.

3.4. Fjords

Fjords are long, narrow and deep sea bays and straits with steep shores composed of crystalline rocks (P.A.Kaplin). On-land fjords, although not as impressive in size, extend along the shelf (Matishov, 1984). According to G.G. Matishov (1987), fjord valleys are controlled by systems of radial and concentric faults and zones of megajointing emerging during arched neotectonic uplifts. As has been reported recently, both fjords and fjord coast systems emerge on shearing of the shelf or continental structures by deep (up to 500-1000 m), uncompensated grabens.

There are several viewpoints on the origin and formation of fjords, the most popular asserting the glacial plowing (*Glaciological Glossary* (1984)). However, no explanation of the mechanism of this ploughing is provided. Indeed, it can be admitted that glacial plowing did occur during the mountain-valley glaciations, but it is highly improbable for the continental glacier to have plucked narrow and deep (up to 2.5 km) valleys in crystalline rock. Moreover, fjord systems within one and the same area are often intercrossing, or oriented at right angles to each other (Fig. 34, 35).

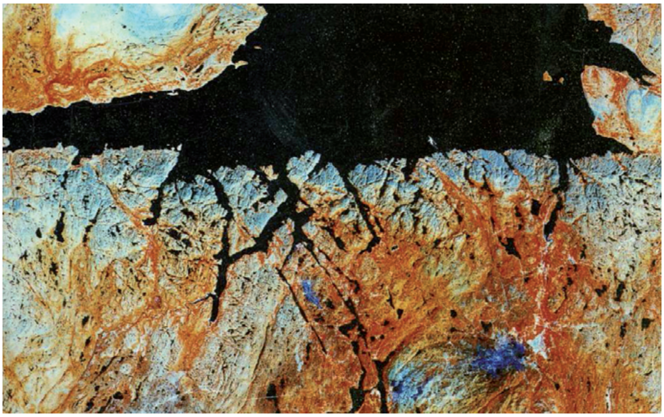

Fig.34. Fjords in north-eastern Norway and adjacent Murmansk region. Three sets of order faults forming the fjords (satellite photograph Landsat – 5 TM).

Fig. 35. Fjord in crystalline rocks in Norway (according to E.Haug, 1914).

Geological and remote sensing surveying have disclosed that fjords running along the Murmansk shore, as well as their smaller analogues along the White Sea and Ladoga Lake shores, are accommodated in faults, predominantly wrench faults. It is the neotectonic development of wrench fault zones, representing a system of parallel, approximated fractures, that has created such huge negative topographic forms as fjords. As distinct from skerry relief, the wrench faults in fjords are deeper located and should be regarded as deep-seated faults.

Apparently, both the development of wrench faults and fjord formation have proceeded not only by the wrench fault-type displacement in the horizontal plan or by extension. These processes are persisting, but of no less importance is a near-fault shearing, i.e. a displacement of blocks in sectors of wrench-type compression. Extruding displacement of near-fault blocks deepens the fjord, produces closed grabens, generates heaps of allochthone material, including boulders and blocks, and forms rock bars. Simultaneously, extended areas create hollows (gorges), either closed or merging with extrusion basins. These processes are accompanied by wrench faulting and downhill creeping of rocky blocks from fjord borders, broadening the fjords. The peculiarities of wrench-fault-type formation of fjords are considered by the example of the Dolgaya Shchel fjord.

3.5. Osar (eskers) ridges as indicators of neotectonic activation

The origin of eskers is explained by several hypotheses relating it, one way or another, to glacial plowing and abrading with thawing water. Thus, one of them holds that eskers emerged inside the glacier tunnels, or pipes, subsequently filled with sand-gravel material.

But, there has been established a conjugation between eskers and neotectonic fractures in the Baltic Shield basement. Both the eskers and esker-aquatic-glacial pathways can be traced to tens, and even the first hundreds of kilometers, along the faults.

The first researcher to note the positional connection between esker ridges and neotectonic faults in the basement was E. Hyyppa (1954). The discovered conjugation between eskers and active faults has allowed to propose a new hypothesis of esker formation. According to Hyyppa, the glacier body, affected by tectonic vertical movements along faults in the crystalline basement, developed a network of radial and transverse cracks which were gradually filled with sandy-gravel deposits while the ice was thawing. This idea was later confirmed by M. Harme (1963), H. Paarma (1963) and E. Penttilä (1968) who established that the esker ridges and esker-aquatic-glacial pathways in Finland are stretching many tens of kilometers along faults, frequently imitating their bent and arched curves. These researchers supported E. Hyyppa's hypothesis, including in the part attributing the cracking of the continental glacier bodies to vertical movements along basement fractures.

Studies at the eastern part of the Baltic Shield have also corroborated the conjugation of eskers and esker pathways with neotectonic fractures in the basement. Ample factual material was obtained by Karelian researchers G.S. Biske, V.A. Ilyin, Ts. G. Lak, A.D. Lukashov, and E.V. Rukhina. They reported of a clearly pronounced confinement of esker ridges to esker-aquatic-glacier pathways and active faults running along them, sometimes as far as many tens, and even the first hundreds, of kilometers (including the eskers stretching to Karelia from Finland).

Eskers in the Baltic Shield East are normally 20-30 m, rarely 50-60 m high and frequently 100-200 m wide at the bottom. The crests are narrow, 2-5 m, sometimes 10 m. Some of the eskers have summits. The slope inclination is usually 30-45º. In length, eskers may by from hundreds of meters to several tens of kilometers (Fig. 36).

Fig. 36. Eskers of the Kola Peninsula. Above – an esker ridge on the western Kola Peninsula (west of the town of Kovdor).

Although the confinement of esker ridges to neotectonic faults has been recognized, which is reflected in terms 'eskers and faults' and 'tectonic movements and eskers' widely used in published eskers studies, their genesis has not been reconsidered. Thus, in the work of E.V. Rukhina (1973) noting the coincidence in esker and fault orientations, it is stated that eskers on the Kola Peninsula 'are associated with juvenile tectonic faults and movements along them'. However, it soon becomes evident that along-the-fault movements are invoked to account for the emergence of fractures in the ice sheet – and nothing else.

