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RESEARCH OF THE BEDROCK GEOLOGY OF THE CENTRAL BALTIC SEA

Algimantas Grigelis

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Abstract Knowledge of bedrock geology of the Central Baltic Sea (CBS) developed gradually in the last decades of the 20th century. In this period, a deep seismic survey, tectonic analysis ranging over an internal structure of entrails and followed hydrocarbon prospective drilling was performed in the eastern segment of CBS. The geological systems have been subdivided into series and regional stages. At the same time marine expeditions made key point to recent sedimentation and geodynamic processes. After the 1990s international and EU-supported geological–geophysical projects were successfully performed in many aspects of the Baltic marine geology. These data enlightened the Baltic Sea history, development, present status and were used as a basis for 1:500 000 or 1:200 000, versus 1:50 000, mapping.

The paper aims to present a historical viewpoint to enlighten the methodology and innovations and to evaluate the exploration of bedrock geology of the CBS as is reflected on existing regional geological maps.

Keywords *Bedrock geology, Phanerozoic stratigraphy, Central Baltic Sea.*

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INTRODUCTION

The bedrock structure of the Baltic Sea in general could be divided into three sections: the northern – composed of Proterozoic [pre–Cambrian] crystalline rocks; the central – made up of broad age scale Phanerozoic sedimentary rocks lying on the Proterozoic basement; and the south–western – built by Phanerozoic sedimentary rocks of different ages folded and metamorphosed during the Alpine tectonic cycle. The border of the central and south–western segments of the Baltic Sea—the Fennoscandian Border Zone and Danish Embayment, respectively—is marked by sub–global tectonic Tornquist–Teysseyre–Sorgenfrei lineament (Fig. 1).

Knowledge of the bedrock geology of the Central Baltic Sea (further — CBS) came gradually in the last decades of the 20th century. The first general data were set up tracing boundaries of the geological systems from adjacent East and West Baltic land areas to the sea bedrock. Geophysical surveys were started in the 1970ies by using 'sparker' methods but were rather imprecise. New continuous seismic reflection profiling using single channel 'air–gun' method appeared in the mid 1970ies. The Central Baltic area was shot during several marine expeditions but little penetration was achieved.

In this period, a deep seismic survey and tectonic analysis ranging over an internal structure of entrails and followed by hydrocarbon prospective drilling were performed in the eastern segment of the CBS. Careful studies of drilling cores using mainly micro-palaeontological methods allowed the exploration of the pre–Quaternary stratigraphic sequence. The geological systems have been subdivided into series and—in best cases—to stages. A tentative correlation of the Cambrian–Ordovician–Silurian regional stages through the Central Baltic area between Estonia and Gotland was also made.

Based on report made at the 10th Baltic Marine Geology Conference held in St. Petersburg, 24–27 August 2010.

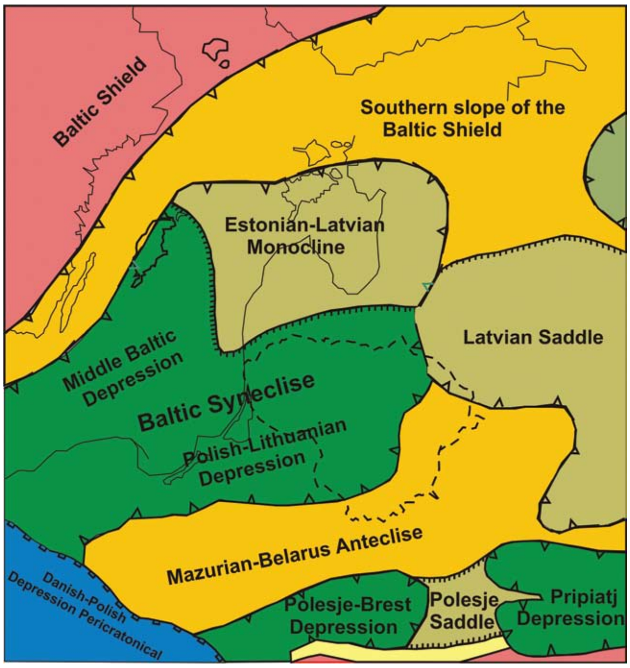

Fig. 1. The tectonic setting of the Baltic region; after P. Suveizdis, 2003.

At the same time, active marine expeditions started (mainly by Soviet vessels, with the SEV programme *"World Ocean"),* making key contributions to the understanding of recent sedimentation and geodynamic processes. After the 1990s, bilateral, multilateral, and EU supported geological–geophysical projects were performed, that essentially completed many aspects of Baltic marine geology.

These data significantly enlightened the Baltic Sea history, development, and present status and were used as a basis for 1:500 000 or 1:200 000 versus 1:50 000 mapping. As a result, tens of geological maps have been compiled and published by extrapolating from the local sea territories to the whole Northern European sea and land area extensions.[1]

The first Marine Geological Colloquium THE BALTIC, held at Parainen near Turku, Finland, on May 27–29, 1987, under Honorary Chairman Professor Heikki Ignatius (1914–2006) and Secretary General Boris Winterhalter, created a valuable beginning for Baltic marine geology cooperation. Growing interests in the sea as a basin of the Late Quaternary (Late Glacial—Holocene—present day) sediments, and also as a place of the recent sea water for millions of people surround the sea, stimulated comparative studies of geological history, palaeogeography, bottom topography, and depositional environment; in particular, its development through the last centuries and decades. Historical events, such as the beginning of extensive agriculture (in the 18th century), the expansion of port constructions (in the 19th century), and the enormous increase of sea transport (in the 20th century), and at least potentially risky marine industry projects in the 21st century, e. g., hydrocarbon exploration, oil and gas terminals, pipelines gas transport, and cable communication, strongly affected the ecological and recreational conditions of the sea. This last decade is marked by the possibly accelerated sea level rise within the context of the postulated Earth climate changes.

HISTORICAL SETTING

Always it is difficult to say who was the first player at the scene in some field of science. This is true also for the bedrock geology of the Central Baltic Sea. Looking through hundreds of publications, two periods of the CBS bedrock geology survey can be distinguished in general.

The first period is characterized by different schemes that appeared showing the distribution of the rocks only in the frame of geological systems; no more detailed data from land areas were used because of a lack of confidence in the rock age correlation. One of the first such schemes, surprisingly, was published by the Quaternary geologist and geographer V. Gudelis in 1970 (Fig. 2). So, in the 1970ies, the data of the CBS bedrock geology began to be compiled, yet in general ways.

