УДК 551.4:551.793(262.24)

А. В. АМАНТОВ (ВСЕГЕИ), В. ФЬЕЛДСКААР (Тектонор, Норвегия)

ВЛИЯНИЕ ГЕОЛОГО-ГЕОМОРФОЛОГИЧЕСКИХ ОСОБЕННОСТЕЙ БАЛТИЙСКОГО РЕГИОНА И ЕГО ОБРАМЛЕНИЯ НА ЛЕДНИКОВЫЙ – ПОСТЛЕДНИКОВЫЙ ЭТАПЫ РАЗВИТИЯ *

Дан анализ региональной геологии и тектоники Балтийского региона преимущественно в пределах Восточно-Европейской платформы и влияния на него ледниковых процессов четвертичного времени. Обычно эти вопросы рассматриваются отдельно, однако ряд этапов геологической и геоморфологической истории, на наш взгляд, существенно воздействовал на развитие и динамику ледниковых щитов и их денудацию. Лишь понимание таких особенностей развития объясняет как положение Ботнических центров развитых четвертичных щитов (с ледоразделом, традиционно смещенным к шарнирной зоне протерозойского заложения, оформляющей прогибы с останцами раннеплатформенных комплексов и палеозойского чехла), так и локализацию основных ледниковых потоков и даже детали рисунка современного поднятия. Взаимосвязанные геологические, геоморфологические и тектонические особенности впадины Балтийского моря и смежных районов формировали характер распространения и распада ледниковых покровов, важнейшим контролирующим фактором выступил рельеф субстрата коренных пород. При благоприятных условиях значимые формы рельефа первого порядка могли служить как центрами ледниковой аккумуляции, так и природными барьерами, участвовавшими в оформлении границ распространения оледенений в течение некоторых временных интервалов. Продолжительность ландшафтного контроля края оледенений релевантными элементами первого порядка (система уступов-глинтов и сопряженных склонов в пределах осадочного чехла) дает представление о пониженной мощности льда периферической зоны, которая недостаточно согласуется с прогноз-моделью на основе закона Глена без дополнительного учета изменений скоростей и термальных вариаций в зоне ложа. В свою очередь и формы рельефа были значительно (но избирательно и с пространственно-временными различиями) модифицированы оледенениями с разительными примерами мощной ледниковой денудации при литологическом и структурном контроле.

Низменность Балтийского моря гетерогенна. Ее фрагмент от Финского залива до Южной Балтики представляет собой часть Балтийско-Беломорской структурно-денудационной формы, образовавшейся при ведущей роли многофазных третичных доледниковых процессов и последующей избирательной мощной плейстоценовой гляциальной и флювиогляциальной денудации, воздействовавших в большей степени на верхнепротерозойские раннеплатформенные впадины и податливый эпипоздневендский осадочный чехол. По-иному выглядят Центральные Ботнические впадины и сопряженные структурные элементы раннего заложения (такие как шарнирная Западно-Ботническая зона) – это важная интегральная часть общей характерной зональности, связанной с ледниковыми покровами, что также отражается в картине современного поднятия и сейсмичности. Наблюдаемое послеледниковое поднятие – результат наложения различных процессов с известной важнейшей ролью гляциоизостатической релаксации. Постсвекокарельскими доплитными процессами и сформировавшимися суперрегиональными рифейскими зонами заложен своеобразный каркас, в различной мере определивший на некоторых этапах развития рисунок поднятий и опусканий, в частности контуры Балтийской антеклизы, а впоследствии щита и даже структурно-денудационной впадины Балтийского моря. Особо отметим Западно-Ботническую шарнирную зону, дооформившуюся в ходе каледонского тектогенеза. Она ограничивает Ботнические прогибы, сложенные раннеплатформенными рифейскими и палеозойскими плитными комплексами, отчетливо выражена в современном ландшафте, контролировала Ботнический ледораздел. Зоне, определяющей ось современного поднятия Фенноскандии, свойственна известная повышенная сейсмичность.

Применительно к Северной Европе проведено моделирование высокого разрешения для анализа изостатической реакции на перераспределение как ледниковых и водных масс, так и осадочного материала (включая известные масштабные оползни континентального склона), а также сопутствующих изменений геоида. Подтвердились лишь некоторые из ранее предложенных реологических моделей. В качестве оценочной основы они принимают специфическую астеносферу мощностью менее 150 км и вязкостью ниже $7{,}0 \cdot 10^{19}$ Па/с с вязкостью нижележащей мантии близкой к 10^{21} Па/с, но при флексурной жесткости литосферы $5 \cdot 10^{23}$ Нм и эффективной эластичной мощности около 30–40 км. Значительные остаточные поднятия с возможной тектонической составляющей, приуроченные к северным и южным группам купольных возвышенностей Скандинавских гор, могут быть вызваны спецификой процессов, контролируемых главными океаническими зонами трансформных разломов Ян-Майен и Сенья.

Ключевые слова: *плейстоцен, Балтийский щит, Русская плита, гляциация, подъем, оледенение, поднятие, изостазия, моделирование, реология, денудация, аккумуляция, неотектоника.*

---

* Статья публикуется на английском языке.

A. AMANTOV (VSEGEI, SPb), W. FJELDSKAAR (Tectonor, Norway)

GEOLOGICAL-GEOMORPHOLOGICAL FEATURES OF THE BALTIC REGION AND ADJACENT AREAS: IMPRINT ON GLACIAL-POSTGLACIAL DEVELOPMENT

Linked geological, geomorphological and tectonic features of the Baltic Sea lowland and adjacent areas strongly impacted the history of glacial grows and decays, while the bedrock landscape seems to be the major linking and controlling factor. First-order landforms could in favorable conditions control both center of ice nucleation, and serve natural barriers shaping its margin during some time intervals. However, in the opposite way, the landscape was also strongly (but selectively and variably in time and space) modified by glaciations, with creation of prominent samples of strong glacial erosion, in its case controlled by the lithological and structural factors. Baltic Sea lowland exhibits part of the super-regional structural-denudation form that was created with dominate role of Tertiary multiphase preglacial erosion and strong selective Pleistocene glacial-fluvioglacial denudation that mostly affected the Meso-Neoproterozoic early platform basins and soft post-Late Vendian sedimentary cover. Central sedimentary basins and relevant ancient hinge zones (like the Western Bothnian zone) could be an important integral part of overall Ice-age pattern, including the shape of post-glacial uplift and seismicity. The observed post-glacial uplift in the Baltic area is the result of various processes, the most important being the glacio isostatic movements. High resolution modeling including glacial isostasy, hydro isostasy, sediment isostasy confirms earlier rheology model of a low viscosity asthenosphere with a thickness less than 150 km and viscosity less than $7.0 \cdot 10^{19}$ Pa/s, and with a mantle viscosity beneath the asthenosphere of viscosity 10^{21} Pa/s. The flexural rigidity of the lithosphere is $5 \cdot 10^{23}$ Nm (effective elastic thickness of 30–40 km). Significant residuals in the present rate of uplift of the northern and southern Scandes Domes could be related to the major Jan Mayen Fault Zone and Senja Fracture Zone.

Keywords: *Pleistocene, Baltic Shield, Russian Platform, glaciation, uplift, freezing, raising, isostasy, modeling, rheology, denudation, accumulation, neotectonic.*

Introduction. The Baltic Sea lowland exhibits heterogeneous structural-denudation form of the platform area with multiple geological-geomorphological conditions and history that includes impact of several Pleistocene glaciations. It is known to share parts of the East-European and younger West-European platforms. Segment of the East-European platform is represented by domains of the Baltic (Fennoscandian) Shield, with neighboring Russian plate to the east and southeast. In the shield area dominantly Precambrian basement of various orogenic cycles is emerging from below a sedimentary cover, which started to develop since Late Vendian or Cambrian time after mature planation.

We mix two stories up: the regional geology and tectonics of the Baltic (in particular belonging to the Eastern European Platform) area and some Quaternary glacial processes. Usually they are described separately without notice of connection. However, the principle item is that older geological – geomorphological history had important influence on the ice sheet behavior. Many items of interrelation are still unclear, but it seems that only the entire geological history explains Bothnian centers of Pleistocene glaciations, displacements of ice-divides in case of developed ice sheets, their usual outer shape, location of major topographic ice streams, uplift pattern with possible tectonic residuals and many other features. Vice versa, duration of the shape-control of ice margins by some first-order bedrock landscape elements (like marginal system of scarps and slopes) provides information about the marginal ice thickness, somewhat different for the classical ice flow law with the rate of shear strain being approximately proportional to the cube of the shear stress, without account of possible basal velocity and thermal variations. We believe that the Baltic Sea geological community is not uniform, so that Quaternary processes are not of only one priority, but overall geological and tectonic history, or at least elements with hidden but valuable impact on the recent development.

So, the aim of the present paper is to describe some geological, geomorphological and tectonic features of the Baltic Sea lowland that could be relevant for the history of glacial grows and decays, as well as linked processes of isostatic rebound and possible neotectonic movements. We also hope that such extensive overview would be helpful for scientists who deal with different geological problems of the Northern Europe, and that it provides additional information about the development of the region.

Geological structure and bedrock landforms. The present day shape of the Baltic Sea lowland is characterized by the marginal lowlands of the shield's slope united with negative forms of the Baltic Sea Proper and Southern Baltic, and by the central lowland represented by the linked basins of the Bothnian Bay and Sea (Fig. 1). So, in spite of numerous common geological features, large-scale negative forms mark zones of two different types: zone of slope of the shield combined with dominant platform depocenters; central zone of tectonic subsidence, isolated from the slope.

The zone of shield's slope runs from the Southern Baltic, Baltic Proper and Northern Baltic with the Gulf of Finland in the direction to the Lakes Ladoga and Onega and then to the White Sea. The saddle of the Åland arch. demarcates the slope from the inner zone of subsided platform strata, which includes the Bothnian Sea and Bay of the Gulf of Bothnia.

In general, marginal lowlands are typical features of slopes of the crystalline shields that underwent intensive multiphase preglacial Tertiary denudation with abundant role of selective Pleistocene glacial – fluvioglacial erosion, like the Baltic, Canadian and Anabar shields. Usually they are more extensive in the bedrock topography, being masked or complicated in the modern topography by the sporadic Pleistocene accumulation. Structural peculiarities and rock properties impacted the topographical factor and erosion variability.