No less remarkable is the interpretation of South Karelia eskers suggested by a group of Quaternary experts from the Karelian Branch of the Russian Academy of Sciences: 'Esker ridges of the Onega Lake region and Povenetsk Bay stretch parallel to offset structures. Our observations suggest that eskers are not only dependent on the bedrock surface morphology, but are genetically connected with such structural elements as faults. Movements along the faults in the Ice Age may have affected the glacier cover by creating sets of fractures in it, subsequently marked by eskers' (Biske et al., 1971, p. 55).

So, G.S. Biske and co-authors, although recognizing the consanguinity between eskers and tectonic faults, consider them glacier-related, thus almost verbatim repeating E.V. Rukhina's conclusion. However, it remains obscure how the sandy-pebble filler found its way to the so intricately shaped glacier fractures. The puzzle remains unresolved as long as we persist on glacial activity, due to the absence of surface moraines on continental glaciers. The proposed hypothesis has retained the contradictory points of earlier views on esker formation while adding more confusion such as jointing of the glacier body under the impact of tectonic uplifting along the basement faults.

A glacier is a viscoplastic body where fissures (mostly transverse ones) emerge only in severely accidented relief (icefalls), or at the glacier's termini collapsing into the sea. Assuming that radial eskers were created by longitudinal regional joints, the emergence of the latter in a 2-3 km thick continental glacier could only have been caused by large-scale, hundreds of meters, vertical uplifts of a regional fault limb. So far, no movements of such a type, or scale, have been recorded along the Baltic Shield faults.

Faults with confined eskers and esker-kame pathways examined on the Kola Peninsula do not indicate to any substantial vertical displacement of one border relatively the other. No dislocations traced along these 'esker' faults have given support for the glaciations theory. They have resulted from horizontal tectonic contraction, predominantly upthrust-wrench faults and overthrusts, with a vertical shifting realized in folding and piling up of loose deposits overlying the fault.

Important insights into the mechanism of esker formation can be gained by studying their inner structure and stratification peculiarities. Wherever the eskers are composed by deposits of dissimilar lithological composition, e.g. alternating layers of sands, shingle, loam and gravel, the bedding is invariably overlapping and anticlinal (Fig. 37, 38, 39).

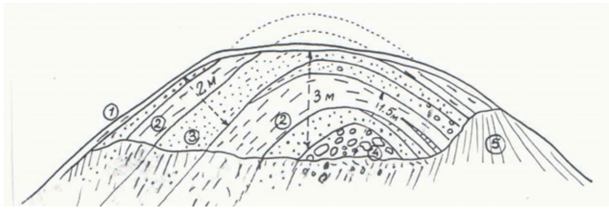

Fig.37. The structure of eskers on the western part of the Baltic Shield. An esker cross section in Norway (after O.Holtedahl, 1958): 1 – soil, 2 – sand, 3 – shingle and sand, 4 – boulder sand, 5 – talus.

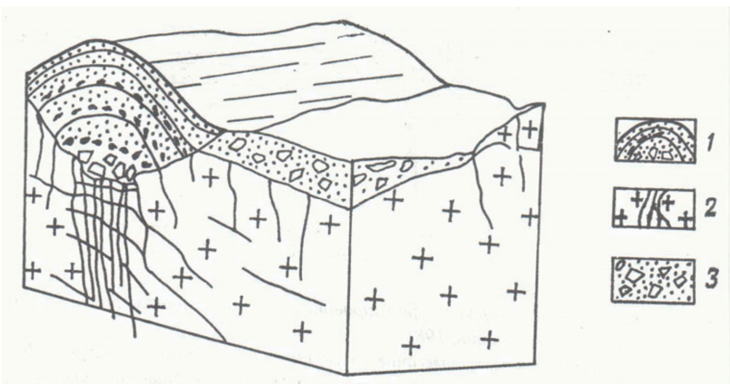

Fig. 38. An esker cross-section in Finland (after P.Lagermo and R. Juntonen, 1991, simplified). 1 – sands, gravel and shingle building up the esker ridge and curved into an open anticlinal fold; 2 – fissures and jointing area in crystalline rocks under the esker ridge; 3 – moraine.

Esker ridges often have an imbricate-fold structure, which rules out the possibility of their being formed by a glacial flow. On the contrary, a combination of anticlinal or imbricate bedding of eskers, their confinement to faults and orientation along the fault axial lines suggest their tectonic origin. In other words, they should be interpreted as over-fault and near-fault folds of a longitudinal compression.

The author proposes the following mechanism of esker formation. The limbs of steeply dipping faults (extensional and normal-wrench faults) are drawn together and joined under horizontal contraction in fault zones, whereupon the jointing zones of crystalline (or any other) rock are compacted and transformed to overthrusts and upthrusts-wrench faults. The process is accompanied by piling-up of loose deposits overlying the fault zones and by extruding of material from fault suture zones.

Estimably, building of a 10-15 m high esker, considering the initial thickness of loose mantle in the fault zone was 5-7 m, requires a 20-30 m value of tectonic compression (converging of fault limbs and compacting of jointing zones). The shape of loose deposits in the emerging ridge is streamlined, anticlinal, which is clearly seen in eskers composed of laminated sediments or deposits of varying lithological composition.

Powerful tectonic compression, causing overthrust and wrench fault-type displacements in the bedrock, may have deformed or bent the initially rectilinear esker ridges (in compliance with a caving effect) that are subsequently scattered and destroyed to form a hilly kame relief and individual ridges. It is possible that in plan the esker ridges are affected by transversal faults as well. Eskers, mounted on fault zones, often take the shape of a chain of isolated, lengthy ridges. Apparently, such esker complexes consolidate wrench faults: esker ridges were formed at wrench fault sites with an upthrust component, while loose deposits at extensional areas not only remained uninvolved in the tectonic piling-up but, on the contrary, subsided.