During the next decade, in 1970–1980, the detailed continuous seismic profiling (CSP) was performed in

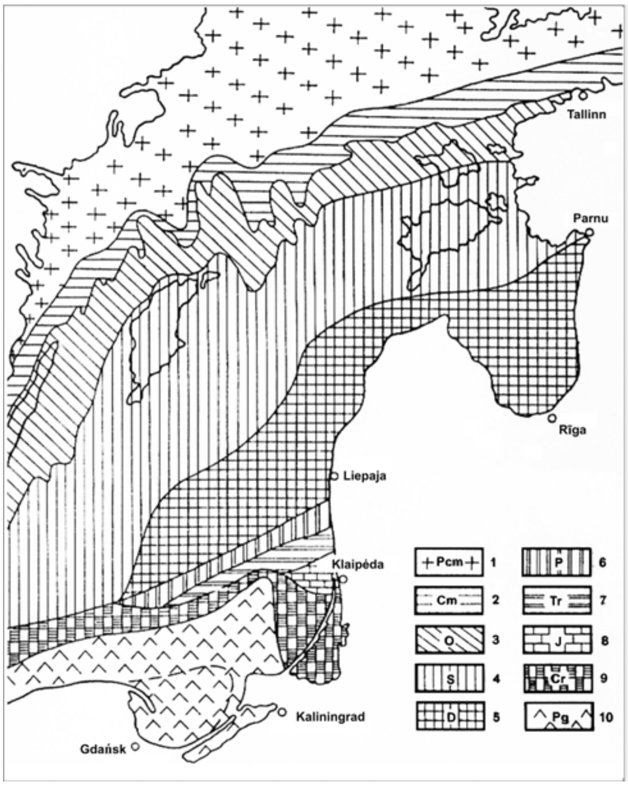

Fig. 2. Geological scheme of pre–Quaternary rocks of the Central Baltic Sea; after V. Gudelis, 1968. Pcm – pre–Cambrian; Cm – Cambrian; O – Ordovician; S – Silurian; D – Devonian; P – Permian; Tr – Triassic; J – Jurassic; Cr –Cretaceous; Pg – Paleogene.

1 **Geological map (*sensu stricto*)** — graphic document showing distribution of rocks and their uniform (identical) age based on the principles of faunal succession (superposition law; Smith 1799), and on the principles of modern stratigraphy.

the south–eastern Baltic (sleeve exploders, Nikolai Sviridov, Vladimir Litvin, Kaliningrad), in the Baltic Proper (air guns, Tom Flodén, Michael Kumpas), the Bornholm Gate (Kjell Wannäs), the Bothnian Sea (Stefan Axberg; all Stockholm). It should be noted, they went not so far as to interpret possible subdivisions of geological systems, but the boundaries of the systems were traced a little better (Flodén 1980). On the other hand, geophysical data development resulted in sound material for comprehensive tectonic analysis, and basic tectonic schemes were completed (Flodén 1982, 1984; Kumpas 1982; Sviridov 1984).

The end of this period is marked by an innovative publication of Ivar Hessland (1914–2006) outlining a completely new task—the geological mapping of the Baltic seabed to be considered as a unit *"that requires cooperation between all the Baltic States"* (Hessland 1988). Besides, it should be noted that the earliest idea about the complex geological mapping of the Baltic seabed was jointly presented by Kaliningrad and Vilnius scientists (Kharin, Sviridov, Grigelis, Repečka 1982) at the IV All–Union Shelf Seas Conference held in Vladivostok but the conference abstracts were not available for foreign scientists, and the presentation was left unpublished. Later, in 1987, the same authors reported about the methods for the geological mapping of the Baltic seabed at the All–Union Symposium held in Moscow at the Institute of Oceanology of the Academy of Sciences of USSR. Thereby, a necessity began to come in full view. In addition, in this period several rather broad compilations on the geology of the Baltic Sea, increasing the knowledge of its history and recent development, were issued thanks to the high level of productivity of scientists both from the eastern side as well as the western side of the sea (Dadlez 1976; Gudelis, Emelyanov, eds 1976; Gudelis, Koenigsson, eds 1979; Martinsson 1974; Voipio, ed. 1981; Winterhalter, ed. 1988; Grigelis, ed. 1991).

One remarkable note clearly defined by Hessland (one year before the USSR collapsed) should be mentioned. Until the end of 1982, when the International Law of the Sea came into force following the first rules established by the Geneva Convention on the Shelf of 1958/1964, the sea areas were open to all nations for free scientific research. After that, when the entire Baltic Sea was considered as a "shelf sea" it became owned by all the surrounding coastal and island states extending the sovereign rights to their waters. The process was ended in the 1990s when the eastern Baltic States got the legal rights to their territorial waters and exclusive economic zone after the restoration of their independence. The domination of the former USSR in Baltic Sea research had ended.

The second period is characterized as when marine geological maps actually depicted the stratigraphy and tectonic settings approaching in details the adjacent land areas. Detailed marine geology data collections were achieved due to several reasons:

- a considerable amount of empirical data on the structure and sequence of the pre–Quaternary sedimentary rocks was collected with marine drill–cores exploration—about thirty in the eastern and southern sectors of the CBS—, and careful studies of well logs by all possible stratigraphical, in particular micropalaeontological methods were completed (RP–GDR–USSR Petrobalt consortium, 1982–1984);
- a large amount of geological data was made available by submarine dredging facilities that fixed the pre–Quaternary sedimentary rock outcrops of various age on the sea bottom (R/V *Dobrynin* and *Shelf* expeditions);
- significant amounts of geophysical records were collected by various methods of continuous acoustic, seismic reflection and seismic refraction facilities, under steadily continuing improvement (many research vessels were involved, but consistently in place were the R/V *Strombus, Aranda, Vėjas, Latvesta, Marina, Lubecki* expeditions);
- confirmations of rock age correlation of land and sea areas, based on the recommendations of the International Stratigraphic Guide (Salvador, ed. 1994), were received for sets of entire Phanerozoic geological systems;
- large–scale geological–geophysical projects––bilateral, multilateral, and EU supported—were successfully executed in many aspects of Baltic marine geology, in close collaboration by senior experienced scientists and junior researchers who chose careers in this world of marine geosciences.

Thus, in the 1990ies the understanding grew to that these data might be used as a basis for appropriate geological maps compilation. The result was that tens of geological maps of 1:500 000 or 1:200 000 scale, versus 1:50 000 scale, have been compiled and published up– to– the present that were extrapolated from local sea waters and extended to entire Northern European seas and land areas. The initiative for regional mappings was taken by the Lithuanian Geological Prospecting Institute (LitNIGRI) the leading geological scientific organization for the East Baltic States at that time under the Ministry of Geology of the USSR.