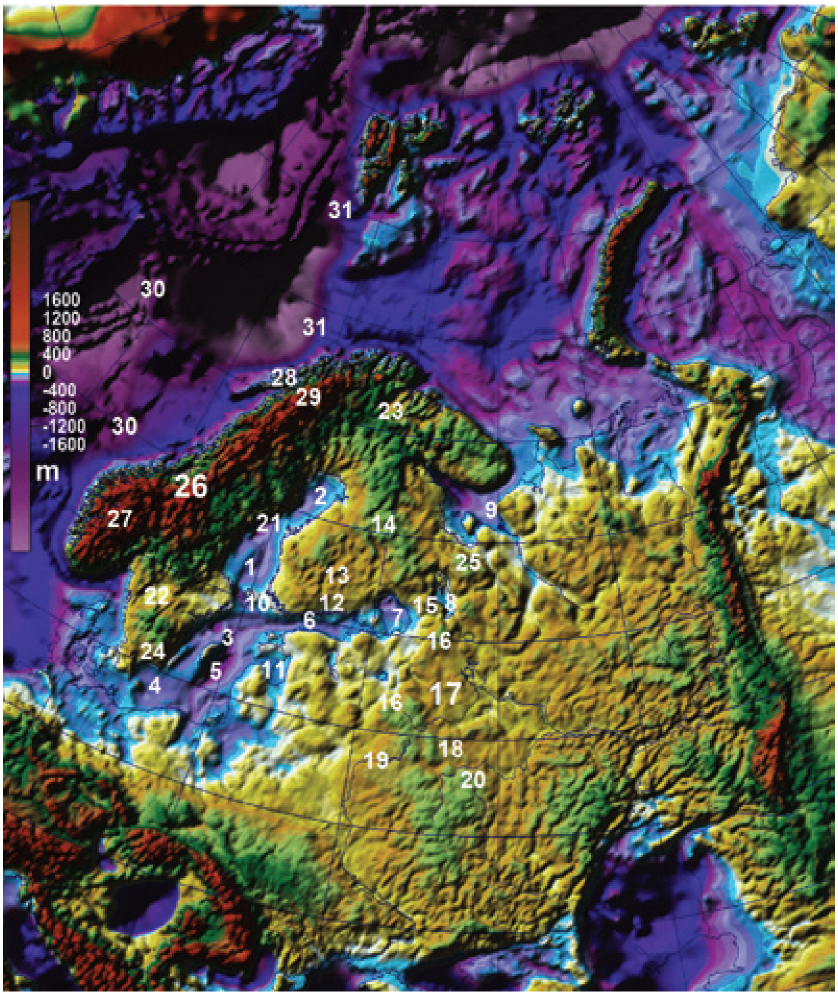


Fig. 1. Simplified map of the bedrock topography (base Pleistocene)

1 – Bothnian Sea, *2* – Bothnian Bay, *3* – Baltic Proper, *4* – Southern Baltic, *5* – Gothland deep, *6* – Gulf of Finland, *7* – Lake Ladoga, *8* – Lake Onega, *9* – White Sea, *10* – Åland archipelago, *11* – Riga bay, *12* – Southern Finland, *13* – Finnish Sea plateau, *14* – Maanselka-Western Karelic upland, *15* – Vepsian High, *16* – Carboniferous plateau, *17* – Russian plain, *18* – Moscow, *19* – Smolensk, *20* – Ryazan, *21* – Härnösand deep, *22* – Västergötland and Lake Vänern, *23* – Inarijärvi, *24* – Lake Mien, *25* – Vetreny Poyas; *26* – Norwegian mountains, *27* – South Scandinavian dome, *28* – Lofoten, *29* – North Scandinavian dome, *30* – Jan Mayen Fault Zone, *31* – Senja Fracture Zone

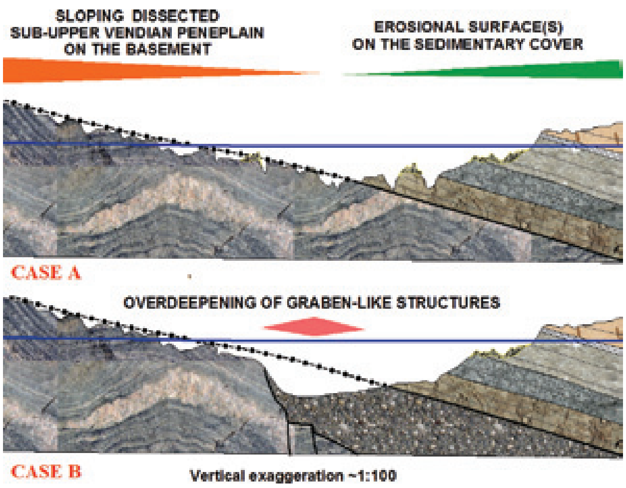


Fig. 2. Principal cross-sections of the subaqueous margin of the Baltic shield. The heterogeneous basement and Upper Vendian cover are separated by the SUV peneplain (thick solid line with skyline dash-dot continuation in exhumed part). In case B negative overdeepened Meso-Neoproterozoic structure is shown

Prominent inner basins occupied by world's largest lakes and seas, like the Baltic and White Seas, mark parts of the marginal lowlands, usually with the deepest parts in zones of the cropping out of the non-metamorphosed sediments that overlap older formations. Simply, the position and shape of all modern great inner basins is linked with the distribution pattern, either of proper sedimentary cover or of early platform deposits with properties more similar to the platform strata than to the metamorphic basement (Fig. 2).

Stratigraphic contact of the basement (or of the early platform units that fill graben-like structures) and the cover is represented by the distinct regional unconformity. This is the mature peneplain, which in the Baltic Sea region is called sub-Upper Vendian or sub-Cambrian depending on the age of the youngest platform sediments in particular areas. Principally it was formed during Vendian, prior to the Late Vendian deposition (in the following called SUV peneplain).

Slope of the Baltic Shield with neighboring sedimentary basins. As mentioned above, the super-regional lowland (called Baltic-White Sea marginal lowland) extends along the margin of the Baltic Shield, marking its boundary with the sedimentary cover (Fig. 1, 2). Formations of both Archean-Mesoproterozoic basement and Neoproterozoic-Cenozoic platform cover are distributed in this zone [1, 11, 30]. We assume that the slope of the shield is at its marginal zone with the Russian plate, so that it can be traced not only under the sedimentary cover, but also on the present exhumed part of the shield, where it has about the same dip. General geomorphic features of this zone are determined mainly by the exhumed SUV peneplain, gently sloping from under the platform cover and (at the opposite side) by the system of escarpments or slopes on the erosion-resistant strata of usually monocline platform deposits [1, 14]. These are commonly tilting gently in concordance with

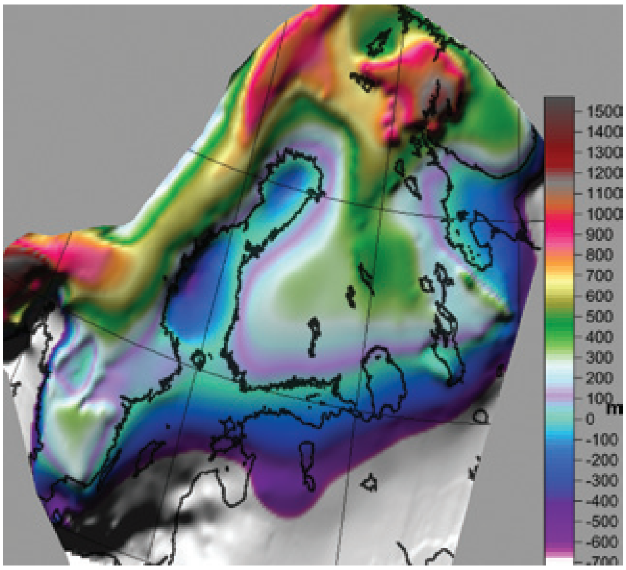


Fig. 3. Sketch map of the Sup-Upper Vendian peneplain with hypothetical skyline continuation in the area of the Baltic shield

the geological structure (Fig. 2). The deepest axis of the lowland generally either coheres with the line of truncation of sedimentary cover, or (more rare) exhibits the outcrop of terrigenous sedimentary unit less stable to denudation, or a combination of both.

Metamorphic and intrusive rocks of the crystalline Archaean-Proterozoic basement of the East-European platform comprise SUV peneplain under the platform cover, emerging from below it in the exhumed zone beneath Quaternary overburden. So far, this exhumed surface forms the shield's slope that represents one flange of the major lowland in the Gulf of Finland, Northern Baltic Proper, and offshore along the coast of Sweden (Fig. 3, 4). It is widespread onshore as well, where it usually has comparable angle of dipping as below the cover, however, somewhere deformed by faults. Continuation of the SUV peneplain can be reconstructed at the adjacent area of the shield by preserved fragments under sedimentary outliers. These are areas of distribution of neptunic dykes filled by sediments of basal formations and weathering crusts. At longer distance from the cover the skyline continuation of the peneplain could easily be reconstructed by tracing summit heights of the crystalline bedrock (Fig. 3). It normally determines macrorelief of adjacent areas, like in parts of Sweden and Southern Finland, up to about 150 m [37, 38, 52]. They also exist in a narrow strip along the front of the Caledonian (Norwegian) mountains and below the easternmost overthrust sheets [48, 49].

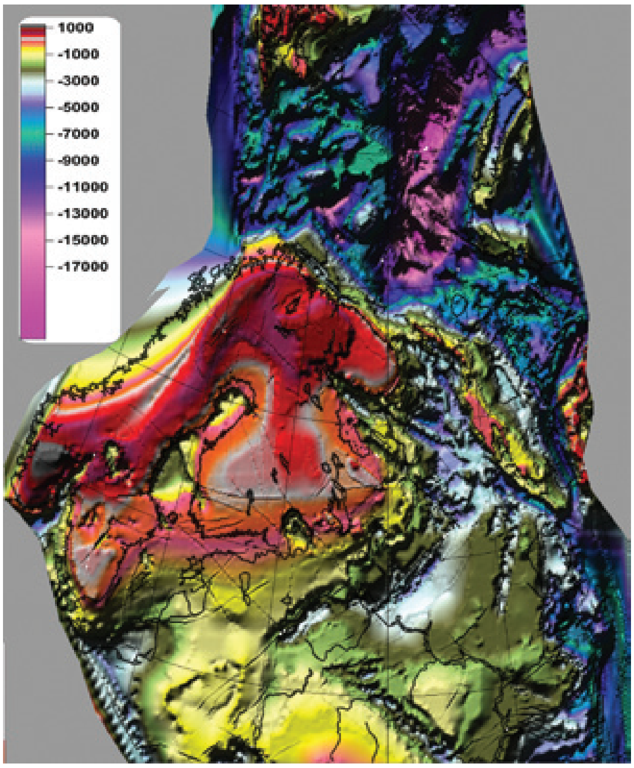


Fig. 4. Sketch map of the crystalline basement with hypothetical skyline continuation in the area of the Baltic shield. Compiled from numerous different sources and interpretations of potential fields in sedimentary basins

The heterogeneous basement usually consists of thick reworked Archean or Lower Proterozoic formations, with major folding and metamorphism at 1.9–1.8 Ga in the Svekokarelian orogenic event. Svekokarelian basement is penetrated by large Gothian intracratonic bimodal granite-gabbro-anorthozite intrusions (1.68–1.5 Ga), in some cases complicated by depressions formed by concomitant sedimentary and volcanic sequences, like in the Gulf of Finland. In spite of paleotectonic reconstructions of rapakivi intrusions (that is beyond the scope of current article), it seems that this particular stage has been driving further tectonic responses of the platform area. These belts of A-type granites and related rocks mark broad zones of extensional corridors that also responded in posterior geological history as broad gentle hinges. One of the relevant broad belt runs from the eastern Lake Ladoga coast to the Northern Baltic and Riga bay via the Gulf of Finland and adjacent onshore area, with continuation to the Southern Baltic. In the region of Åland archipelago it joins with the Bothnian rapakivi belt.

It would not be strong exaggeration to suggest that the above-mentioned belts were responsible for the pattern of the Baltic anteclise and later shield, as well as of the modern shape of the shield and the Baltic Sea lowland. However, we are here focusing on the supposed gentle hinge zones hundreds kilometers wide, and not linear sutures or megaflexures. At the early-platform tectono-thermal anomaly stage the emplacement of hot material preceded intensive landscape modification and further erosion. After the thermal field slowly normalizing the remaining compositional anomaly could possibly cause a tectonic response. Some Svekokarelian fault zones could control partial zonal remelting of the crust. It was probably relatively short time between the main Svekokarelian event and rapakivi emplacement; this is likely in agreement with the expected correspondent thermal crust-mantle anomaly. Moreover, the transcontinental variations in the mentioned granites are believed to be indicative of broad regional changes in the composition of the lower crust of Laurentia and Baltica [21]. Overall precursing Svekokarelian pattern is noticeable north of the Gulf of Finland around the giant Central Finnish Granite massif. Curvature of a major crust conductivity anomaly [35] around that massif is in agreement with the curvature of the exhumed SUV peneplain and the shoreline of the Gulf of Finland and eastern Bothnian Sea. This requires additional attention since even the low-angle sloping of the SUV landscape could in its case determine ice-age basal temperatures zonation with possible prolonged frozen ice bed conditions in the belt along the eastern Bothnian Sea during ice movement in eastern directions. Possible influence of lateral crust – mantle variations on the strength of the lithosphere and its instantaneous elastic response is disputable. We had not enough data to account possible variations in ice-age relevant isostatic modeling.