Since elongated fault zones contain sediments varying in genesis from fluovio-lacustrine to marine, eskers may be composed of deposits differing in lithology, genesis and age. And this is actually observed. Eskers are commonly built up by sandy-pebble deposits (with loam and clay bands) of the lacustrine-alluvial and marine genesis (Fig. 39, 40, 41).

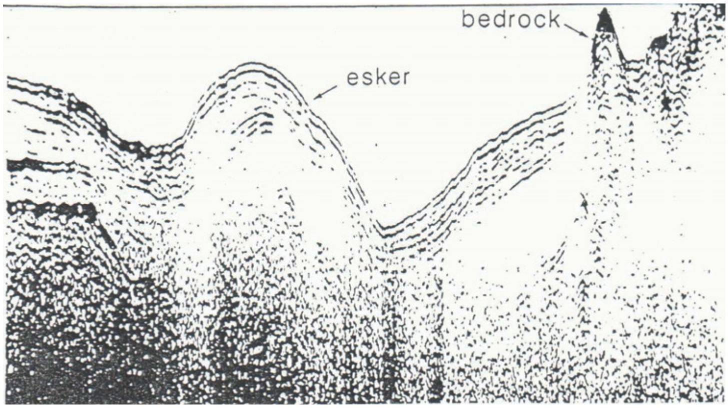

Fig.39. The structure of an esker at a lake bottom in Finland (according to radar surveing of the lake ice, P.Johansson, 1995).

It can be seen how the lake deposits, including contemporary ones, are curved in an open anticlinal fold.

Actually, the scheme illustrates the modern age of the esker and its tectonic origin.

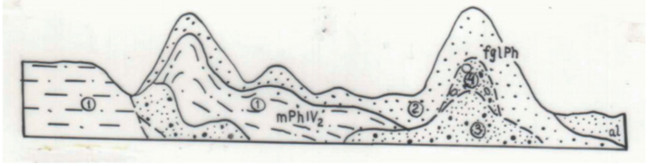

Fig. 40. The structure of eskers in the eastern part of the Baltic Shield.

Esker structure at the Lotta River, Kola Peninsula (after A.A.Nikonov, 1964):

1 – loam and sandy loam (postglacial marine depositions),

2 – sand, 3 – shingle-gravel sand, 4 – shingle-boulder sand.

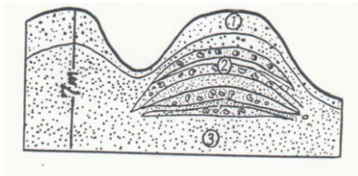

Fig.41. An exposed esker ridge in Karelia (after G.I.Goretsky, 1949): 1 – dissimilar-grain and fine-grain sand; 2 – dissimilar-grain and fine sand with sea mollusk shells from the sublittoral zone; 3 – coarse-grain sand.

When a fault zone does not contain any loose deposits, there are no eskers. Instead, such areas accommodate crushed bedrock, tectonic gorges or shear-type dislocations. Folds of longitudinal compression, resembling eskers, are easily modeled on laboratory scale (Gzovsky, 1975).

Eskers can be regarded as indicators of late Quaternary and Holocene upthrust-wrench fault movements along the basement fractures.

3.6. Drumlins

Ridge relief complexes, classified as drumlins, are widespread on the Baltic Shield. They often form wide, unbroken fields where the ridges are parallel (or subparallel) to one another and oriented in one direction.

Drumlins can be: 1) rocky, 2) with a rock core, 3) composed by the moraine.

A striking feature of drumlin relief is a distinct alignment of its ridge and hollow strikes with the fault tectonic structure of both the basement and mantle.

What is the mechanism of drumlin formation? There are several hypotheses, all based on glacial exaration.

Let us consider the weaknesses of these hypotheses. Firstly, they do not take into account the physical-mechanical characteristics of ice and actual glacier flow whereby neither bedrock nor boulder-containing rocks are scoured. Secondly, glacialism disregards the tectonic structure of drumlins' basement and the obvious association between fault groups and the strikes of drumlin fields.

Our explorations on the Kola Peninsula and Karelia have shown that the ridge (drumlin) relief and a system of converging, linearly oriented faults constitute a single paragenetic system. These linear parallel faults run along inter-ridge depressions, whereas the transverse ruptures split the ridges into sections.

Systems of linear ruptures forming ridges and hollows shear all Archean and Proterozoic metamorphic and intrusive formations. As revealed by research at Imandra, Porya Guba, and Chupa drumlin fields, they were caused by low-relief faults. If a horizon marker was available, the author determined the amplitude of fault dislocations. Shifting along the Porya Guba and eastern side of the Kandalaksha graben achieves 200-300, whereas on the north-eastern Kola Peninsula fault displacement has created a drumlin relief of the first hundreds of meters high. In a band of classical drumlin relief (after N.N.Armand) in the Lyavozero-Kontozero area (central part of the north-eastern Kola Peninsula) there have been discovered (L.M.Grave (1966)) about 100 discontinuities with a horizontal (wrench-fault) displacement forming the drumlin relief. According to L.M.Grave, horizontal offset there varies between 200 to 450 m and is accompanied by several tens of meters' warping.

As we observed on the Kola Peninsula and Karelia, systems of parallel, linearly oriented faults not only produce the inter-ridge hollows but affect the ridges' (i.e. the drumlins') morphology as well. Wrench-fault displacements have produced subsidiary reverse-and-thrust-type fractures. Reverse-and-thrust-type plates, tectonic slickensides and other forms of compression, alongside with crushing and displacement in metamorphous and intrusive rocks, can also be observed at well-exposed drumlin areas, with roches moutonnees as their rims. Both the complex stratification of rock and inner structure of drumlin ridges are exposed at areas sheared by normal faults of a later generation.