Besides, East Baltic geologists had a rather progressive scientific management system (interdepartmental committees, commissions, regular meetings, fast publications, etc.) and actively working team of highly qualified scientists and mapmakers. This resulted in the compilation of a significant set of regional geological maps of the East Baltic ("Pribaltika"); eleven authors (from Lithuania, Latvia and Estonia) of complex geological maps at a scale of 1:500 000 of various subject matters (first ten maps in 1980, and eight later in 1982) and its monographic description were awarded the highest State Award of the USSR in 1984. Therefore, the group had a *'bon appetite'* for the next work area – the Baltic Sea.

However, when 'Baltics' came onto the international scene, our weak point was poor English communication; for western partners, the problem was absolute ignorance of Russian. It took time to overcome some points of English grammar and syntax to make it a bit more idiomatic.[2]

METHODOLOGY, INNOVATION

It is a bit difficult to evaluate scientific achievements when you yourself are partial participant of many events in Baltic marine geology for over thirty years. Nevertheless, the author wishes to take some responsibility and present his personal view regarding what is what in Baltic Sea stratigraphic studies? Rephrasing Professor Eugen Seibold[3] who once expressed that geophysics offers 1/2 , lithology 2/3 and biostratigraphy at least 9/10 of the results of sedimentary rock subdivision, this might fit modern chronostratigraphy requirements. Therefore, it does not reduce the importance of seismostratigraphy, lithostratigraphy, chemostratigraphy, magnetostratigraphy, climatostratigraphy etc. as useful methods, but of speculative value because their lack relative or absolute geological time dating.

The first steps were that data on erosional/denudational surfaces, lithologic change, peneplain features, and generalized pre–Quaternary surfaces were used towards the identification of seismic reflectors. However, the main problem was still a definition of the tentative age of rocks. A better understanding was achieved when marine well logs (drilled by Petrobaltic Consortium) were used for the comparison and correlation of strata sequences using all possible biostratigraphic determinations. For this purpose the best Polish, Lithuanian, and Latvian stratigraphers were involved in examining borehole materials by palaeontological and micropalaeontological methods. It was worth doing!

Complex geological, geophysical and geomorphological data including deep marine boreholes studies collected during about two decades of Baltic Sea investigations, were summarized in a wide-ranging monograph *"Geology and geomorphology of the Baltic Sea"* (1991). The monograph tied with a set of three coloured maps at a scale 1:500 000 of these types: geological, Quaternary and geomorphological (1993).[4]

A few innovative ideas have been brought forward to better understand the structure and tectonics of pre–Quaternary sedimentary rocks.

The sub–Quaternary surface. M. Repečka (1991, compiled in 1988) first published a schematic map of the pre–Quaternary surface of the entire Baltic Sea, from Bornholm to the Åland islands, with an isopach interval of 40 m, and traced the set of submerged palaeochannels incised in the pre–Quaternary surface. Buried glacial palaeochannels of different parts of the CBS were studied by Sviridov *et al.* (1976), Flodén (1980), Sviridov and Litvin (1983). Several sets of palaeochannels first were described by M. Bjerkéus, L.Ž. Gelumbauskaitė, E. Sturkell, T. Flodén and A. Grigelis (1994). L.Ž. Gelumbauskaitė (1995, 1996) first described the morphology and morphostructure of the Gotland depression (the GOBEX project) and presented a detailed map of the pre–Quaternary surface of the eastern CBS. T. Flodén *et al.* (1997) first described the set of channels eroded in the Devonian bedrock of the eastern CBS. L.Ž. Gelumbauskaitė (2000) first completed a detailed analysis of the sub-Quaternary topography of the Klaipėda submarine plain (the INCO-COPERNICUS MASS Project). The conclusion was that palaeochannels originated in the Pleistocene reshaped Late Triassic denudation surface on the Klaipėda submarine plain to depths of 60–80 m.

The Upper Riphean–Lower Cambrian. T. Flodén *et al.* (1980) recognized the open (unfilled) erosional valleys extending through the Cambrian strata in the western Bothnian Bay. The sub–Cambrian peneplain was defined as a highly reflective surface.

The Cambrian–Silurian. T. Flodén (1975) defined some seismic markers around Gotland, calculated the sound velocities, and estimated the strata thickness by comparing the velocities data from the borings on Gotland, Gotska Sandön, Öland, and Fårö islands. Later, a system of seismic markers was set up by Flodén (1980) for the entire Cambrian–Devonian sequence of the CBS.

The Cambrian. S. Hagenfeldt (1989) performed studies of Acritarch–based stratigraphy of the Lower and Middle Cambrian from the Baltic depression, compiled a correlation chart, and proposed the extension of depositional areas for six successive zonal moments of the Early to Middle Cambrian. A. Grigelis, G. Kharin, S. Kanev, V. Vail and S. Hagenfeldt (1992) first interpreted the Cambrian lithostratigraphy of the CBS, comparing it with the trilobite zonation of northern Poland; seven marine borehole sections in the south–eastern and south Baltic were used for the correlation (Fig. 3). Regional stages were distinguished in the Lower, Middle and Upper Cambrian; seismic marker **Cm3** was tied in with the basal layer of the Moebergella beds, and **Cm5** was matched with the transition of the Lower Cambrian sandstones to the Middle Cambrian shales. A full section of the Cambrian rocks was drilled in C9 borehole (Gdańsk depression, eastern slope), and in B16–1 also A8–1 boreholes (south–western Baltic, Bornholm depression). The paper was published in Russian and left unused by western scientists.

The Ordovician. Based on marine boreholes and island outcrop data, the Ordovician lithostratigraphic

2 Nevertheless, that is OK for me personally that I born Lithuanian and speak four languages instead of one.

3 Eugen Seibold (Germany), famous stratigrapher and micropalaeontologist, Academician, former IUGS President.

4 This work was finished in 1989, published in Russian by Nedra in 1991, but left not in use by western scientists; however, the manuscript was also translated into English but was not published because of essential reforms that came after collapse of the USSR.

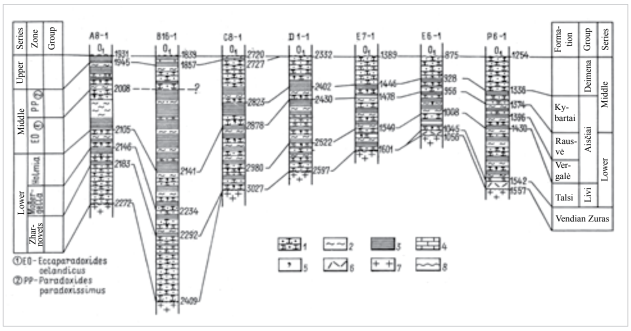

Fig. 3. Cambrian stratigraphy in marine boreholes drilled in Bornholm (A8–1), Gdańsk (B16–1, C8–1, D1–1) and Gotland (eastern slope; E7–1, E6–1, P6–1) depressions; after A. Grigelis *et al.*, 1991. 1 – sandstone; 2 – siltstone; 3 – argillite; 4 – limestone; 5 – glauconite; 6 – pyroclastic rocks; 7 – magmatic rocks of crystalline basement; 8 – stratigraphic unconformity.