The next younger important generation of Meso-Neoproterozoic Riphean-Early Vendian structures completed the development of the heterogeneous basement in the interval 1.5–0.7 Ga, This happened under the influence of several Grenvillian-Sveconorwegian events and preceding creation the SUV peneplain. Such structures are usually infilled by unmetamorphosed sandstones, conglomerates, siltstones and claystones; effusive layers may occur in association with usual sill-and-dyke swarms of dolerite magma [1, 17, 59].

Different types of Riphean negative structures can be determined in this segment of the East-European platform [1]:

– marginal pericratons, like Mezenck-Barentsevomorsky trough which extends along the north-eastern margin of the craton. The description stays beyond the tasks of this paper;

– extensive linear aulacogens developed along major sutures or fault zones inside Archean – Proterozoic domains. The White Sea Riphean basin is the typical example of such structure, determining prominent features of the north-eastern flank of the Baltic-White Sea marginal lowland;

– Baltic type of less elongated negative structures that were formed mostly within Svecokarelian domain. They are often spacely related to the above mentioned rapakivi granite-gabbro-anorthozite intrusions of Gothian (Subiotnian) complex.

Subiotnian magma emplacement could potentially have caused rotational distortion at the margin, with wallrock asymmetric uplift and associated faulting. In addition, relatively slow cooling of large magma volumes could have caused changing body shape. Also, uplift and erosion of the country rock together with erosion of the magmatic rocks would cause significant isostatic movements. The combination of such processes finally shaped the Riphean basins of the Baltic type that exhibits negative structures comprised by thick sedimentary sequences from hundreds of meters to almost 2 km [1, 17]. There are, however, also indications of secondary erosional shape for some clay and claystone units that could have broad extent. Separation into several units likely happened in connection with Svekonorwegian orogeny, and the pattern of overall erosion seems to be influenced by gentle hinge zones. The Åland Sea, Landsort, Ladoga-Pasha and other basins belong to the Baltic type of negative structures. Why do we mention them in connection with the Quaternary development? It would not be strong exaggeration to say that major super-regional Riphean tectonic zones determined specific skeleton that took part in shaping of uplift – subsidence patterns in geological history, including Cenozoic and even the recent uplift. Also, they impacted landscape development as structural-denudational basins, even becoming common ice avenues during ice sheet development.

Such lowlands have prominent appearance in both the bedrock topography and modern landscape, with the shape approximately corresponding to the outline of negative structures. The most contrast lowlands of structural-denudative origin thus have been formed by Pleistocene glacial exhumation of fragments of negative structures comprised by sedimentary rocks that are relatively soft in comparison with surrounding crystalline frame [16, 18].

Usually Riphean sandstones were removed with evident deepening of the bedrock surface in comparison with surrounding crystalline frame. Some of these bedrock landforms in their deepest part often have typical profile and morphometric parameters of glacial cirques including headwall and lip. This gave possibility to separate family of giant glacial cirques of non-mountain areas [19]. In the deepest proximal part bedrock roof somewhere rests on troughs marks of at least 200–350 m.b.s.l., like in the horseshoe marginal overdeepening of the Landsort trench. "Critical depth" of deepening depends mainly on pliability of the rocks to glacial erosion, fracturing, on the angle of substratum beneath ice masses and in some cases their thickness. Main evidences of the erosional nature of such troughs come from the absence of relevant modern graben-like displacements along SUV peneplain on continuation of such landforms in the area of distribution of platform cover [1].

Platform sedimentary cover overlays heterogeneous Early Vendian to Riphean and older intrusive and metamorphic rocks. The cover has been formed under the major influence of events at craton's margins and development of major platform basins and structures, like first-order Mezen, Moscow or Baltic syneclises. Total thickness of the cover exceeds 3000 m in the Southern Baltic close to the main depocenters (Fig. 3, 4), while in other offshore areas it does not exceed hundred meters, but gradually increasing with distance from the shield. Reduction of the cover is due to obvious erosional truncation (Fig. 2), while major significant erosion stages completed the depositional cycles. Dislocations are seldom close to the shield, and according to shallow seismic profiling the displacements usually do not exceed 20–40 m [1]. Further south, like along the axial part of the Baltic syneclize, more extensive zones of faulting and folding, usually of Caledonian and Hercynian age, complicate the structural pattern. Most intensive sequence dislocations are well known in the suture zone of Teisseyre-Tornquist lineament along the margin of the East- and West-European platforms [56].

Main stages of the development of the East-European Platform (or complete cycles) started mainly in terrestrial conditions, then took turns by marine expansions with following stable marine deposition and were finished by significant erosion transformations, one of important for the Baltic region history was at the end of Caledonian cycle.

Major bedrock landscape elements both on the Fennoscandian Shield and the Russian plain usually reflects a mosaic of different older exhumed pre-Mesozoic surfaces (like the most distributed SUV peneplain) and younger wide (mostly) sub-horizontal plains [8, 16, 30, 38, 48, 51]. Their ages are often questioned because of rare sedimentary remnants and saprolites [13, 37, 55]. Some prominent tablelands were often interpreted as Middle Eocene-Oligocene, Paleocene-Eocene and (or) very Late Cretaceous-Paleocene levels, with Neogene (likely Miocene-Early Pliocene) age of the lowermost widely distributed surfaces. The Finnish Sea plateau or Lake Region Facet [52] at 100–160 m presumably represents the youngest widespread surface north of the Gulf of Finland that truncates exhumed and dissected tilted SUV peneplain. Equivalents of the sub-horizontal step-wise surfaces at the Russian Plain are widely distributed here on different levels [5] with sloping in southern directions and could be traced along the Maanselka

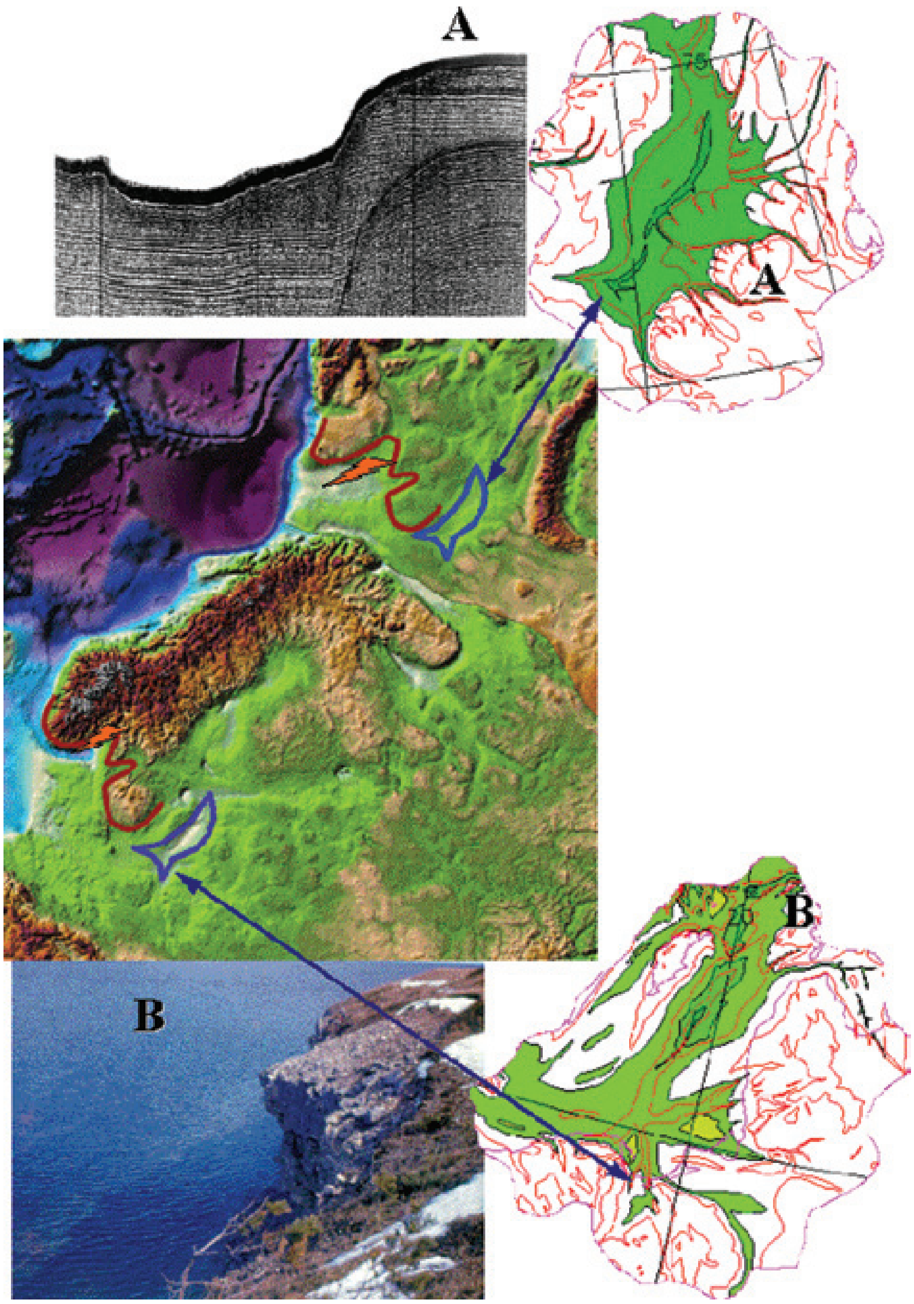


Fig. 5. Some features of semblance between the resulting glacial activity of the Fennoscandian and Barents ice sheet

Dark red line shows speculative allometric line of modern to weak erosion activity; orange arrow – major ocean terminating ice streams of the segment; blue outline – "blind ice stream" with intensive glacial-fluvioglacial activity. Bedrock topography of matching lowlands is zoomed in by inset maps linked by blue arrows. *A, B* on inset maps and photos show equivalent system of prominent scarps and slopes (*A* – shallow seismic profile of 120 m escarpment in Cretaceous, *B* – scarp in Paleozoic limestones, island of Western Estonia)

axial watershed area [16]. Cenozoic successions are well known in Byelorussia. Remnants of Oligocene-Lower Miocene marine clays were preserved in the Smolensk region at about summit heights of 145–200 m. Local Lower-Middle Miocene limnic sediments northeast of Moscow are preserved at the plain in 110–150 m range [8], while very rare remnants of marine saltwater (likely Upper Miocene) species at 130–150 m indicate ingression of the sea from the south at least up to the latitude of Ryazan. Other remnants, including Pliocene sediments and weathering crusts, allow prediction of preglacial surface in areas less affected by glacial erosion. However, in the direction of the shield, Tertiary levels have been dissected and worn down by denudation in the direction to the Baltic Sea.

Computer technologies enables tracing of gradual surface changes from non-glaciated areas to randomly glaciated belt and commonly glaciated area. Such method can predict deviating pattern of glacial erosion increasing progressively in the lowlands on pliable sediments and less prominent relief transformations of the highest and oldest surfaces [18]. This appears to be quite effective element of approximating differential erosional lowering of preglacial Pliocene surface.