Thrusts and reverse faults, modeling the drumlin surfaces and complicating their structure, can also be seen in drumlins composed by unconsolidated deposits. S.I.Rukosuev reports of the imbricate-fold structure of drumlins in Karelia composed by "moraine" and attributing its origin to some glacial activity. This only means that drumlins built by "moraines" were under the same (or similar) tectonic stresses as adjoining rocky and semi-rocky counterparts on their common drumlin field.

Our studies have also included the drumlin relief of the Rybachy Peninsula. The drumlins are clearly interpreted from aerial mapping and in morphology are close to the immense drumlin fields of North Canadian Shield (*Canada's Heritage of Glacial Features,* Prest, 1983).

The Rybachy drumlins are built up by sedimentary Riphean formations – sandstone and argillaceous slate. They are peculiar in being arranged in two prominent, differently oriented bands: one in the Peninsula's south, oriented north-eastward, and the other in the Peninsula's north, oriented north-westward. Regarding this relief as glacial heritage would either require to recognize the existence of two glacial epochs with two glaciers moving in different directions – or one glacier with lobes. But even these assumptions cannot be satisfactory because the Rybachy drumlins represent a series of parallel, crest- and rampart-shaped, open anticlinal folds – symmetrical, asymmetrical or monoclinal. The folds are composed of Riphean sandstone and argillaceous slate and have the following dimensions: height of 2-3 to 10-30 m, width of the first tents of meters to 100-300 m, sometimes more. The length of the systems of folds consisting of ridges-folds split by transverse fissures is 20-40 km (Fig. 42). The dip of fold limbs varies between gentle to steep (up to vertical); the fold plunging crowns are often ruined.

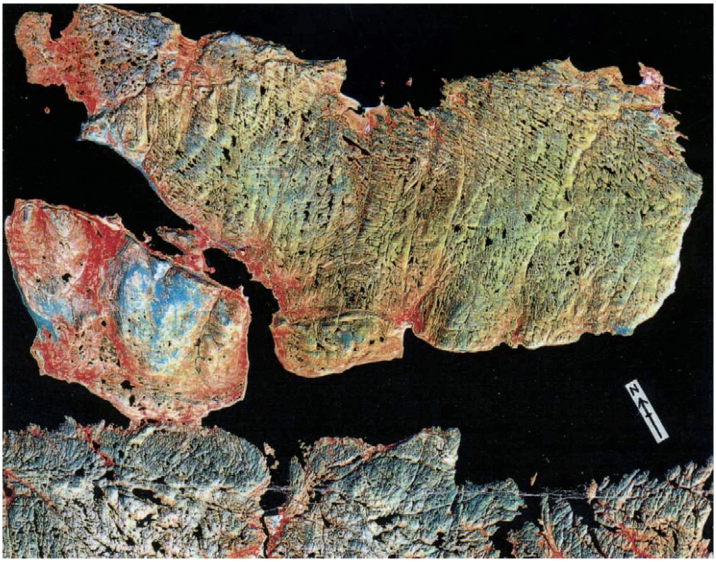

Fig.42. Continuous "drumlin" fields on Riphean sandstone and schist of the Rybachy Peninsula. The orientation of "drumlin fields", which is actually a tectonic cuesta, varies on different parts of the peninsula from north-eastward to north-westward (satellite photograph Landsat 5-TM).

The age of this formation is still unclear due to the fact that it is composed of nothing but Riphean rocks. They may be dated as Alpine or Neocene tectonic cycles. The folds are sheared by marine Holocene abrasion scarps, up to 60-80 m of their surface being complicated by marine offshore bars of the same period.

So, whatever the drumlin type, they have one common feature – they emerged as the result of horizontal tectonic contraction. The drumlins created on areas of outcropping crystalline basement are rocky; whereas at places where the basement was overlain by loose deposits and metamorphous sediments, the drumlins became fold-imbricate or fold.

3.7. “Hilly moraine” relief

The structure of “hilly moraine” relief unambiguously demonstrates that all its morphological peculiarities, no matter whether it is composed of bedrock, ‘moraine’ or boulder-free sand, are controlled by fault (rupture) tectonic processes. Spacing between ruptures determines the hill size across, while the kinematic type of ruptures – the hill morphology and inner structure. In its elementary form, the “hilly moraine” relief came into being as the result of tectonic crushing of crystalline rocks in the basement. Outcropping crystalline rocks created a knob-and-kettle relief from bedrock and products of decomposed displaced blocks and plates, i.e. boulder-block-crushed stone material.

The “hilly moraine” relief emerged due to activation of the fault network, tectonic movements in the basement, both vertical and horizontal. These movements brought about deformations in the overlying sedimentary mantle, thus producing a knob-and-kettle relief. Both its morphology and structure depended on the thickness of overlying loose deposits and the power of fault-tectonic processes.

The same processes created kames the difference being that tectonic deformation in this case affected the marine and alluvial sand and gravel strata.

3.8. Terminal moraine ridges

There are three major groups of terminal moraine ridges on the Baltic Shield: Salpausselka in Finland and Southwestern Karelia, Tersky Keivy on the Kola Peninsula, and Ra in Norway and Sweden.

Salpausselka consists of three arching ridges of about 500 km in length, crossing southern Finland from south-west to north-east. There are two distinct ridges of 20 to 80 m high and tens to hundreds of meters, sometimes 2-3 km, wide. In cross section, the ridge is seen to be composed by sand, gravel, shingle, and also boulder sand (‘moraine’), all interlaid by washed-out, laminated sand bands. The origin of some shingle and sand in Salpausselka sections was found to be marine (Hyyppa, 1966). Both the fact that ‘terminal moraine’ ridges are composed of sandy-gravel-shingle deposits (what is more, of the marine origin) and the insignificant share of boulder sands in their structure, obviously contradict their glacial genesis.