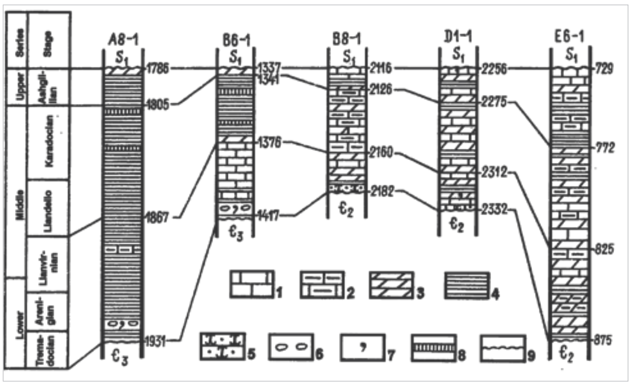

Fig. 4. Ordovician stratigraphy in marine boreholes; after S. Kanev, 1989 in A. Grigelis *et al.* 1991. 1 – limestone; 2 – clayey limestone; 3 – marlstone; 4 – argillite; 5 – sandstone; 6 – conglomerate; 7 – glauconite; 8 – bentonite; 9 – stratigraphic break.

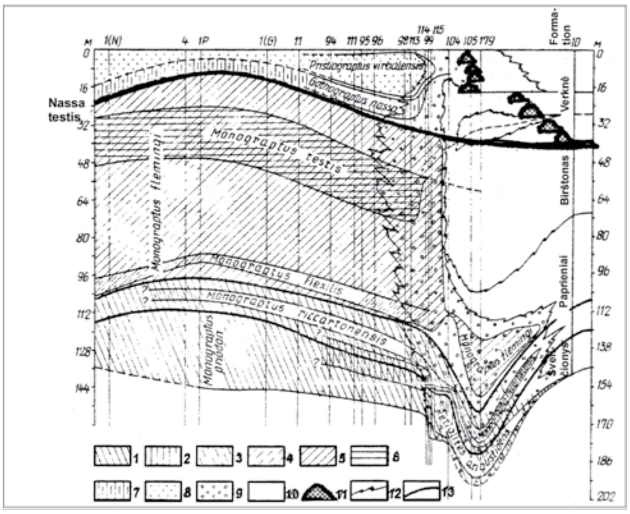

Fig. 5. Distribution of dominant graptolites in Llandovery and Wenlock series on the profile of Nida—Ukmergė; after J. Paškevičius, 1985. … 9 – transition zone between clayey and calcareous facies; 10 – calcareous facies; 11 – reefogenous structures; 12 – boundaries between facies; 13 – age boundaries. Author's remarks on correlative markers: Top Wenlock=Rootsiküla=Lower Melnik=Klinteberg=S5A s.m.; Nassa=Base Rootsiküla=Base Melnik=Mulde/Halla=S4 s.m.; Testis=Top Jaagarahu=Top Bielsk=Top Slite; s.m. – seismic markers, T. Flodén, 1980.

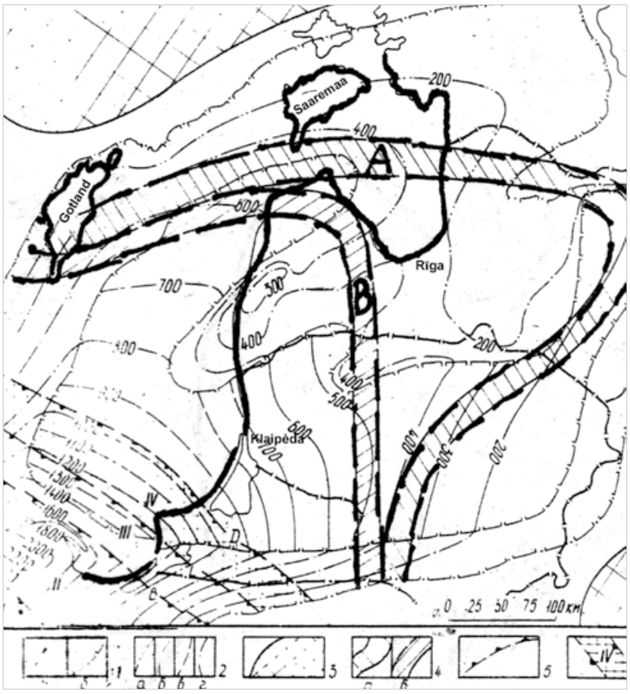

Fig. 6. Distribution of Silurian sedimentary rocks; after P. Lapinskas, 1987. 1 – recent distribution; 2 – isopachs, m; 3 – land; 4 – zones of flexures: A – Kolka zone, B – Ventspils zone; 5 – SW border of Baltic pericratonic basin; 6 – Sambian marginal zone.

correlation was well–defined by the trilobite and, to a lesser extent, by conodont biostratigraphy (Ulst 1990; Modliński 1982; in Grigelis, ed. 1991). Subdivision to regional stages was given, and seismic markers for the CBS were correlated (Fig. 4).

The Silurian. A. Grigelis, G. Kharin, S. Kanev (1992) completed an extensive analysis of the Silurian of the entire Baltic Sea and proposed biostratigraphic correlation of graptolite (south Baltic–northern Poland) and carbonate (north Baltic–Estonia—mid Baltic–Gotland) facies. Main seismic markers **S1** to **S10**, defined by Flodén (1980), first got their chronostratigraphic interpretation being bound up with the faunal zonation. As is shown below (Figs 5–7) the **top of zone Monograptus testis = top Bielsk = top Jaagarahu -= top Slite = top S4** was found to mostly correlative level that solved the problem in question. The paper was published in Russian and left unused by western scientists.