At the beginning of the Pleistocene erosional stage on the Fennoscandian Shield and neighboring parts of the Russian Platform the relief was flat with widely distributed Tertiary tablelands. Paleowatershed area was determined by the Maanselka-Western Karelic upland with the continuation southeast at the west of the Lake Onega area via the Vepsian High and higher segments of the plateau, which consists of resistant Carboniferous carbonate rocks [16]. This relative upheaval could bear thicker permafrost on glacial expansion, with later stable cold-based conditions, resulting in very low erosion, as seen in distribution of elements of paleo-landscape and weathering crusts of different type [13]. Remnants of Akanvaara Eocene marine sediments [55] mark the same zone. Occurrences of Tertiary microfossils and saprolites [24, 55] do not limit the extent of the submarine area, especially because they coincide with the high altitude topographic watershed zone [16] in connection with the Baltic area. Tertiary marine expansions do not require specific tectonic movements, and could be connected with the much higher Early Eocene ocean level [33]. Even if it was of short duration, they were wide, covering significant parts of the modern shield and adjacent platform. Intensive destruction of accumulated formations during Miocene at 15–8 Ma was connected not only with tectonic deformations, but worldwide sea-level fall in the range of 56–185 m (average estimations are close to 80–90) [26, 31] with relevant deepening of the drainage channels.

Most prominent modification of the bedrock landforms was likely connected with Tertiary uplift and erosion [11, 47] with high input of glacial and fluvioglacial erosion of the Upper Vendian, Paleozoic and younger soft sedimentary formations [16, 18]. It deepened and reshaped continuous peripheral lowland that followed the line of truncation of the sedimentary cover. Selective denudation of the monocline strata also formed paired system of inferior "inner" subparallel lowlands along the outcrops of terrigenous sedimentary units less stable to denudation. However, during some stages they were able to guide peripheral topographic ice streams and grow in outsized landforms in auspicious conditions. Gotland deep could serve a sample for the Baltic Sea, exhibiting major "blind lowland" of fast-flowing stream, but without well-developed ocean termination. Such landforms seem to be common in peripheral areas of large-scale ice sheets developed on sedimentary domains (Fig. 5). They are associated with large amount of adjacent deep tunnel valleys, preferably engraving deep into the pliable sediments of the distal slope of the lowland. Part of them dies out on the resistant limestone units that guide frontier scarps. In the same way tunnel valleys are widely distributed aside the peripheral lowland. We have here focused on the major landform arrangement of the slope of the shield and the neighboring sedimentary basins because it seems to impact the shape of the ice sheet over time, for example giving reduced ice thickness on slippery sediments.

Bothnian central zone of tectonic subsidence. The lowland of the Gulf of Bothnia is separated from the Baltic–White Sea marginal lowland by the Åland saddle. Many features of general geology, like character of the basement and cover, are comparable with the slope of the Baltic Shield. Bothnian lowland, marked by extensive Riphean basins, comprises mainly of sedimentary rocks overlain by the Upper Vendian-Cambrian-Ordovician succession [22, 58, 59]. The rock types have similar properties as sequences distributed along the Baltic–White Sea margin (slope) of the Fennoscandian Shield. Prominent differences are the depressed position of the sub-Cambrian (or sub-Late Vendian) peneplain, with two isolated tectonically induced basins of the Bothnian Sea and Bothnian Bay. The Cambrian-Ordovician strata of the Gulf of Bothnia have fragments of continuous platform area, which, because of the subsided position, survived periods of erosion.

The Bothnian lowland roughly matches both the shape of the center of last glaciation and the maximum postglacial uplift. More precisely, the long-lived western Bothnian hinge zone along the Swedish coast was the uplift axis. Also, it is the first-order zone of tilting the landscape elements of the overall slope in the direction to the uplift centers along the Atlantic slope (Fig. 8, *A*), also well known for its seismicity [41]. This could be related to isostatic uplift, however, the seismicity is not evenly distributed around the Bothnian Sea and Bothnian Bay, but more concentrated along the western Bothnian hinge zone.

Such coincidence of the central depression with extensive sedimentary basins and ancient tectonic zones is attractive geological peculiarity that is typical for many other glaciated areas, like the Hudson Bay sedimentary basin of the North America as well [2].

As mentioned above the additional Bothnian rapakivi belt marks possible broad hinge zone along the Swedish coast of the Bothnian Sea, and corresponds to the prominent modern bend of the topographic surface. In spite of sparse data, this seems to be important also in the determination of the shape of Riphean basin, at least for the Bothnian Sea. The extensional zone of Gothian age roughly follows the shape of the modern coastal area. It possibly controlled large rapakivi intrusions together with conjugated northwestern zones. Large rapakivi pluton likely follows the northeast Bothnian Sea coastline (at least to Örnsköldsvik) accompanied by rapakivi massifs like Strömsbro, Sundsvall and Nordringå [39].

General northwestern direction of main structural design step faults (which one can follow in Satakunta, Aranda and Evle grabens) in the posterior Riphean sequence is combined with major northeastern one, parallel to the trend of the Caledonian belt and possibly reactivated due to its development. Extensional Riphean belt continues southwest of the Bothnian Sea, where it is exhibited by the direction of Tuna dykes with the possible age about 1.45 Ga [50]. Numerous kimberlite-like dykes of alnoites, silicocarbonates and beforsites dated 1.15 Ga occur in the Kalix and Lulee archipelagos and on the adjacent mainland of the NW Bothnian Bay, as well as alkaline intrusive bodies at 0.55–0.575 Ga [36], which is in agreement with the supposed long-lived changes of the deep structure.

Parallel or sub-parallel reflectors with stable seismic signature of rather uniform dip at the seismic profiles across the Riphean sequence of the northern part of the Bothnian Sea [22] may indicate wider primary sedimentation of some Mezo-Neoproterozoic units, with significant erosion at the end of Late Riphean and in the Early Vendian. Since Late Vendian several tectonic episodes influenced the Bothnian basins during the platform development, but Caledonian event seems to be the most important. Probably at that time compressional stress, bending and subordinate faulting deformations, forcefully revived old structural elements. As a result, chain of foreland depressions occurred, from Västergötland to Bothnian Sea–Bothnian Bay and Inarijärvi. It is elongated in the northeastern direction with axis close to the Lake Vänern shore, being traceable now in the skyline topography of the exhumed sub-Cambrian peneplain (Fig. 4), often with preserved outliers of the sedimentary cover. This cover has been more widespread in Cenozoic like circular depression around lake Mien, with indications of a Cambrian cover over Mien at the time of impact in the Early Tertiary [37]. Complete separation of the Paleozoic outliers of the central basin in the area of the Åland saddle could be caused by glaciations [2]. In addition, there seems to be a tendency of spatial migration of ice domain centers to the pre-glacial depressions with sedimentary bedrock. This migration could be mostly controlled by the preglacial landscape, maybe caused by reducing heat flow into the sedimentary basins, or increased compaction of the sediments due to the ice sheet load, water exchange with major sedimentary aquifers, or possible tectonism.

The preservation of Cambrian and more erosion-resistant Ordovician sediments at the northwestern steepest flank of the major syncline, and wide outcrops of carbonate mounds [22, 59] caused erosion variation and thus changing topography of the bedrock surface [16, 18]. Major overdeepening of the bedrock surface took place offshore along the Swedish coast with intensive plucking of the Riphean sediments and culmination at the Härnösand deep. Temporary ice streams seem to have produced "blind lowland" to the southeast, but less developed than the Gotlands one (Fig. 5).

Modeling. The observed post-glacial uplift in the Baltic area is the result of various processes, the most important being the glacio-isostatic movements. But hydroisostasy and redistribution of sediments as erosion and accumulation are important contributors to the uplift history. One task of our preliminary high-resolution modeling (with the grid density of 10 km) was to examine previously established lithosphere and mantle rheology.

Ice thickness. Automated modeling accounts for general concentric pattern of ice sheets, fast-flow ice stream erosion, time changes at glacial grow and decay, topographic factors, different ice-bed conditions, geology converted to erodability parameter, fault-and-fracture zones, precipitation and many other factors [34, 40]. Our rather simple automated estimations of the ice thickness consist of (Fig. 6):

– preliminary initial assessment of an oversimplified general ice-sheet sketch with averaged typical values and forms known to be associated with modern ice-sheets in agreement with Glen-Nue flow-law, using approximate glacier mass-balance and separate volume control at the growing and decay stages and reasonable variable long-term balance ratio between ablation gradient and accumulation gradient. Prediction is performed at this stage with input of compilations of outlines of the ice sheets with 1000 years interval in the case of last 20 000 years. Different precipitation scenarios could also be involved at this stage. However, spatial-temporal reconstruction of past accumulation rates is known to be a huge challenge in ice-sheet simulations [40];

– detalisation of ice-thickness distribution from a given subglacial topography;

– further zonal corrections of ice thickness due to reapproximations of possible ice-streams (determined at previous stage) with variable stress at the base and small basal drag, variable substratum of ice-sheets in time and space due to sedimentation and erosion, areas of different termination, heat flow, etc.

Ice sheets and caps are known to develop similar [4], possibly according to laws of viscoplastic or elasto-visco-plastic flow with known principles and mechanics [12, 42, 44, 45, 53, 57]. Low-exponent flow law models under low-stress differs from the more classic approach, and was introduced as a gateway for construction of the relatively thin model of the Laurentide ice sheet [45].

For our modeling the starting point is a simplified variant of general shallow-ice approximation model combined (in the case of Arctic shelf glaciations) with shallow-shelf approximation [46]. This model includes parameters for basal resistance (Fig. 6, *A*). History of ice nucleation with isostatic adjustments is accounted for. Analysis of present ice thickness in Greenland and Antarctic was performed using ETOPO1 global relief model of the Earth's surface and ice base compilation [15]. Mathematical fit of ice thickness variations was taken from numerous regular slices for calibration of the model. Preliminary grid at the first stage is generated via sets of prospected ice isopachytes setting the general shape of marginal slope and thickness of the central part. Analysis of the age (t) of the ice sheet outline with (t+1) and (t–1) outlines is used for corrections of ice mass-balance, which involve the trend of development of general growing or decay with expected different friction due to varying basal parameters.

Analysis of shape of outline is performed in addition to set expected ice lobes and preliminary ice streams if they are recorded as outstanding external tongues or arcs bowed outside in respect to separating zones bowed in reversed direction. 'Voronoi' diagrams and other methods are involved at this stage to forecast distribution of ice velocity at the surface of the ice sheets (Fig. 6, *B*).

Resulting simplified preliminary ice-sheet sketches undergo further improvement and corrections as described below. Used approximations fit well when averaged bottom topography is applied. Lowlands are also analyzed to extract topographic ice-streams with increasing search window and median difference filtering, adjusting relevant features to them. Several substages with different search window are required for increasing the result quality (Fig. 6, *C, D*). Domains of low basal velocity and possible long-term frozen base are distinguished by using input of higher resolution grids, like upstream slopes with isometric landforms, tor regions (with relatively isometric elevation standing above the surrounding area with resolute summit area, steep slopes and local relief of first hundreds meters), etc. Topographic ice streams are accounted as regions with variable properties [44].

We adjust zonal corrections due to basal slipperiness variations, accumulation – wastage balance of continental versus oceanic segments, slope gradient in sufficient cases, etc. (Fig. 6, *E*). Special correction grids of e.g. bedrock type are applied. Rock types of the glacier base and their changes over time are accounted for, like areas with cover of interglacial soft sediments. Such corrections are disputable, but could be of significance because of increasing basal velocities over time. The ice sheet could thus be significantly thinner where deformable sediments (Fig. 6, *F*) underlay the ice.