Clues to the ridges’ origin lie in their structure, and in the structure of the basement. The structure of Salpausselka deposits is imbricate (Saarnisto, 1985). Moreover, the ridges are confined to large, arcuate faults that can be traced to more than five hundred kilometers. This dependence was first noted by A. Tammekan (1955) who wrote that the Salpausselka ridges lie within a large contour accommodating the interface of gravitational anomalies. North of the ridges, the gravitational anomalies are positive, whereas south of them they are negative. A. Tammekan attributed it to the trend of general uplift in southern Finland. In V.E. Gendler’s view (1980), the major fault zone in southern Finland ‘appears to be aligned with bands of fluovioglacial deposits – the Salpausselka ridge. And this is hardly accidental. We should suggest the possibility of along the faults movements when those deposits were formed’. This assumption is confirmed by satellite surveying: photographs show a distinct structural-tectonic association of Salpausselka ridges with arcuate faults in the basement. Considering the imbricate-thrust inner structure of the ridges and their association with arcuate faults in the basement, this complex represents overfault compression ramparts stabilizing a set of arcuate faults of the overthrust type.

Terskye Keivy. The system of the Terskye Keivy “terminal moraine” can be traced along the south and south-east coasts of the Kola Peninsula. They comprise three subparallel ridges. The longest of them (northernmost) is over 250 km. In height they vary from 15-20 to 60- m, in width – from 100-150 to 400-700 m. Here and there, these formations are composed by washed out gravel sands, shingle, ‘moraine’, varved clays and sandy loam. When examining in 1972 and 1977the ridge profile cut by the river Strelna, we established their anticlinal folding (the Northern Keiva) and dislocation (the Second Keiva). Varved clay of the northern ridge revealed a complex of marine and brackish-water diatomic flora, whereas the boulder loam and gravel sands of the second ridge were found to contain complexes of foraminifer and sea mollusk shells. The shells were in different states of preservation: from intact valves of cyprine and balanus in the "moraine" to shell detritus in gravel deposits (Chuvardinsky, 1973). The author also encountered a complex of foraminifer and Radiolaria in a 30 m thick sand layer and overlying glacial-marine boulder loam, in a section of the southernmost ridge (Morskaya Keiva) in the mouth of the Ponoy River (Chuvardinsky, 1973).

It is highly meaningful that the ridges are confined to arcuate faults. The easiest mapped is the regional Tury-Nizhneponoysky fault (wrench-overthrust type) aligned by a set of eskers and, farther on, east of the Varzuga River, by the Northern Keiva ridge. This alignment has been noted by many geologists. This fault has been included into the manual *Methods of Structural Geology and Geological Mapping* (Kushnarev et al., 1984) to illustrate the Quaternary fault tectonic impact on relief formation, barring of the lakes lying north of the ridges.

Drilling at the Pyalitsa-Pulong section of the Northern Keiva has disclosed an area with severely tectonically crushed bedrock beneath it.

Based on the available data, the author cannot but interpret the Terskye Keivy Ridges as over-fault and near-fault ramparts of longitudinal compression. The ridges arose by horizontal compression of fault suture zones and thrusting of southern limbs over the northern ones. The marine and continental deposits, overlying the suture zones, were piled up to form ridges, subsequently developing secondary imbricate-thrust and offset structures. The product of suture zones, i.e. friction breccias, was extruded to form the ridge core. It is for this reason that the cross sections in some of the ridges' inner parts contain considerable amounts of gold.

The Ra Ridges. These "terminal moraine" ridges of the glacial period are widely spread in southern Norway and Mid-Sweden. They confine the Norwegian graben from the northeast and northwest, the total length of the belt being not less than 300 km. According to W. Holtedahl (1958), the ridges are commonly 20-40 m in height and approximately 500-800 m in width. Their inner structure is highly singular. It is reported that at places the ridge is composed of boulder-free clays with its surface overlapped by a thin shingle layer (the Ra's 'shell'). In other places, the ridge core is also composed of boulder-free and weakly bouldered clays, but is overlapped by thick, up to 10 m and more, layers of sands, shingle, and gravel sands. The profiles also contain varved clays with marine mollusk shells.

Another peculiar feature of the ridges is their anticlinal structure suggesting a tectonic horizontal compression. These tectonic processes were post-sedimental. The marine clays, shingle and gravel strata were crumpled into open anticlinal folds after their deposition. The age of the long belt of anticlinal ridges, known as Ra, is the Holocene.

Since the Ra Ridges are actually delineating the tectonically active Norwegian graben from the north, it can be suggested that they, in turn, contour the set of faults confining the graben from the north as near-fault compression structures.

"Terminal moraine" ridges of the Baltic Shield have much in common with those found on the Russian platform. The affinity is confirmed by various evidence including mapping drilling, which also proved that: a) the structure of 'terminal-moraine' ridge is fold and imbricate, shaped by rocks of the Cenozoic, Mesozoic and even Paleozoic mantle; b) 'terminal-moraine' belts are conjugated with faults piercing the mantle, active at the neotectonic stage and having a common paragenesis. Since both the structure and tectonic origin of 'terminal-moraine' belts on the Russian platform have been discussed earlier (Chuvardinsky, 1998), we adduce here only the argumentation of V.I. Babak, V.I. Bashilov and N.I. Nikolaev (1982): 1) distribution of terminal glacial formations on the platform depends on the fault-block structure of the basement; 2) terminal glacial formations should be interpreted as rampart-like, near-fault structures of tectonic origin.

Chapter 4.
Neotectonic activation of graben and issues of glacial tectonics

The author has devoted several seasons to field geological and geomorphological surveying in the Kandalaksha and Ladoga graben, as well as the minor Ivanovsky graben in northeastern Kola Peninsula. A description of these structures is presented below.

4.1. The Kandalaksha graben

The Kandalaksha fault graben is one of the largest offset structures in the conjunction zone of the North-East Baltic Shield and the Russian platform. It stretches southeast away from the city of Kandalaksha across the White Sea towards the Dvinskaya Bay.

Here is presented the structure of the northwest Kandalaksha graben, the most accessible for land surveying.