I. Tuuling (1998) developed Ordovician–Silurian geophysical studies of the north–eastern Baltic Sea, using both previous and new CSP data making the key point the detailed seismic correlation of strata sequence in the area studied. M. Bjerkéus (1999) studied sediment structures in the Phanerozoic bedrock of the CBS paying attention mainly to glacially incised valleys (palaeochannels) first described in 1994–1995 and to the Late Silurian and Lower to Middle Devonian development and seismic geology. A. Monkevičius (1999) developed a model of glacial incisions in the Mesozoic of the CSB and described channel–forming

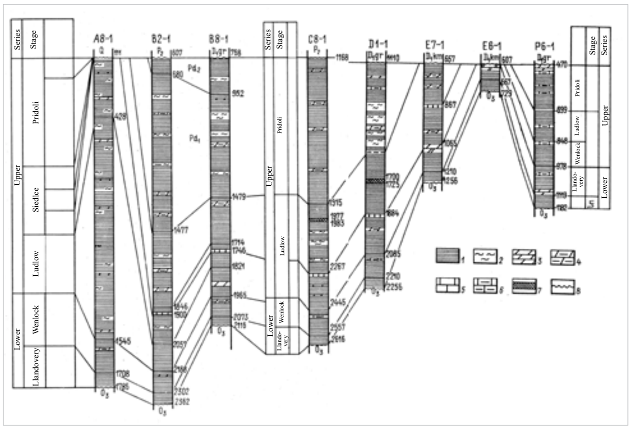

Fig.7. Silurian stratigraphy in marine boreholes drilled in water areas of Poland, Kaliningrad, Lithuania and Latvia; after S. Kanev, 1989 in A. Grigelis *et al.* 1991. 1 – argillite; 2 – siltstone; 3 – marlstone; 4 – clayey marlstone; 5 – limestone; 6 – clayey limestone; 7 – diabases (intrusion); 8 – stratigraphic break.

processes possibly determined by fossil cryogenic structures.

J. Lutt and A. Raukas (eds 1993) published a description of the geology of the Estonian shelf. Several seismic markers defined by T. Flodén (1980) for the Cambrian–Silurian sequence were reinterpreted.

The Devonian. M. Kumpas (1977) mapped a Lower–Middle Devonian submarine cliff southeast of Gotland and first used Latvia's onshore borehole data for the stratigraphic correlation of defined CSP reflectors.

The Devonian and Lower Carboniferous. The stratigraphic interpretation of the main seismic markers **D1 to D4** and **C1**, defined by Flodén (1980), was corrected after correlation with marine borehole logs

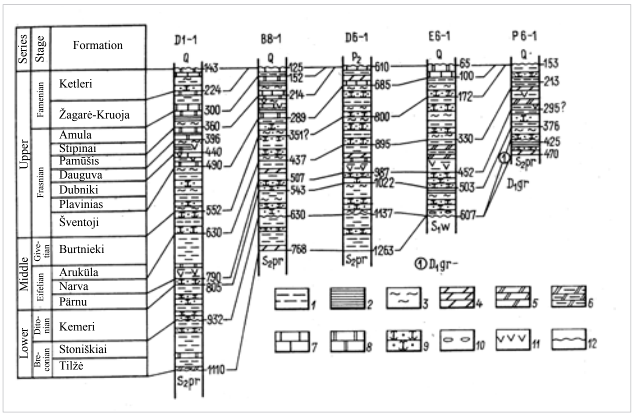

Fig. 8. Devonian stratigraphy in marine boreholes drilled in water areas of Kaliningrad, Lithuania and Latvia; after S. Kanev, 1989 in A. Grigelis *et al.* 1991. 1 – clay; 2 – argillite; 3 – siltstone; 4 – marl; 5 – dolomite marl; 6 – clayey marl; 7 – limestone; 8 – dolomite; 9 – sandstone; 10 – conglomerate; 11 – gypsum; 12 – stratigraphic break.

defined by S. Kanev (Fig. 8; in Grigelis, ed. 1991). The Devonian stratigraphy of the CBS has been well–based using regional stages of the Eastern Baltic land area biostratigraphically determined by fossil fish and brachiopod remains.

The Permian. Permian rocks were first mapped on the CBS by S. Kanev (1989, in Grigelis, ed. 1991) by means of marine boreholes data and lithostratigraphic correlation with the land area of western Lithuania–Kaliningrad–north–western Poland (Fig. 9). The cyclostratigraphic sub–division (left margin of figure) was elaborated for the Polish–Germany Upper Permian Zechstein basin (Budowa geologiczna Polski, 1968).

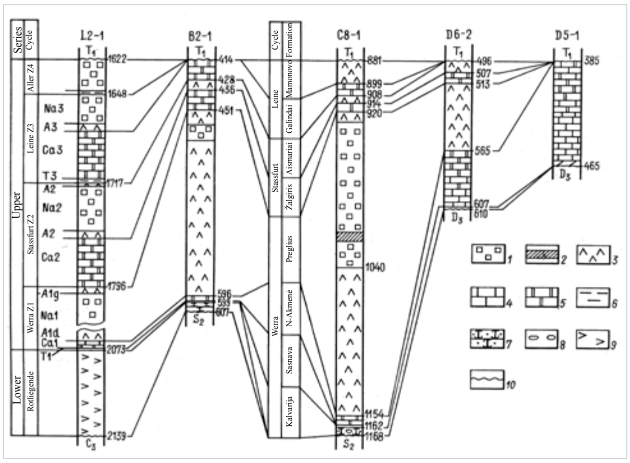

Fig. 9. Permian stratigraphy in marine boreholes drilled in water areas of north–west Poland, Kaliningrad and Lithuania; after S. Kanev, 1989 in A. Grigelis *et al.* 1991. 1 – rock salt; 2 – kalium salt; 3 – anhydrite; 4 – limestone; 5 – dolomite; 6 – clay; 7 – sandstone; 8 – conglomerate; 9 – effusive rock; 10 – stratigraphic break.

The Triassic, Jurassic and Cretaceous. Mesozoic rocks first mapped by A. Grigelis and S. Kanev (1989, in Grigelis, ed. 1991) on the CBS by means of marine boreholes data, micropalaeontology (foraminifers) of

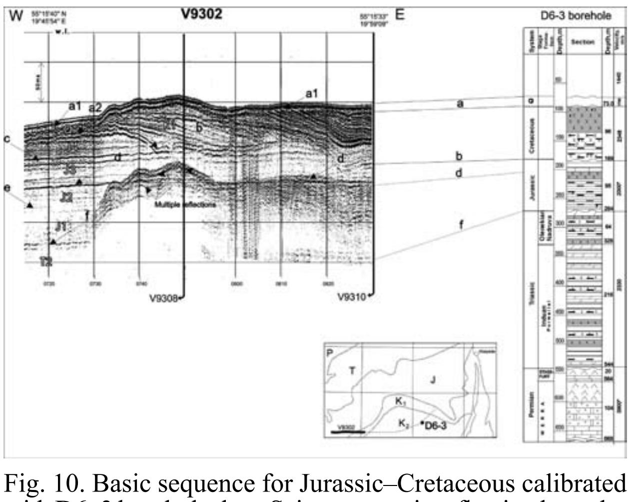

Fig. 10. Basic sequence for Jurassic–Cretaceous calibrated with D6–3 borehole data. Seismoacoustic reflection boundaries, Mesozoic sequence of the south–east Baltic Sea; seismic line V9302 shot by T. Flodén, R/V Vėjas, 1993; V9308 and V9310 – cross points of seismic lines. Borehole D6–3 micropalaeontological stratigraphy and interpretation by A. Grigelis, 1997.