In spite of very gentle uphill slopes and linked occasional escarpments with relatively low height (often less than 30 m), many of them significantly reduced the speed of ice expansion. The majority of them even served as natural barriers, strongly controlling the shape of last glacial maximum. An example is the escarpment on the resistant Carboniferous limestones bounding

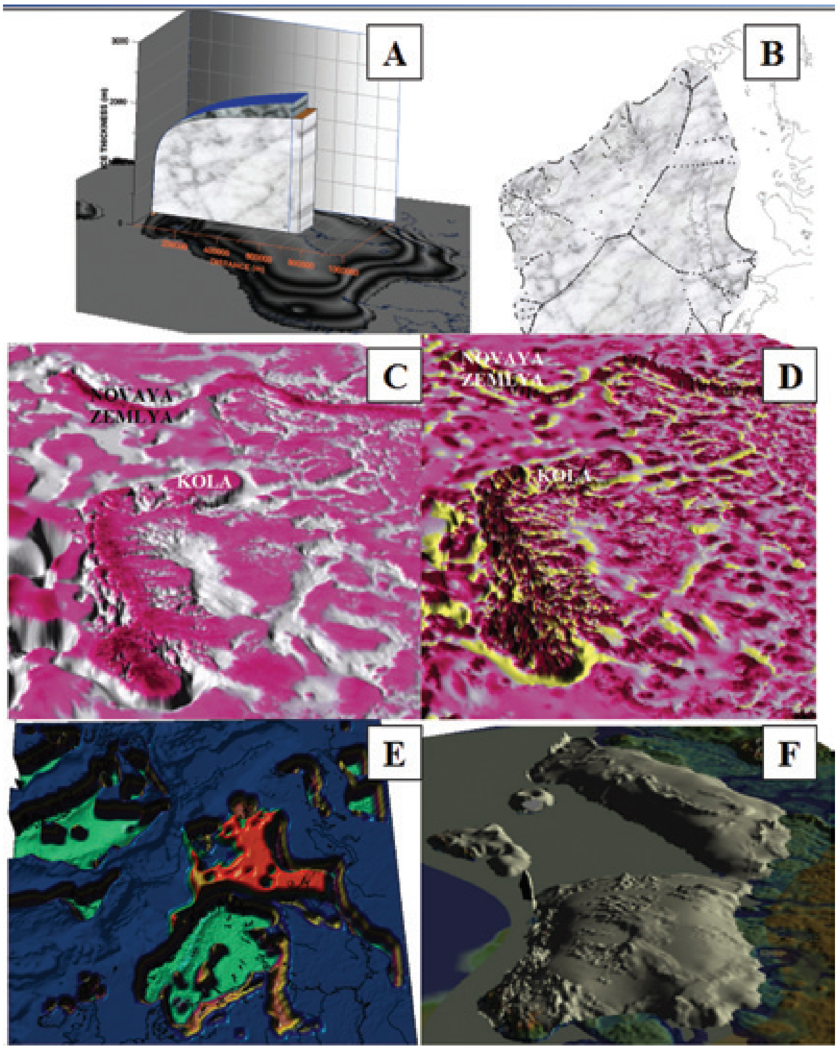
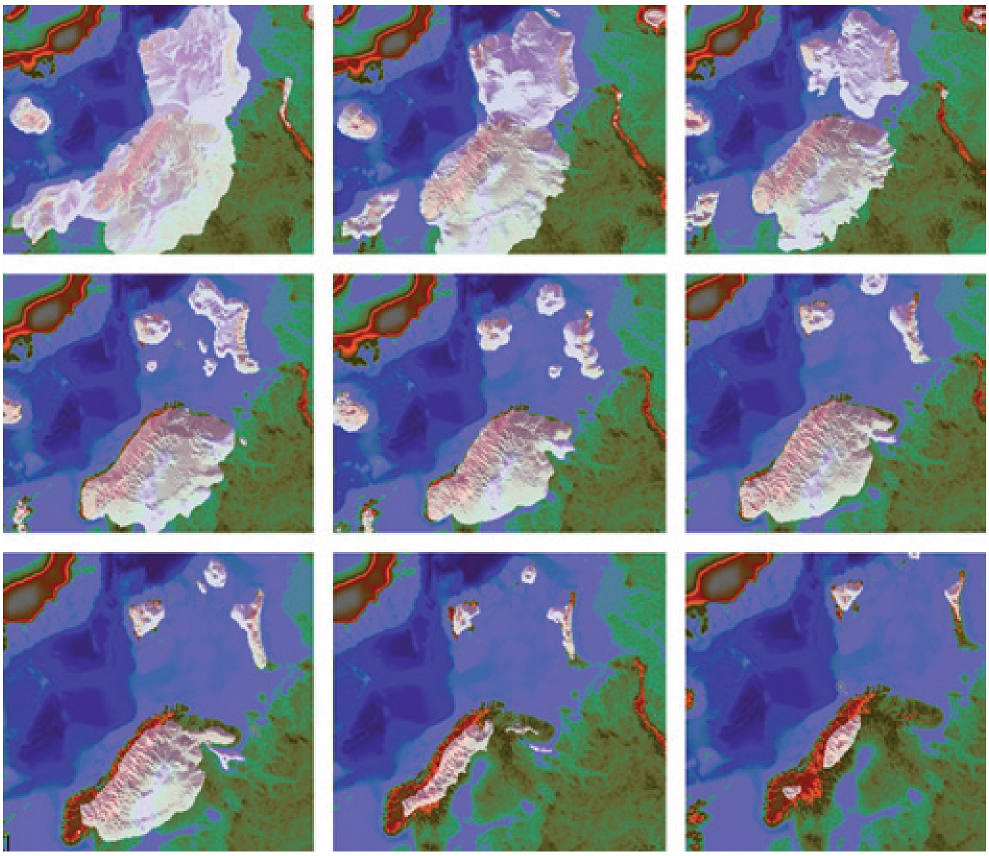


Fig. 6. Samples of ice thickness module procedures

A – starting ice approximation using the flow-law; *B* – Voronoi tessellation in estimation of surface velocities pattern; *C, D* – landscape analysis with separation of landscape elements of different order; *E* – variable bedrock properties; *F* – final ice thickness model

Fig. 7. North Atlantic ice sheets decay scenario in cal. years BP compiled from numerous sources

Upper row 17 000 (left) – 15 000, middle row 14 000 – 12 000, lower row 11 000 – 9 000



Carboniferous plateau. Ice advance of that age seems to be controlled by the frontal parts of the slopes, and only 2–3 000 years later ice was able to cross the barrier separating high and lower-middle steps of the Russian plain (Fig. 8, *A*). This seems to be hardly possible in classic flow-law model without ice-sedimentary rocks interaction.

Lowest-level slopes and scarps of the Baltic Sea that determine comparable, but more subsided landscape along the margin of the platform cover were likely among factors controlling the ice sheet shape at 13 800–14 200 years ago (Fig. 8, *B*). Other bedrock features, like large isolated highs including the ones in the metamorphic domain (Vepsian High, Vetreny Poyas), played a significant role at that time. The final ice sheet deglaciation used in the calculations is shown in Fig. 7. The shape of the ice sheets versus geomorphology is shown in Fig. 8.

Hydro-isostasy. Four main postglacial stages are usually recognized in the history of the Baltic basin between a freshwater lake and a brackish water basin connected to the outside ocean by narrow straits [54]. The hydro-isostasy depends on the palaeo relief, because the extent of the area covered by water has not been constant through time. In addition changes in eustatic sea level over time have to be taken into account; we use the well-known ocean level curve from R. Fairbanks (1989), and geoidal-eustatic changes induced by the deglaciation are important component [27]. The palaeo relief is a function of the isostatic response. In addition to the palaeo relief, the area covered with water (ocean or lake) also depends on the extent of glacier. Fig. 9 shows the spatial distribution of water used in the water load calculations.

Sediment redistribution. Plio-Pleistocene erosion and sedimentation could significantly impact the postglacial uplift. For modeling purpose we determine the changes in surface load caused by glacial and postglacial erosion and sedimentation over 1000 years intervals. This is done by utilizing a largely automated interpretation of regional geological and geomorphological observations that is constrained by plausible bounds on the rate of erosion of various lithologies and the known general pattern and behavior of glacial ice (ice boundaries over time, the dendritic pattern of ice movement, geometry of fast-flowing ice streams, plausible changes in frozen-bed conditions, etc.) [18]. Mass-balance between erosion and deposition is taken care of at all times, including also remaining eroded material in the ice body.

The first glaciations likely dominated the shaping of the major bedrock landforms, although it is possible that in some areas the deepening was distributed evenly over all the cycles. Younger glaciations mainly removed sediments left by their predecessors and accumulated during interglaciations, locally incising and changing the dip of the bedrock surface. The degree of lowering of the surface in zones of repeated erosion strongly depends on scenarios of interglacial sedimentation.

Knowledge of bedrock topography, measure of its overdeepenings and its lowering from reconstructions of older relief facets serve as important validation steps in determination of the erosion magnitude. However, it cannot be used for deciding on erosional rates without account the history of intermediate deposition. In many cases glacially shaped topography, with elongated basins alternating with conformal ridges and riegels produced multiple local depocenters for interglacial (postglacial) sedimentation. For such areas a pendulum could illustrate erosion and posterior sedimentation, when the nature "masked its wounds". Local zones of deep erosion appeared as zones of profound sedimentation with maximum rates immediately after glacial retreat, but roles reversed again at the next advance. For example, strongly increased thickness of recent postglacial sediments on reduced Quaternary section represented by the latest tills may in many cases indicate zones of preceding intensive erosion of comparable amount.

Late Pleistocene – Holocene uncompacted sediments that were accumulated after glacial retreat, like the varved clays, were approximated in time-slices by separate automation module (Fig. 10). Numerous local overdeepenings of the resulting heterogeneous late-glacial surface were shifted into correspondent local depocenters with relatively rapid accumulation after glacial retreat. As a result, a thick (tens meters over wide areas) veneer of sediments was deposited. Huge landslides at the continental slope, like Storegga slide [32], impacted rebound isobases locally.

In erosion zones exhibited by lowlands and overdeepenings the rebound effect of sediment redistribution and of the hydro-isostasy could often be linked, complicating resulting pattern in time. The post-glacial accumulation used in the calculations of sediment isostasy is shown in Fig. 11.

Uplift residuals and tectonic component. The dome-like uplift of Fennoscandia is usually regarded to exhibit glacial isostasy. Opinions about simple pattern of uplift of the region as a single dome prevail. M rner [43] suggested that the Fennoscandian uplift consists of two main components; one exponential, due to glacio-isostasy, and one linear related to the tectonism. Some argue that the effect of deglaciation may have been dominated by an exponential, glacio-isostatic rise, which died out a few thousands years ago, while an approximately linear uplift centered in the middle of Fennoscandian Shield may still be active. Ideas of interplay of tectonics and isostasy are popular [10], when isostatic rebound is not assumed as the main or exclusive cause of uplift [6, 9]. Several scientists have developed ideas about the major role of active neotectonic faults and, thus, dominating the mosaic block pattern of the uplift [3, 7, 9], but conception of domal isostatic uplift with subordinate tectonic component and local rare fault complications appears to be more solid. Connection of recently active fault zones, flexure bends and different hinge lines with Phanerozoic or older structural plan is relevant in this discussion. Global consistency of the ancient geotectonic frameworks with patterns of glacial nucleation and isostatic motions seems to be noticeable and important for understanding the essence of processes.

If assuming the total crust movements as a joint result of the isostatic component and the tectonic factor, it looks important to separate them. The only one possible way we know is forecasting the rate of the modern isostatic uplift from high-resolution models and its comparison with the observed uplift to get tectonic residuals from extraction [29]. Definitely, there are many uncertainties in the models, and the observed rate of uplift is estimated slightly different. To get less model-dependable residuals we tried different ice-sheet models and scenarios, filtering unstable model-dependant deviations.