Dislocations with a break in continuity are salient both in the land and sea bottom relief and yield to geomorphological mapping. The axial part of the Kandalaksha graben, the Kandalaksha Bay, accommodates three faults of NW strike, i.e. Karelian, Kandalaksha and Kolvitsy, which can be referred to deep-seated regional faults. They are traceable from the Telyachy-Oleny-Anisimov island group in the SE direction (strike azimuth SE 130-140°) almost to the latitude of Porya Bay, where they are cleft by a substantial latitudinal fault (Fig. 43).

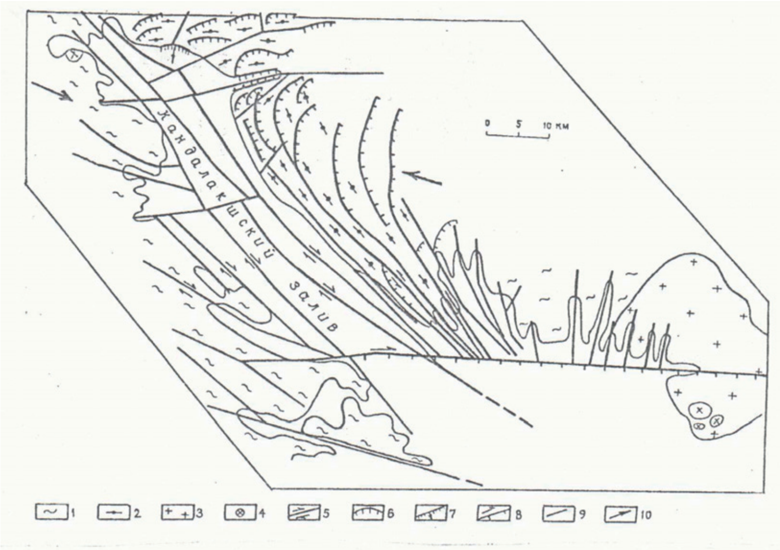

Fig.43. Fault tectonic diagram of the north-western part of the Kandalaksha graben (constructed by V.G.Chuvardinsky, 1992).

1 – gneiss of the White Sea series; 2 – rocks of the franulitic formation; 3 – granitoids; 4 – massifs of alkaline ultrabasic rocks; 5 – Riphean sandstone; 6 – wrench faults; 7 – thrusts; 8 – normal faults; 9 – wrench-normal faults; 10 – faults (undifferentiated); 11 – direction of regional tectonic compression.

The Kandalaksha and Kolvitsy grabens merge at the south-east extremity of this fault zone. The junction is marked by a narrow underwater hollow of more than 100 m in depth. Besides these major wrench faults, the Kandalaksha graben area (both land and aquatic) accommodates lower-order wrench faults, that are often parallel to the main fault, and a great number of subsidiary faults.

Faults in the axial part of the Kandalaksha graben are viewed as wrench faults due to their greater lengths and stable strikes, and also because they are clearly expressed as narrow linear depressions. These geomorphological indicators of a wrench-fault-type displacement along the faults can be supported by geological ones. By and large, the Kandalaksha graben area is well-exposed, although non-uniformly.

Moreover, the Kandalaksha Bay water area is densely scattered with lakes-skerries, almost completely denuded. This is highly revealing regarding the structure of the bay bottom and fault tectonic processes, the more so that major wrench faults come at places in contact with the islands, shearing and displacing some of them.

The author can provide the following geological substantiation of horizontal displacement along these faults: 1) vertical fault surfaces carry sets of striae and furrows, as well as shear stairs, suggesting wrench-fault-type horizontal and subhorizontal displacement along the faults in the south-eastward direction; 2) dykes of alkaline-ultrabasic rocks, developed on the island-skerries, that are separated by faults, are displaced relatively each other, even on adjacent islands. Horizontal shifts along the wrench faults are also indicated by dykes of alkaline-ultrabasic rocks in the Kandalaksha graben east (Chuvardinsky, 1998, 2000).

The western part of the graben was also found to accommodate wrench faults including the greatest of them, the Startsevsky, with an apparent slip of 1.9 km, and wrench faults of Ovechy Island.

Another evidence of continuing tectonic restructuring of the graben, wrench fault movements in its axial part is the earthquakes with magnitudes of up to 5.1 occurring in Kandalaksha Bay, reportedly caused by upthrust-wrench fault displacements in the axial part of the Kandalaksha graben (Assinovskaya, 1986).

Horizontal contracting of the Kandalaksha graben is also supported by abundant neotectonic overthrust structures found at extremities of regional wrench faults and as isolated structures. A description of overthrusts and upthrusts within the graben is given in Sections 2 and 3.

Our findings suggest that the type of neotectonic processes in the north-west Kandalaksha graben was horizontal contracting, but not extending, as demonstrated by predominant development of compression and wrench fault structures.

The structural zone, lying within the contour of the Kandalaksha Bay hollow, represents a series of various-order parallel and subparallel wrench faults conjugated with numerous subsidiary faults of north-east, sub-lateral and other strikes. Tectonic dislocation in this zone is mainly realized as dissimilar-amplitude shifting of large and small wedges, flat blocks and tectonic breccias along faults of north-west to south-east strikes. In reality, it is a wrench-fault displacement in the south-eastward direction complicated by movements along upthrusts, normal-wrench and normal faults of unrelated directions, whereas the faults controlling the dislocation process are wrench faults in the axial part of the Kandalaksha Bay hollow.

4.2. The Ladoga graben

The graben is located in the south-east of the Baltic Shield and the Russian platform. By and large, it coincides with the Ladoga Lake hollow. Its shape is nearly rectangular and, similarly to the lake, it is oriented in the north-westward direction. The most informative and easiest accessible for field surveying is the north-western part of the graben, with a tectonic skerry and fjord topography. The bedrock on both the islands and coast is highly, sometimes uninterruptedly, exposed. It is here that the author was doing his field work in the course of the seasons of 2002, 2003, 2004, 2006 and 2008.

According to some researchers, the Ladoga graben originated in the Riphean, was rejuvenated in the Late Cenozoic and exposed to vigorous tectonic activation in the Quaternary (Milanovsky, 1994). Our studies corroborate the concept of graben's neotectonic activation persisting till nowadays, which is manifest by fairly frequent, small-magnitude earthquakes in its northern part.