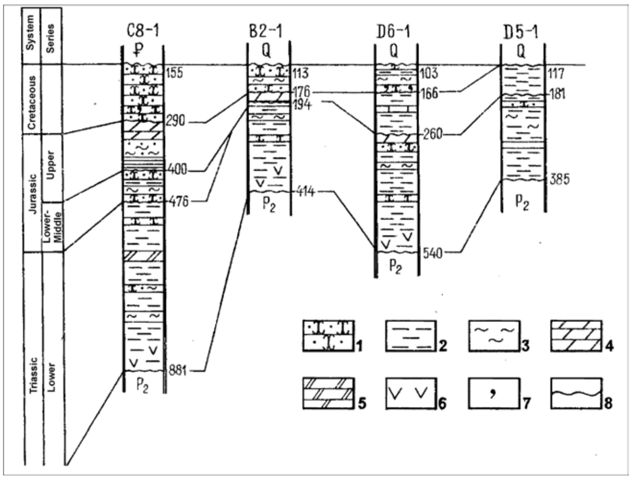

Fig. 11. Mesozoic stratigraphy in marine boreholes drilled in water areas of north–west Poland, Kaliningrad and Lithuania; after S. Kanev and A. Grigelis, 1989 in A. Grigelis *et al.* 1991. 1 – sandstone; 2 – clay; 3 – siltstone; 4 – marl; 5 – dolomite marl; 6 – gypsum; 7 – glauconite; 8 – stratigraphic break.

the Jurassic and Cretaceous strata and lithostratigraphic correlation with the land area of western Lithuania–Kaliningrad–north–western Poland (Fig. 10; Fig. 11).

A. Grigelis (1995a), based on CSP data collected during *R/V Latvesta* (1993) and *R/V Vėjas* (1993–1995) cruises, first elaborated the principal seismostratigraphic subdivision of the Upper Permian to Upper Cretaceous sequence of the south–eastern CBS divided into 12 seismic units; an extension was made in 1999.

First constructing 3–dimensional plots, A. Janson (1985) the studied the sub–Mesozoic peneplain and tectonic patterns south of Öland, southern Baltic Sea. A. Grigelis (1995b) was first to describe two periods of peneplanation in the CBS area related to (1) the entire Carboniferous and Early Permian, and (2) the end of the Paleogene to the Neogene, when the sub–Permian and sub–Quaternary peneplains were formed.

The Paleogene and Neogene. The terrigenous deposits of limited extension occur on the sea bottom in submerged old–shore cliffs at the Sambian coast (Paleogene) but of little extension at Leba Peninsula (Neogene).

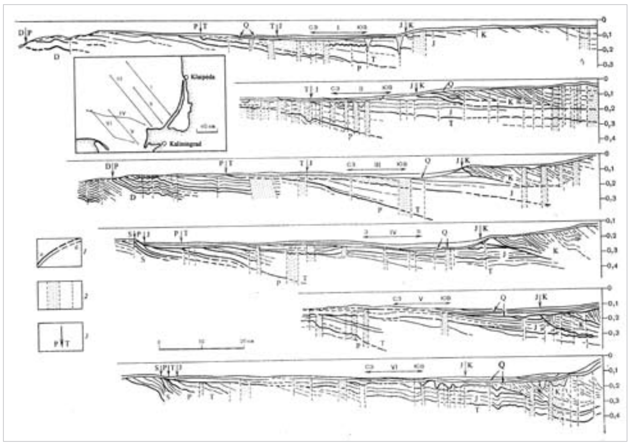

Fig. 12. Schematic seismogelogical sections of the Alpine structural complex; after N. Sviridov, 1984. 1 – limits of seismoacoustic complexes; 2 – possibly fractured zones; 3 – stratigraphic boundaries.

Tectonics. K. Wannäs (1979) and M. Kumpas (1982) interpreted horst tectonic structures in the Bornholm Gat of the southern Baltic, by means of CSP data. N. Sviridov (1981) published an innovative paper summarizing CSP data on fractured and folded deformations and tectonic zones in the layered structure of the Paleozoic, Mesozoic and Quaternary sedimentary cover of the CBS south–eastern and north–western sectors. N. Sviridov and E. Levkov (1981) were first to describe glacio–deformations on the CBS bottom by means of CSP data. N. Sviridov (1984) was first to explicate the fractured and folded deformations in the Alpine (Permian–Neogene) tectonic structural complex of the south–eastern Baltic Sea (Fig. 12).

V. Puura, N. Sviridov, A. Amantov, A. Brangulis and S. Kanev, in 1989, were first to complete a schematic map and to describe the tectonics of the sedimentary (platform) cover of the entire Baltic Sea (in Grigelis, ed. 1991).

P. Söderberg and T. Flodén (1991) developed the studies of gas induced pockmarks along the deep crustal structures in the Stockholm Archipelago. P. Söderberg (1993) drew conclusions about the location of gas induced pockmarks along tectonic faults in the sedimentary bedrock sequence. T. Flodén (1981) first described seismic data processing procedures, introduced by the Marine Geological Research Group in Stockholm, based on the main original programme K:KART and concurrent programmes.

P. Gravesen and M. Bjerreskov (1982) presented in detail the geology of Bornholm Island that helped in the later construction of the CBS geological map (1993). P. Ahlberg (1986) summarized a general view of *"Den svenska kontinentalsockelns berggrund"* presenting a black and white scheme of the bedrock geology with stratigraphic subdivision to only geological systems.

In 2004, V. Puura summarised an idea about the development of the geological structure of the Baltic seabed, as (1) fracturing and folding in the Svecofennian to Jotnian periods (1.9–1.8 to 0.6 Ga), and (2) to great peneplenization and sedimentation periods in the Phanerozoic (since 0.6 Ga), related to the Caledonian compression and to the late Hercynian rifting along the TTS zone and in the Oslo rift belt.

EVALUATION

Some geological maps relevant to this research should be mentioned below:

Flodén's map, 1982/1884

This schematic map, entitled "The Baltic Sea. Pre–Cenozoic geology", with a scale of 1:4 million, black and white, analogous (on paper), with a simplified legend containing 17 symbols. The stratigraphic subdivision is given only for geological systems. Tectonics, as is shown on a separate sheet, displays lineaments and faults primarily revealed from CSP, but not especially related to the basement or to any specific level in the sedimentary cover. A pre–print description was announced in 1982 (30 pp.). Flodén extrapolated the data regarding the bedrock geology of the central Baltic (1980) to the whole Baltic Sea. The tectonic data were used for further maps compilation.