The Earth's response to glaciers, water change and sediments has been modeled by using a layered viscous model overlain by an elastic lithosphere [23]; more details on the modeling technique cf. [28, 29]. The asthenosphere has a thickness less than 150 km and viscosity

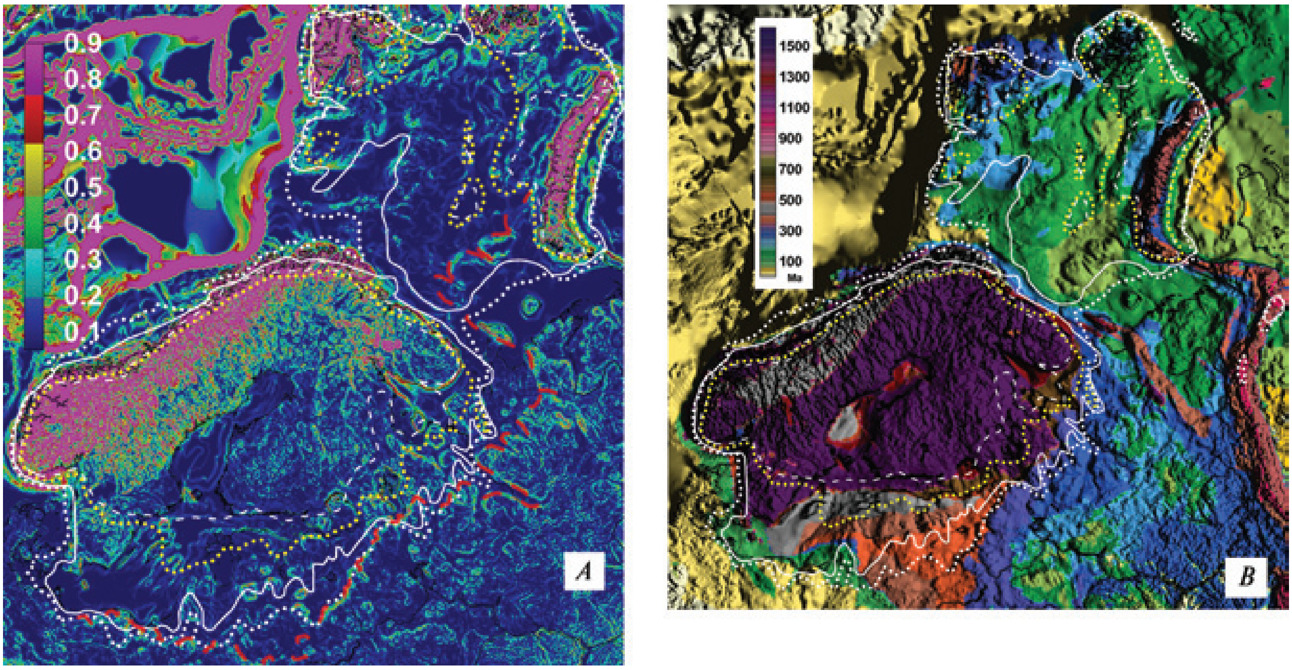


Fig. 8. Shapes of ice sheets and geological – geomorphological features

A – Filtered slopes of the bedrock topography in the range 0.2–1 degree. Red dash line marks the largest system of auto-determined slopes and escarpments (i. e. Carboniferous escarpment), separating high and lower-middle steps of the Russian plain and neighboring areas; *B* – simplified geological map in the isotopic age grid form (Ma) compiled from numerous sources in overlay with the bedrock topography.

Approximate outlines of the last ice sheet compiled from different sources (cal. years ago) at: 13000 (white dash), 14000 (yellow dot), 15000 (white line), 15800 (white dot) are shown on both maps

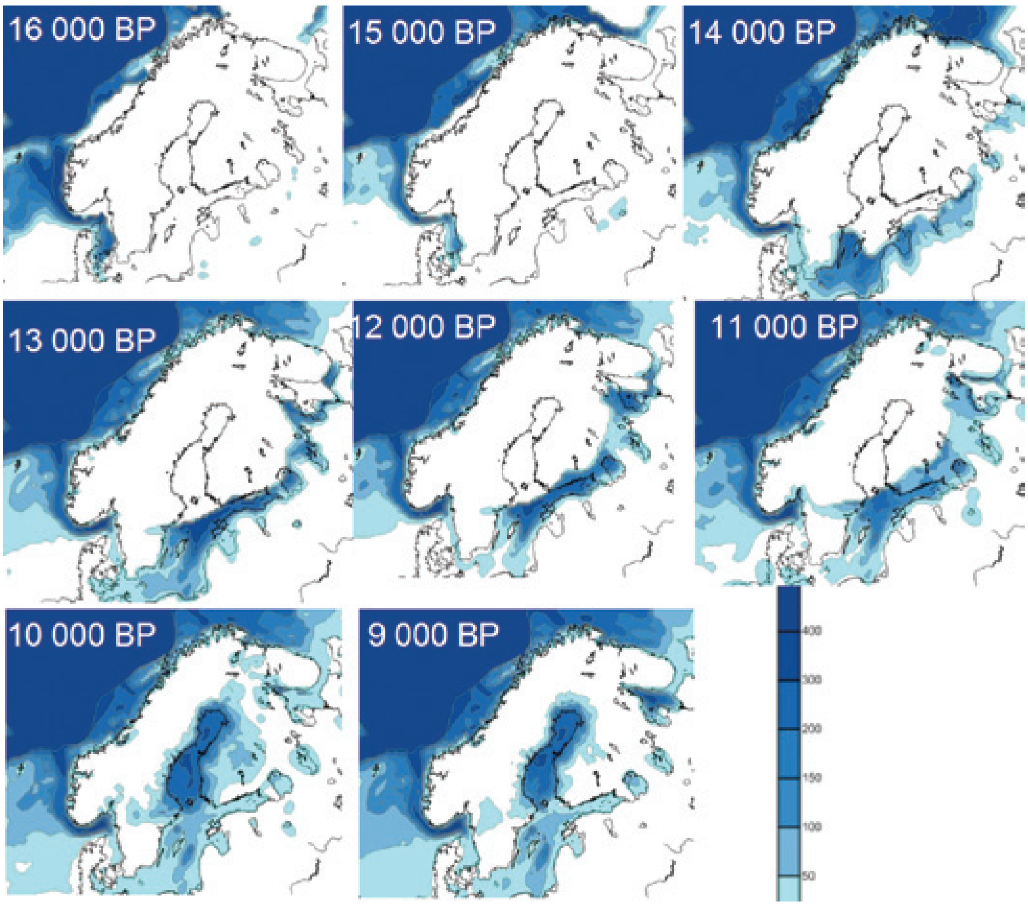


Fig. 9. Sea level changes scenario in cal. years BP from the modeling

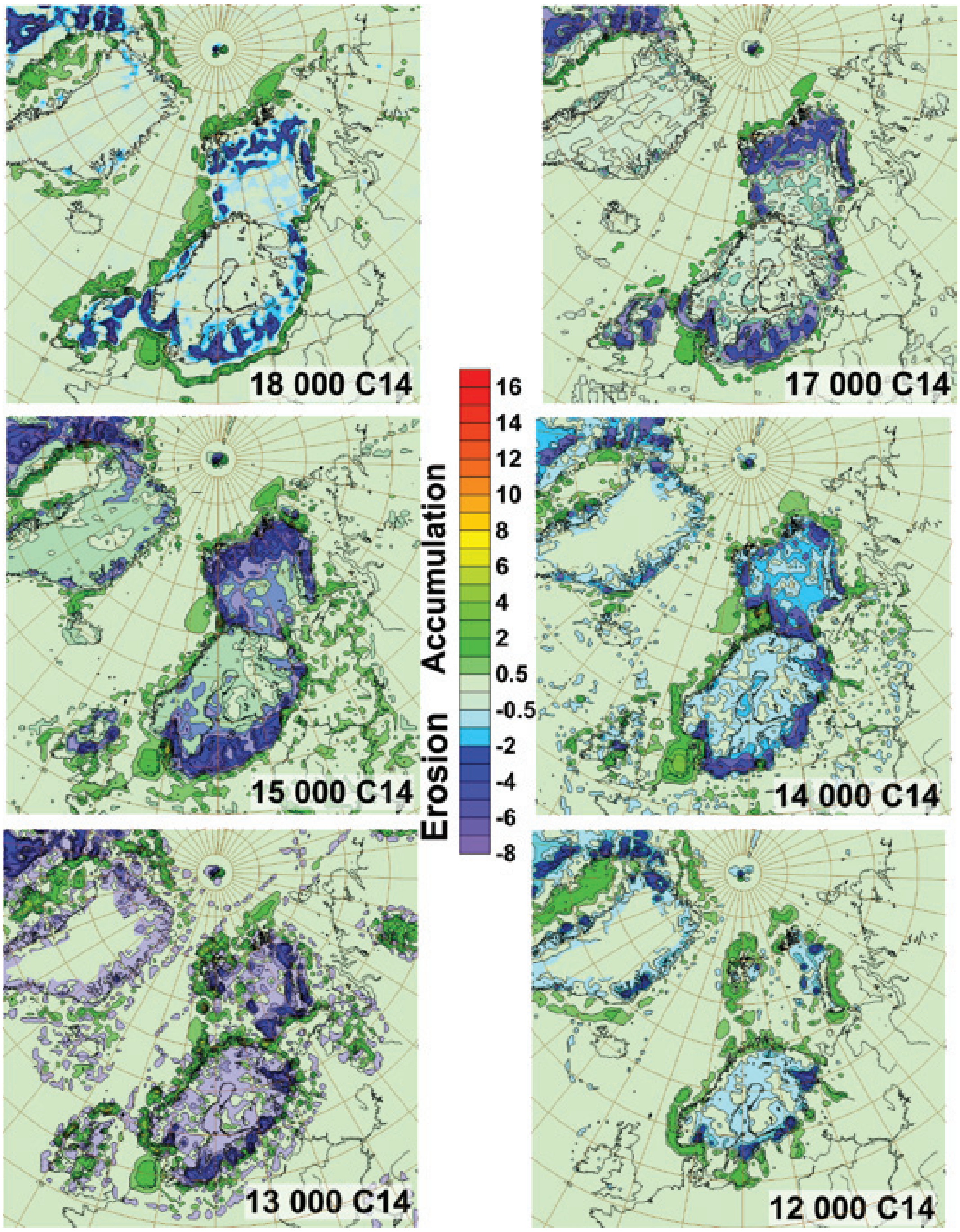


Fig. 10. Sample time slices of erosion – accumulation approximations involved in overall isostatic rebound modeling

less than $7.0 \cdot 10^{19}$ Pa/s beneath the lithosphere [29]. The mantle viscosity below the asthenosphere was estimated to 10^{21} Pa/s, and the flexural rigidity to 10^{23} Nm (effective elastic thickness of 20–40 km).

The modeling is now done with much higher resolution than has previously been done; the spatial resolution is now 10 km and 1000-year time intervals. The resulting calculated present rate of uplift (Fig. 12) confirms above rheology model.

In spite of the close fit between observed and calculated present rate of uplift, two positive residuals seem to occur: of the South Scandinavian dome and the northern one (NSD and SSD) with adjacent Lofoten area. They exhibit distinct highlands also in the summit height topography of Norwegian mountains, often considered to be indicative of the Base Tertiary Surface [25, 47]. The coastal mountain uplift pattern seems to be also in agreement with the possible Paleozoic post-Caledonian uplift axis, which we assume comparable to the axis of the skyline reconstruction of the SUV peneplain. However, uplift axis and centers are displaced westwards closer to Atlantic margin. The major role of a varying stress regime, associated with North Atlantic plate reorganization and Tethyan closure events, was considered the most likely mechanism in the warping of the Scandinavian Base Tertiary Surface by A. G. Doré, who suggested that the initial topography allowed the continental ice sheets to nucleate, with consequent erosion and isostatic elevation [25].