Axial structures, shaping the north-western part of the Ladoga graben, are wrench faults of near-meridian and north-west strikes, and multitudinous transversal overthrusts and normal faults. Faulting has produced a typical block-tectonic (skerry-fjord) relief. The wrench faults mostly have a north-west strike and, while in the central part of the zone they are near-meridian (NNW 340-350^{o}), the eastern and western flanks have NW –300-310^{o} and sometimes 290^{o} strikes.

These are steeply dipping faults, shearing the Archean, Proterozoic and Quaternary formations and expressed in the land and lake bottom topography as linearly oriented depressions, i.e. gorges, fjords and narrow underwater grabens. The wrench fault fissure surfaces are fairly visible on fjords borders and fjord-like straits. Normally, their near-vertical or slanted surfaces feature slickensides and sets of parallel furrows and striae oriented along fissure lines. Typical of the wrench fault surfaces are transverse shear stairs, arched cavities and mylonite “leather coats” on slickensides.

The Ladoga graben has also numerous overthrusts; their lying walls can be seen everywhere. Overthrust fissure surfaces are usually gently sloping, up to 20-25^{o}, whereas their front parts are 60-70^{o} steep, i.e. are essentially upthrusts. The fault planes carry slickensides with clusters of well-expressed parallel and subparallel furrows and striae. Quite often one encounters cemented mylonite, while the surface of slickensides developed on the Ladoga series schist carries sometimes a mylonite “leather coat”.

Overthrusts of the Ladoga graben, similarly to the Kandalaksha graben, are conjugated with regional wrench faults. But they are peculiar in being displaced (overthrust walls and blocks) in the same direction with the general wrench fault displacement.

Neotectonic activation of the Ladoga graben becomes evident from the morphology of the lake basin and activated movements along deep-seated faults oriented along the basin’s strike – from north-west to south-east. Rejuvenating of transverse faults is manifest in fault-line scarps. That faulting has been the most active in the Late Cenozoic, especially the Quaternary until nowadays, is confirmed by small-magnitude earthquakes persisting in the graben’s northern part. At the neotectonic stage, the Ladoga graben (at least its northern part) has been experiencing horizontal contraction, to which testifies the predominant development of wrench faults, overthrusts and subsidiary faults. Recent shifting along wrench faults and overthrusts has produced a skerry-fjord relief and deep, narrow tectonic grabens in the Ladoga Lake north.

Transverse tectonic benches, splitting the lake basin into several parts, should be regarded as wrench faults. As for the southern half of the Ladoga graben, it must have been the place of discharge and piling of rock fragments dislocated from the graben's northern part.

4.3. The Ivanovsky graben

The Ivanovsky graben in the North-East of the Kola Peninsula occupies the fjord-resembling Ivanovskaya Guba bay and the valley of the downstream Ivanovka River flowing to the Barents Sea. The author explored this structure in 1989-1990. The graben strike is south-eastward (120-125^{o}); it is 25 km long and 0.2-0.3 to 2.2 km wide. The Ivanovsky fjord lies in Archean granitoids, but also contains Riphean sandstone and clay schist along the shore area and partly on the bottom. The graben is cut by dozens of transverse dolerite dykes dated as Paleozoic since they are cleaving Riphean deposits. Moreover, the author has discovered dykes with dolerites containing xenolites of Riphean sandstone.

The graben structure is peculiar in that none of the 10 mapped dolerite dykes, crossing the fjord from shore to shore, are displaced in the horizontal plan. Since the fjord borders exhibit traces of shearing, are everywhere complicated by normal, sometimes stair-shaped, faults and bear no traces of wrench-fault or overthrust displacement, this structure can be classed as extension grabens. Judging by the presence of Riphean sedimentation strata, it emerged in the Upper Proterozoic. During the Paleozoic, it was a center of magmatic activation expressed both as intruding sills and numerous dolerite dykes, and also a small alkaline massif. At the neotectonic stage, the graben has experienced horizontal extension that has given rise to a neotectonic extensional structure. The value of horizontal stretching in it varies from the first hundreds of meters to 2 km.

Evidently, the impact on the grabens has been different: contraction in the case of the Kandalaksha and Ladoga and extension in the case of the Ivanovsky.

4.4. On the arched uplift of the Baltic Shield

The idea of arched uplifting of Fennoscandia was proposed by A.P. Karpinsky about 100 years ago. Based on the findings of the day, Karpinsky regarded the Baltic crystalline Shield as a Fennoscandian horst that rose to form the major normal faults and tectonic depressions of the White Sea, the Finnish Bay, and Ladoga and Onega Lakes (A.P. Karpinsky, 1984).

However, the concept of purely tectonic uplifting of both the Baltic Shield and the entire Fennoscandia was later transformed to the effect that the uplift occurred upon removal of the ice sheet load.

Nonetheless, the tectonic concept has persisted till nowadays. Thus, A.D. Arkhangelsky wrote in 1933 that elevating of both the Baltic and other Shields occurred within a very long geological period, so that the Holocene movements of the Shield have merely inherited the ancient tectonic uplift. G. Stille, M.M. Tetyaev, and V.V. Belousov reported of a long trend for uplift (since the Late Precambrian). Still, it is the hypothesis of glacial isostaty that prevails. There have appeared numerous schemes illustrating a concentric arched uplift of the Shield with maxima around the Gulf of Bothnia.

The basis of the glacial isostaty concept was shattered by N.I. Nikolaev (1962, 1967), who came to the following conclusions: 1) glacial isostaty needs reconsidering; 2) 'the De Geer-Hegbom scheme has acted hypnotically for 50 years so that any comparison of geological and geophysical data and ensuing interpretation have invariably obeyed the regularities of their scheme, i.e. a single arch created by compensational cleaving of the crust' (1967, p. 66); 3) 'the De Geer-Hegbom idea of a uniform arched glacioisostatic uplift does not take into consideration the block structure of the crust and erratic manifestations of tectonic movements' (1967, p.67).