Ahlberg's map, 1986

This geological map is entitled "Den svenska kontinentalsockelns berggrund", drawn at a scale of 1:1 000 000 on two sheets, black and white, analogous, based on complex geophysical and geological data. The map exposes the geology of the Bothnian Sea on one sheet and the entire Baltic Sea on the other. The legend in general contains 16 symbols: 13 for geological systems from the Tertiary to the Jotnian and sub–Jotnian, and three for magmatic rocks. Tectonic fault zones are shown. Published in Swedish, an explanatory note appeared in 1986 (101 p.).

Grigelis' map, 1993

This map is entitled "Geological map of the Baltic Sea bottom and adjacent land areas", drawn at a scale of 1:500 000 on six sheets (181x161 cm each), analogous, coloured. The map shows the distribution, age, and boundaries of various stratigraphic units and tectonic fault zones. The geological boundaries are drawn with due account of the pre–Quaternary surface topography. The legend contains 180 symbols. The map area embraces the Baltic Sea (without the Bothnian Sea). The Phanerozoic is subdivided to geological series and/or regional stages. The tectonic fault zones are simplified. The single explanatory note (125 pp.) and the extended description were published in 1991 (420 pp.; Nedra, St. Petersburg).

Brangulis' and Vingisaar's map, 1997

The geological map is entitled "Bedrock map of the Gulf of Riga", drawn at a scale of 1:200 000, analogous, coloured, based on CSP and borehole data. The map exposes the Silurian–Devonian sedimentary rocks sequence, subdivided to regional stages and formations in 18 symbols. The isohypses of the bedrock surface, set of buried valleys, faults, and geological cross sections are displayed. An explanatory note contains 30 pp.

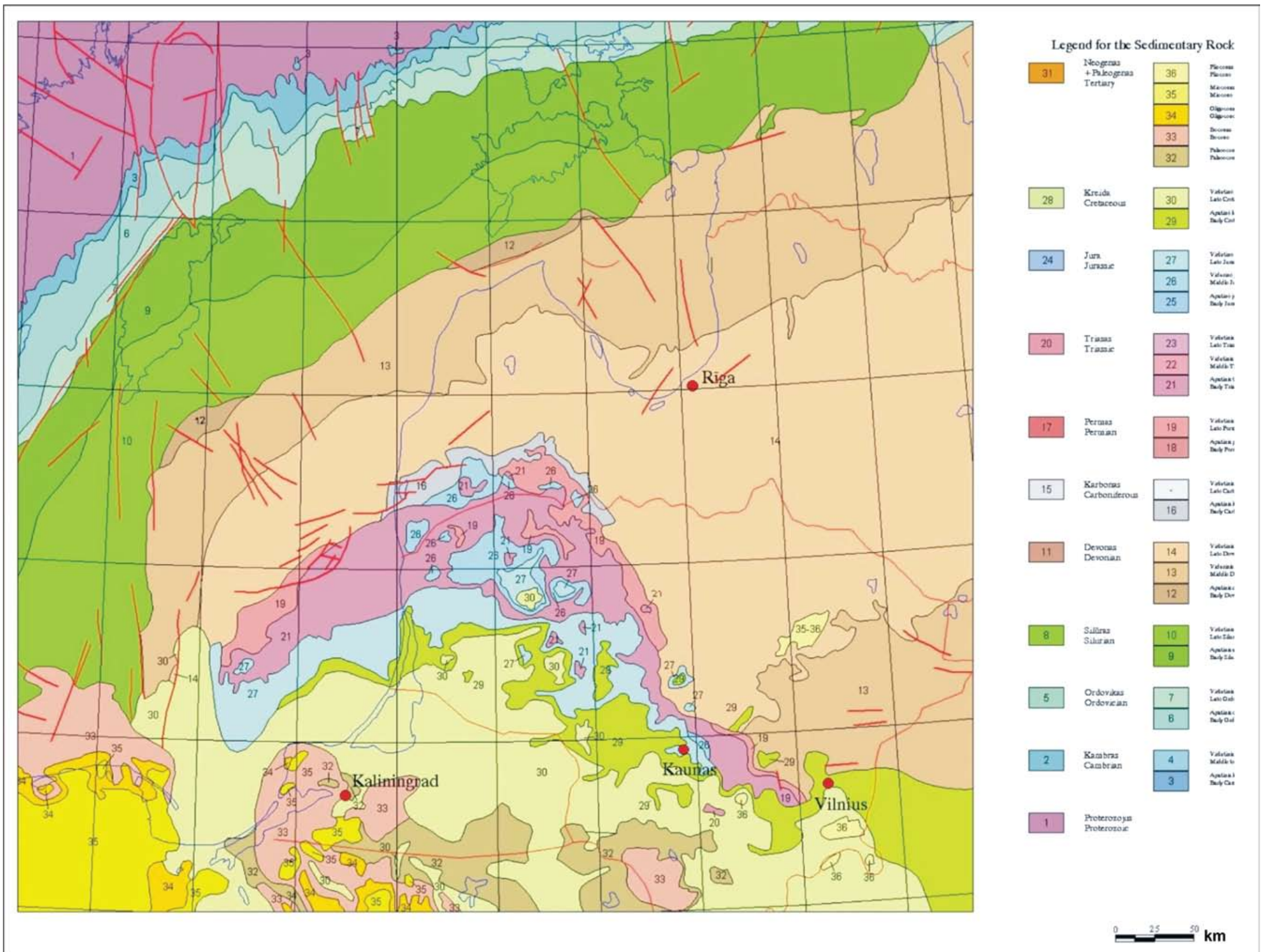

Fig. 13. Basic geological map of the Central Baltic Sea and Eastern Baltic land areas, original version at a scale of 1:500 000, compiled by A. Grigelis, 1998; integrated into the geological map of Northern Europe, 2002 (see Fig. 14).