Discussion of possible uplift mechanisms of NSD and SSD is outside the purpose of this paper, but we would like to point out its possible connection with the ocean

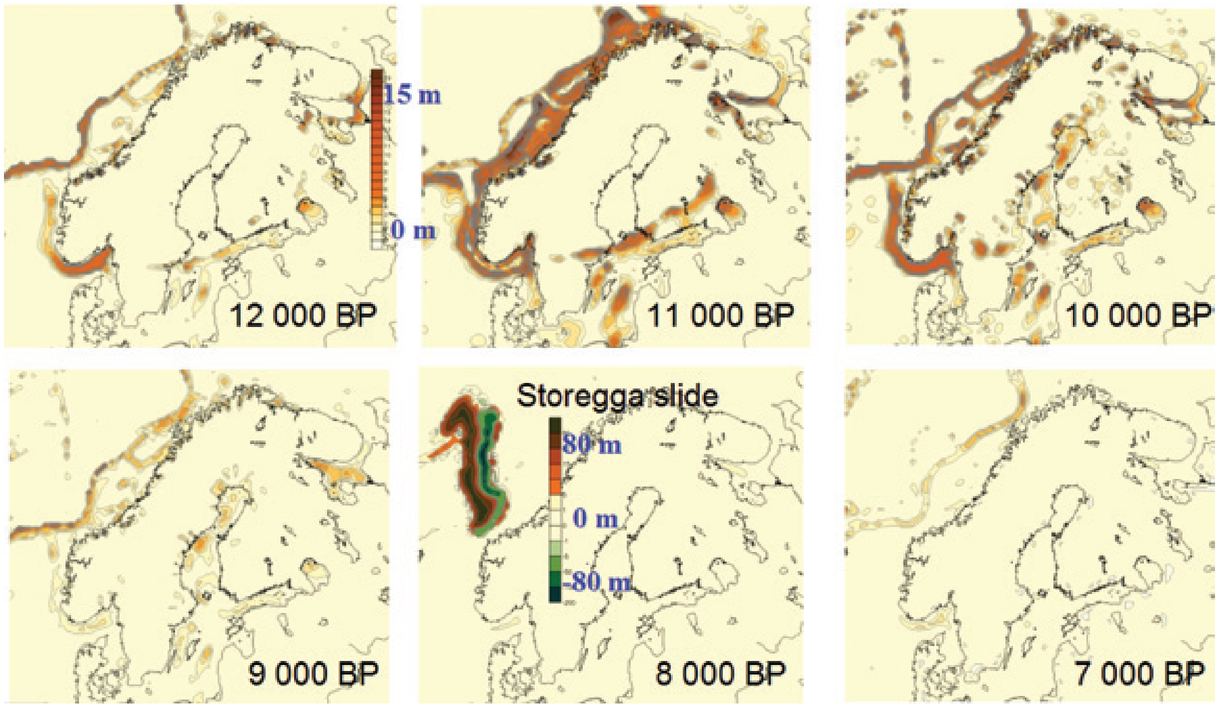


Fig. 11. Sample time slices of post-glacial accumulation approximations involved in overall isostatic rebound modeling (cal. years BP). Storegga slide is simplified after Haflidason et al. [32]

evolution, with special focus on the first-order leaky transform fault zones mirrored in contrasting spreading configurations of the North Atlantic oceanic domain. In addition to deviations in stress pattern, possibly they control variations in temperature field, heterogeneity of the asthenosphere, and varying fertility [20]. Jan Mayen Fault Zone (JMFZ) could be of major importance in the case of the SSD, while Senja Fracture Zone could impact the NSD and Lofoten area.

SSD has its equivalent on the opposite side of Atlantic, in Eastern Greenland. Caledonian belts precursed both East Greenland and Norwegian mountain ranges. Highest mountains above 3500 m are known south of Scoresby Sund. However, if to assume melting of the present ice sheet, and to account uplift due to heavy erosion of the coastal areas with implication to reconstruction of Tertiary surfaces, than the major ("anomalous") uplift of the East Greenland mountain range (orogen) would be displaced further north to the now-a-day zone of highest sub-ice mountain plateau.

Conclusion. Linked geological, geomorphological and tectonic features of the Baltic Sea lowland and adjacent areas strongly impacted the history of glacial grows and decays, while the bedrock landscape seems to be the major linking and controlling factor. First-order landforms could in favorable conditions control both center of ice nucleation, and serve as natural barriers shaping its margin. However, the landscape was also strongly modified by the glaciations. This effect varied over time and space, in some periods could create prominent samples of strong glacial erosion, in its case controlled by the lithological and structural factors.

Baltic Sea lowland exhibits part of the super-regional structural-denudation form that was created with dominant role of Tertiary multiphase preglacial erosion and strong selective Pleistocene glacial-fluvioglacial denudation that mostly affected the Meso-Neoproterozoic early platform basins and soft post-Late Vendian sedimentary cover. Central sedimentary basins and relevant ancient hinge zones (like the Western Bothnian zone) could be an important integral part of overall Ice-age pattern, including the shape of post-glacial uplift and seismicity.

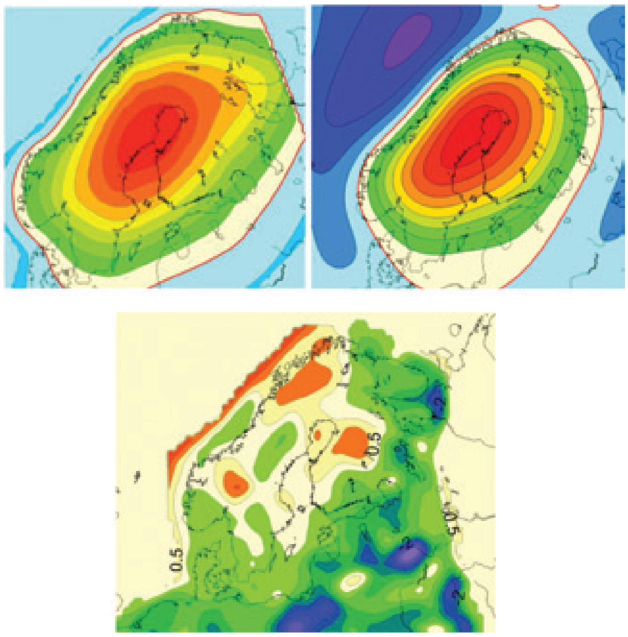


Fig. 12. Observed (upper left) and calculated (upper right) present rate of uplift in Fennoscandia (contour interval 1 mm/yr). The difference between the calculate and observed uplift is shown in lower part of the figure

Glacial erosion and sedimentation significantly impacted the total glacial rebound, but the pattern and rates of glacial erosion were strongly variable in time and space. More distinct radial pattern at the early stage with selective exhumation of relatively resistant formations caused developing stable topographic ice-streams in favorable zones at later stages.

The observed post-glacial uplift in the Baltic area is the result of various processes, the most important being the glacio-isostatic movements. High resolution modeling including glacial isostasy, hydro isostasy, sediment isostasy confirms earlier rheology model [28] of asthenosphere with a thickness less than 150 km and viscosity less than $7.0 \cdot 10^{19}$ Pa/s, mantle viscosity beneath the asthenosphere with viscosity 10^{21} Pa/s, flexural rigidity of the lithosphere of $5 \cdot 10^{23}$ Nm (effective elastic thickness of 30-40 km).

Significant residuals in the present rate of uplift of the northern and southern Scandes Domes could be related to the major Jan Mayen Fault Zone and Senja Fracture Zone and explained by viscosity variations caused by mantle temperatures, different fertility or other factors.

We would like to thank professor Larry Cathles for inspiring and fruitful discussions, and Marina Amantova for digitizing work.

1. *Амантов А.В.* Геологическое строение осадочного чехла бассейнов северо-запада России // Осадочный покров гляциального шельфа северо-западных морей России. – СПб., 1992. – С. 25–47. (*Amantov A.* Geological structure of the sedimentary cover of the basins in Northwestern Russia // Sedimentary cover of the glacial shelves of the Northwestern seas of Russia. St. Petersburg, 1992. P. 25–47, in Russian).

2. *Амантов А.В., Воронов П.С.* О возрасте и генезисе современных фигур Балтийского и Канадского щитов // Регион. геология и металлогения. 1993. № 1 – С. 77–86. (*Amantov A., Voronov P.* On the age and genesis of modern figures of the Baltic and Canadian Shields // Regional Geology and Metallogeny. 1993. N 1. P. 77–86, in Russian).

3. *Бискэ Г.С.* О природе послеледникового поднятия Балтийского щита // Изв. Всесоюзн. геогр. общества. – Л., 1970. № 1. – С. 37–38. (The nature of the post-glacial uplift of the Baltic Shield // Izvestya Geographitcheskogo Obshestva. Leningrad, 1970. N 1. P. 37–38, in Russian).

4. *Воронов П.С.* Методика составления карт палеокриоизогипс и палеоизотерм Арктики и Антарктиды для эпохи максимального четвертичного оледенения // Докл. на ежегодных чтениях памяти Л.С. Берга. XIII–XIV. – М.: Наука, 1968. – С. 81–93. (*Voronov P.* Methods of compilations of paleokrioisogyps and paleoisotherms for Arctic and Antarctic in Quaternary Ice Maximum epoch // Annual L.S. Berg Memories. VIII–XIV. Leningrad: Science, 1968. P. 81–92, in Russian).

5. *Исаченков В.А.* Дочетвертичные поверхности выравнивания северо-запада Восточно-Европейской равнины // Изв. АН ЭССР. Геол. 32. 3. 1983. – С. 118–122. (*Isatchenkov V.* Pre-Quaternary surfaces of leveling of the Northwest of the East European plain // Izv. AN ESSR. Geology. 1983. Vol. 32. No. 3. P. 118–122, in Russian).

6. *Кошечкин Б.И.* Голоценовая тектоника восточной части Балтийского щита. – Л.: Недра, 1979. – 158 с. (*Koschechkin B.* Holocene tectonics of the Eastern Baltic Shield. – Leningrad: Nedra, 1979. 158 p., in Russian).

7. Лукашов А.Д. Новейшая тектоника Карелии. – Л.: Наука, 1976. – 109 с. (*Lukashov A.D.* The latest tectonic of Karelia region. – Leningrad: Nauka, 1976. 109 p., in Russian).

8. *Можаев Б.Н.* Новейшая тектоника Северо-Запада Русской равнины. – М.; Л.: Недра, 1973. – 232 с. (*Mozhaev B.* Recent tectonic of the northwestern part of the Russian plain. – Leningrad: Nedra, 1973. 232 p., in Russian).

9. *Николаев Н.И., Бабак В.И., Медянцев А.И.* Вопросы неотектоники Балтийского щита и норвежских каледонид // Сов. геология. 1967. № 3. – С. 3–22. (*Nikolaev N.I., Babak V.I., Medyantsev A.I.* Problems of neotectonic of the Baltic Shield and Norwegian Caledonides // Soviet Geology. 1967. N 3. P. 3–22, in Russian).

10. *Никонов А.А.* Проблемы неотектоники северо-восточной части Балтийского щита // Тектонические движения и новейшие структуры земной коры / Под ред. Н.И. Николаева. – М.: Наука, 1967. – С. 191–198. (*Nikonov A.A.* Problems of neotectonics of the northeastern part of the Baltic Shield // Tectonic movements and latest structures of the earth crust / N.I. Nikolaev (ed.). – Moscow: Nauka, 1967. P. 191–198, in Russian).