This inference was supported by G.S. Biske whose studies of relief and neotectonic manifestations in Karelia and Finland have led her to suggest that 'Fennoscandia does not undergo an arched uplift being formed by intricately tessellated sections, each moving fairly independently' (Biske, 1970, p.35). Similar conclusions for the Kola Peninsula and Karelia were arrived at by S.A. Strelkov, V.I. Bogdanov, G.Ts. Lak and A.D. Lukashov. Earlier, a critical review of the classical glacial isostaty concept had been suggested by Finnish geologists Harme (1963) and Paarma (1963) emphasizing the great role of fault tectonic processes in the shaping of the central Baltic Shield relief.

The measured values of contemporary uplift rates of the Baltic Shield shores are highly informative and can be accepted, although with the following reservations: a) the values of uplift rates obtained at the Baltic Sea shore should not be extrapolated either to the Sea's bottom or that of the Gulf of Bothnia's bottom, where no such measurements were carried out; nor should they be extrapolated to entire Fennoscandia; b) a half-century-long observation of the sea level is but an instant in the Holocene history, to say nothing of the Quaternary period. Future observations may reverse the sign of movements (which has, incidentally, been recorded at some parts of the Baltic shore); c) structurally, both the Gulf of Bothnia bottom and central hollows in the Baltic Sea are rejuvenated Riphean aulacogens tectonically active in the Pliocene – Quaternary (E.E. Milanovsky, 1983; R.N. Valeev, 1978).

It is these fault-tectonic movements, but not the conjectural glacial loads of hypothetical ice sheets that caused alternate uplifts and subsidence of graben rims and bottoms.

Meanwhile, the problem of arched uplift of the Baltic Shield, either on the whole or partly, should be approached from the standpoint of general geotectonics. Here the discovery of V.G. Zavgorodny and A.T. Radchenko (1988) may shed some light. While investigating the Kola Precambrian tectonics, they noted a far-reaching regularity: riftogenesis is preceded by a pre-riftogenic uplift. It can be presumed that Cenozoic arched uplifts on the Baltic Shield preceded the rejuvenation and restructuring of Riphean grabens.

As reported by F.N. Yudakhin (2002), analysis of tectonic-physical, seismic and geophysical data has demonstrated that arched uplifting of Fennoscandia is the result of powerful horizontal compressing of the Mid-Atlantic spreading zone and penetrating of an astenospheric lens into the Earth's crust.

4.5. About the glacial tectonics

There was a time about one and a half a century ago when German naturalists, interested in displaced strata of chalk rocks on Møn and Rügen Islands in the Baltic, tried to explain their origin by terrestrial, tectonic forces. However, upon arrival of the glaciations concept, these and similar dislocations were attributed to the thrusting impact of the Scandinavian ice sheet. The glacier was also made responsible for shearing and displacing rock blocks from their bedding (outliers). Thus took shape a new theory now called 'glaciotectonics'.

It is amazing how glacial tectonics, while dealing with the origin of dislocations and outliers, can ignore the evidence on dynamics and geological activity of contemporary cover glaciers as well as the theoretical insights of such glaciologists as P.A. Shumsky, W.Badd, W. Patterson, L. Llibutry, I. Vertman, I.A. Zotikov, and V.G. Khodakov. Likewise disregarded are the data accumulated by soil mechanics, geodynamics and structural geology. If at least some of these materials were given due consideration, all glaciological hypotheses could be consigned to oblivion.

The author, relying on a large body of factual data on the structure and paragenetic association between 'glaciotectonic' structures and active basement faults, suggests the following:

1. Imbricate-overthrust morphological structures on the surface of the platform mantle, generally regarded as glaciotectonic dislocations, have a tectonic origin. They were created by wrench-fault displacements along fractures in the basement and ensuing deformations in sedimentary mantle. Both the extrusion of slabs and wedge scales from sedimentary mantle to the surface and their piling in near-fault ridge imbricate-overthrust dislocations have been caused by transformation of stresses from wrench-fault- to upthrust type on areas of wrench fault lateral contraction.

2. Erratic masses are, actually, scales of sedimentary mantle or isolated and crushed large rock blocks extruded up the dip from medium and lower horizons of the platform mantle and basement. Subvertical displacement of outliers within the platform may vary from tens of meters to the first kilometers.

3. Great-scale wrench fault displacements along deep-seated faults not only displace mantle deposits, but transform them to tectonic breccias and mélange incorporating sizable outlier facies (allochthonous tectonites), containing crystalline rock blocks and boulders.

4. The numerous disruptions in the sedimentary mantle considered above are not confined by the fault area, as believed by glaciotectonic proponents, but have a linear-zone development and coincide with areas of dynamic impact of faults, predominantly wrench faults: both deep-seated, regional or subsidiary, and lower-order upthrusts, as well as with areas with diapir structures.

An exhaustive description of the mechanism of tectonic dislocation in the platform mantle rock and outlier formation is given in the monograph of R.B. Krapivner (1986).

Conclusion

1. The ample evidence presented in this book testifies that the very basis of the glacial theory, namely, its reliance on glacial exaration relief on the Baltic Shield, represented by fjords, skerries, roches moutonnees, stria on crystalline rock, is false. The "glacial-related" erosion was actually produced by fault-neotectonic processes.

2. Other types of "glacial-related" relief, such as oses, kames and terminal moraine bars are also shown to be formed by faults and surface folding.

3. As disclosed by full-depth drilling on Greenland and Antarctic ice sheets, and also by detailed studies of their physics and dynamics, ice sheets could not have produced the "glacier-related" relief on the Baltic and Canadian Shields, including the scattering of boulders all over the Northern Hemisphere. The impact of a glacier is one but significant: it preserves the pristine geological surface. Glaciers cannot plough the surface; what their bodies do retain are traces of dust-like, fine-earth substances.

4. Time has come for revising the well-established theory and considering the new geological concepts emphasizing the significance of neotectonic processes.

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