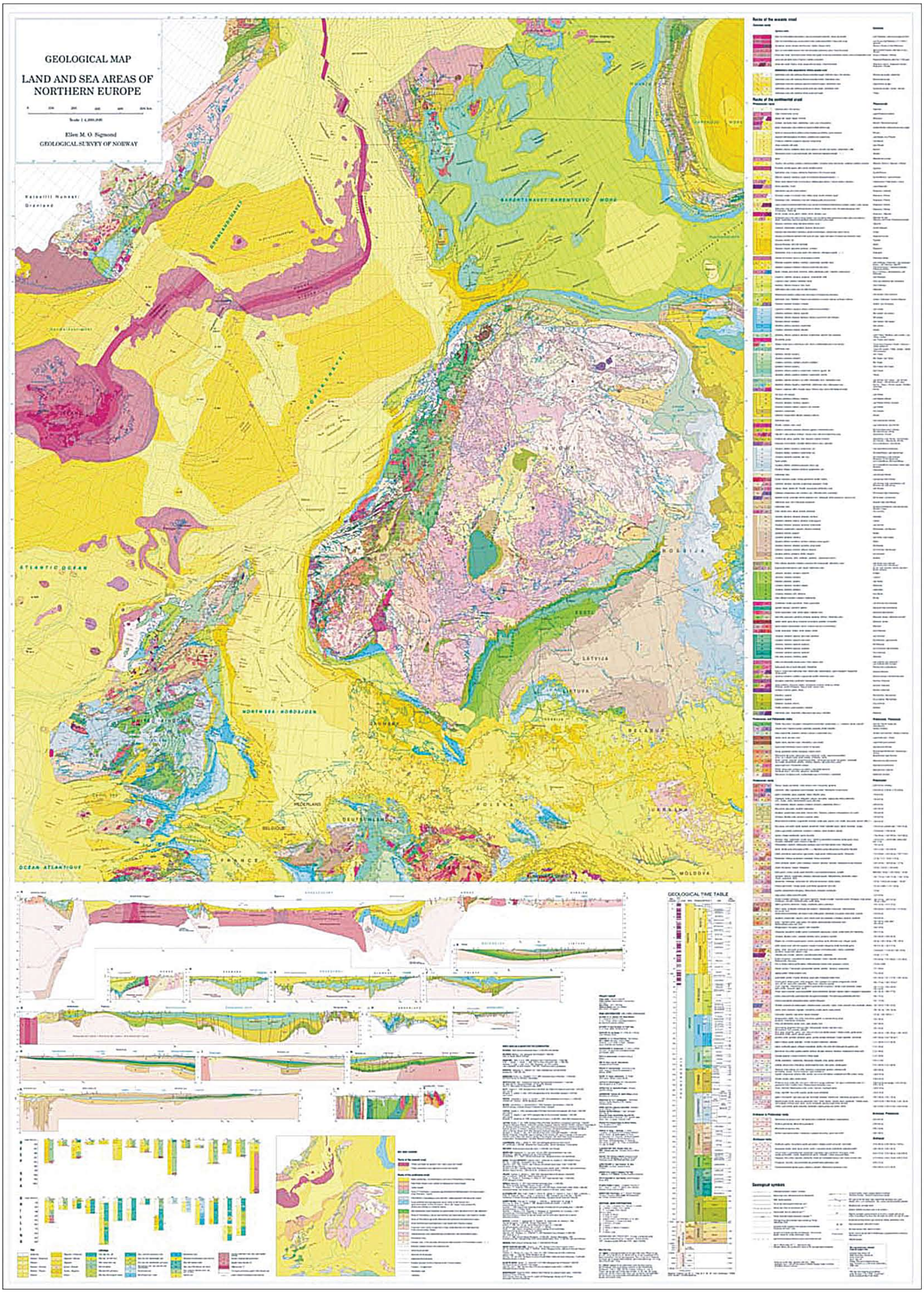

Fig. 14. Geological map „Land and sea areas of Northern Europe“, scale 1:4 mil.; compiled by Ellen M. O. Sigmond and others, NGU, 2002.

Sigmond's map, 2002/2007

This geological map is entitled "Land and sea areas of Northern Europe", drawn at a scale of 1:4 million, analogous, coloured. The legend is arranged according to the age of rocks, contains 439 lithologic and petrologic symbols. The map area embraces the seas of the entire North Europe (North Sea, Celtic Sea, adjacent Atlantic Ocean, English Channel/La Manche, Baltic Sea, Beloje More, Barents Sea, and the western part of the Kara Sea. Regarding the Central Baltic Sea and Eastern Baltic land areas, an original geological map drawn at a scale of 1:500 000, first compiled by A. Grigelis in 1998 (Fig. 13; still unpublished), is integrated into the Geological map of Northern Europe in 2002 (Fig. 14). The Phanerozoic stratigraphy is subdivided on this last to geological series and stages portrayed by 231 lithologic symbols. The Proterozoic to Archean series are grouped by radiogeochronological data within the time interval of 0.54 to 3.2 Ga (billion years). The map has 15 geological–tectonic sections and insets. The map was published in 2002, and an extended description in 2007 (NGU, Trondheim, 100 pp.).

Asch's map, 2005

This map is entitled "The International Geological Map of Europe (IGME–5000)", drawn at a scale of 1:5 million, digital, coloured, legend with numerous stratigraphic symbols. The entire European area is depicted, including the North Sea, Baltic Sea, Irish Sea, and Mediterranean, and shows stratigraphic subdivision to regional stages and formations, tectonic detailed, and insets. A detailed description of the project background, history, geology and developed GIS and database methods was published in 2003 (Geologisches Jahrbuch, SA 3, BGR, Hannover, 190 pp.).

One Geology Europe map 2010 (in preparation)

The geological map as a part of EU Project "One Geology Europe (1GE)" would be based on IGME–5000, drawn at a scale of 1:1 million, digital, coloured. The vocabulary under preparation contains : (1) 152 Quaternary—Cambrian age terms; 35 Proterozoic– –Archean age terms; (2) 45 events/environmental terms; (3) 40 events/process terms; (4) approximately 50 lithology and petrology terms. The depicted area is planned for the North Europe (1st stage). The stratigraphic subdivision is to be done to stages and formations; the map would have tectonic details, and insets.

CONCLUSION

There are two important points to be concluded. First, compiled geological maps of the Phanerozoic (pre–Quaternary) sedimentary cover of the Baltic Sea in the latest three decades significantly developed through the results of both geophysical and geological surveys. Crucial support of these elaborations was produced through the study of the detailed stratigraphy of deep marine boreholes drilled in the south–eastern and southern Baltic Sea for oil prospecting purposes. Other side, these data would have never improved or have been enhanced if no new drilling data were received. Deep seismic surveys could be an important source of new data, but it offers only half of the necessary results. However, in the immediate future, it is not anticipated that a regional survey would be provided, except, limited plots for local possible oil–bearing tectonic structures are likely.

Second, considerable progress was made in the last decade by moving from analogue to digital geological map versions. Simplified stratigraphic legends are replaced by extended vocabularies; therefore, the relative age of rocks, the lithology and petrography, events and environment processes are indexed and coded. That allows a significant increase in capacity of information depicted on the maps. It makes it also possible to be, say, on sentry–go with permanent map amendments when new data are received or appeared.

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