11. *Пуура В.А.* К проблемам кайнозойской тектоники и формирования речной сети в Балтоскандии // Палеотектоника Прибалтики и Белоруссии: Материалы VIII сов. по тектонике Белоруссии и Прибалтики / А.В. Раукас (ред.). – Таллин, 1980. – С. 77–81. (*Puura V.* On the problems of Cenozoic tectonics and development of the drainage in Baltoscandia // Paleotectonic of the Pribaltica and Belorussia / Est. Acad. of Sci. – Tallinn, 1980. P. 77–81, in Russian).

12. *Рыбак О.О.* Математические модели континентальных ледниковых щитов // Криосфера Земли. 2008. Т. XII. № 1. – С. 12–23. (*Rybak O.* Mathematical models of the continental ice sheets. A comparative description // Kryosphere of Earth. 2008. Vol. XII. N 1. P. 12–21, in Russian)

13. *Стрелков С.А., Евзеров В.Я., Кошечкин Б.И.* и др. История формирования рельефа и рыхлых отложений северо-восточной части Балтийского щита. – Л.: Наука, 1976. – 164 с. (Strelkov S., Evzerov V., Kotschechkin B. et al. History of the relief and unconsolidated sediments of the north-eastern part of the Baltic Shield. Leningrad: Nauka, 1976. 164 p., in Russian).

14. *Таваст Э., Раукас А.* Рельеф коренных пород Эстонии. – Таллин: Изд-во Валгус, 1982. – 196 с. (*Tavast, E. & Raukas, A.* The bedrock relief of Estonia. Tallinn: Valgus, 1982. 196 p., in Russian).

15. *Amante C. & Eakins B.W.* ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis / National Geophysical Data Center, NESDIS, NOAA, U.S. Department of Commerce. 2009. 25 p. (http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/docs/ETOPO1.pdf).

16. *Amantov A.* Plio-Pleistocene Erosion of Fennoscandia and its Implication for the Baltic Area // PPIG CXLIX. Warszawa. Proceedings of the Third Marine Geological Conference "The Baltic", 1995. P. 47–56.

17. *Amantov A., Sederberg P., Hagenfeldt S.* The Mesoproterozoic to Lower Palaeozoic sedimentary bedrock sequence in the Northern Baltic Proper, Aland Sea, Gulf of Finland and Lake Ladoga // Prace Panstwow. Inst. Geol. CXLIX, Warsaw, 1995. P. 19–25.

18. *Amantov A., Fjeldskaar W., Cathles L.M.* Glacial erosion of the Baltic Sea region, and the effect on the post-glacial uplift // Harff, J., Björck, S. and Hoth, P. (eds). The Baltic Sea Basin. Springer. 2011. P. 53–75.

19. *Amantov A., Amantova M.* Giant glacial cirques of non-mountainous terrains // EGU General Assembly Geophysical Research Abstracts. Vol. 14. EGU2012-1751-1, 2012 (http://meetingorganizer.copernicus.org/EGU2012/EGU2012-1751-1.pdf; http://adsabs.harvard.edu/abs/2012EGUGA..14.1751A).

20. *Anderson Don L.* Speculations on the nature and cause of mantle heterogeneity // Tectonophysics. 416 (1-4), 2006. 7–22.

21. *Anderson J.L., Morrison J.* Ilmenite, magnetite, and peraluminous Mesoproterozoic anorogenic granites of Laurentia and Baltica // Lithos. Vol. 80, 2005. 45–60.

22. *Axberg S.* Seismic stratigraphy and bedrock geology of the Bothnian sea, Northern Baltic // Stockholms Contributions in Geology. Vol. XXXVI: 3, 1980. 153–213.

23. *Cathles L.M.*, 1975. The viscosity of the earth's mantle. Princeton University Press, Princeton, New Jersey, 1–386.

24. *Cleve-Euler A.* Die Diatomeen von Schweden und Finland // IV. Kungl. sven. Vetensk.-Akad. Hand., 4. Ser., 5. 1955. 232.

25. *Doré A.G.* The base Tertiary surface of southern Norway and the northern North Sea // Nor. Geol. Tidsskr. 72, 1992. 259–265.

26. *Eberli G.P., Anselmetti F.S., Isern A.R., Delius H.* Timing of sea-level changes and currents along Miocene platforms on the Marion Plateau // W.A. Morgan, A.D. George, P.M. Harris, J.A. Kupecz, and J.F. Sarg (eds.). Cenozoic Carbonate Systems of Australasia: Society for Sedimentary Geology, Special Publication 95, 2010. 219–242.

27. *Fjeldskaar W.* Geoidal-eustatic changes induced by the deglaciation of Fennoscandia // Quaternary International, 9, 1991. 1–6.

28. *Fjeldskaar W., Cathles L.* The present rate of uplift of Fennoscandia implies a low-viscosity asthenosphere // Terra Nova, 3, 1991. 393–400.

29. *Fjeldskaar W., Lindholm C., Dehls J.F., Fjeldskaar I.* Post-glacial uplift, neotectonics and seismicity in Fennoscandia // Quaternary Science Review. Vol. 19, 2000. 1413–1422.

30. *Floden T.* Seismic stratigraphy and bedrock geology of the Central Baltic // Stockholm Contrib. Geol. Vol. 35. 1980. 240 p.

31. *Isern A.R., Anselmetti F.S., Blum P.* Constraining Miocene sea level change from carbonate platform evolution, Marion Plateau, Northeast Australia, Sites 1192–1199 // Proceedings of the Ocean Drilling Program, Initial Reports. Vol. 194, 2002. 1–88.

32. *Haflidason H., Sejrup H.P., Nygård A.* et al. The Storegga Slide: architecture, geometry and slide development // Marine Geology. 213. 2004. 201–234.

33. *Haq B.U., Hardenbol J., Vail P.R.* Chronology of fluctuating sea levels since the Triassic (250 million years ago to present) // Science. 235. 1987. 1156–1167.

34. *Heimbach P., Bugnion V.* Greenland ice-sheet volume sensitivity to basal, surface and initial conditions derived from an adjoint model // Annals of Glaciology. 50(52). 2009. 67–80.

35. *Korja T.* et al. Crustal conductivity in Fennoscandia – a compilation of a database on crustal conductance in the Fennoscandian Shield / Korja T., Engels M., Zhamaletdinov A.A., Kovtun A.A., Palshin N.A., Smirnov M.Y., Tokarov A.D., Asming V.E., Vanyan L.L., Vardaniants I.L., and the BEAR Working Group // Earth Planets Space. 54. 2002. 535–558.

36. *Kresten P., Printzlau I., Rex D.* et al. New ages of carbonatite and alkaline ultramafic rocks from Sweden and Finland // Geol. Foren. Stockh. Forh. 99, 1977. 62–65.

37. *Lidmar-Bergström K.* Regional analysis of erosion surfaces in southern Sweden // Fennia 163(2). 1985. 341–346.

38. *Lidmar-Bergström K.* Long term morphotectonic evolution in Sweden // Geomorphology 16: special issue on Palaeoweathering. 1996. 33–59.

39. *Magnusson N.H.* et al. 1958. Karta över Sveriges berggrund. Karta i 3 blad. 1:1 mil / N.H. Magnusson, P. Thorslund, F. Brotzen, B. Asklund, O. Kulling, G. Kautsky, J. Eklund, W. Larsson, P.H. Lundegårdh, S. Hjelmqvist, S. Gavelin, O. Ödman.

40. *Marshall S.J., Pollard D., Hostetler S., Clark. P.U.* Coupling ice-sheet and climate models for simulation of former ice sheets // A.R. Gillespie, S.C. Porter and B.F. Atwater (eds.). The Quaternary Period in the United States. Developments in Quaternary Science. Vol. 1. Elsevier Publ., 2004. 105–126.

41. *Mäntyniemi P.* A Tale of Two Earthquakes in the Gulf of Bothnia, Northern Europe in the 1880's. // Geophysica. 41(1-2). 2005. 73–91.

42. *Montagnat M., Duval P.* The viscoplastic behavior of ice in polar ice sheets: experimental results and modeling // Physique. 5. 2004. 699–708.

43. *Mörner N.-A.* The Fennoscandian uplift and Late Cenozoic geodynamics: geological evidence // Geojournal. 3.3. 1979. 287–318.

44. *Pattyn F.* A new three-dimensional higher-order thermomechanical ice sheet model: basic sensitivity, ice stream development, and ice flow across subglacial lakes // J. Geophys. Res., 108, 2003. 1–15.

45. *Peltier W.R., Goldsby D.L., Kohlstedt D.L., Tarasov L.* Ice-age ice-sheet rheology: Constraints from the Last Glacial Maximum form of the Laurentide ice sheet // Annals of Glaciology. 30. 2000. 163–176.

46. *Pollard D., DeConto R.M.* Modeling West Antarctic ice sheet growth and collapse through the past five million years // Nature. 458. 2009. 329–332.

47. *Riis F.* Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data // Global and Planetary Change. 12. 1996. 331–357.

48. *Rudberg S.* Vasterbottens berggrundsmorfologi // Geographica. 25. 1954. 457 p.

49. *Rudberg S.* The sub-Cambrian peneplain in Sweden and its slope gradient // Z. Geomorphol. Suppl. Band 9. 1970. 157–167.

50. *Söderlund U.* U-Pb baddeleyite ages of Meso- and Neoproterozoic dykes and sills in central Fennoscandia: A review // E. Hanski, S. Mertanen, T. Rämo and J. Vuollo (eds.). Dyke Swarms – Time Markers of Crustal Evolution. Proceedings of IDC-5. Taylor & Francis Group, 2006. 75–84.

51. *Soderman G.* Planation and weathering in eastern Fennoscandia // Fennia 163. 2. 1985. 347–352.

52. *Tanner V.* Die Oberflachengestaltung Finlands. Bidrag till kannedomen af Finlands natur och folk. Utg. Finska Vetenskaps-Soc. 86. 1938. 762 p.

53. *Tarasov L., Peltier W.R.* Laurentide ice sheet aspect ratio in models based on Glen's flow law // Ann. Glaciol. 30. 2000. 177–186.

54. *Tikkanen M., Oksanen J.* Late Weichselian and Holocene shore displacement history of the Baltic Sea in Finland // Fennia. 180. 1–2. 2002. 9–20.

55. *Tunni R.* The reflection of geological evolution in Tertiary and interglacial diatoms and silicoflagellates in Finnish Lapland // Geological Survey of Finland. Bull. 320. 1982. 40.

56. *Ziegler P.A.* Geological atlas of Western and Central Europe. Shell Internationale Petroleum Maatschappij BV. – Amsterdam, 1990. 240.

57. *Zweck C., Huybrechts P.* Modeling of the northern hemisphere ice sheets during the last glacial cycle and glaciological sensitivity // J. Geophys. Res. 110. D07103. doi: 10.1029/2004JD005489. 2005. 1–24.

58. *Wannäs K.O.* Seismic stratigraphy and tectonic development of the Upper Proterozoic to Lower Paleozoic of the Bothnian Bay, Baltic Sea // Stockholm Contrib. Geol. 40 (3). 1989. 83–168.

59. *Winterhalter B.* On the geology of the Bothnian Sea, an epeiric sea that has undergone Pleistocene glaciation // Geol. Surv. Finland. Bull. 258. 1972. 66.

Амантов Алексей Владиславович (Alexey Amantov) – канд. геол.-минер. наук, вед. науч. сотрудник, ВСЕГЕИ (Lead. scientist, Ph. D., VSEGEI, SPb). <uazam@mail.ru>.

Вилли Фьелдскаар (Willy Fjeldskaar) – гл. науч. сотрудник, исслед. компания Тектонор, Норвегия, профессор, Ун-т Ставангера (Head. scientist, professor UIS, Ph. D., Tectonor, Norway). <wf@tectonor.com>.