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LATE QUATERNARY CLIMATE VARIATIONS IN WEST ANTARCTICA AND THEIR IMPACT ON THE MARINE SILICEOUS MICROALGAE

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Abstract. Main **objective** is the reconstruction of late Quaternary climatic events in the northern and north-western parts of the Antarctic Peninsula shelf based on species variation, abundance and ecological structure of diatom complex in bottom sediments. **Methods:** siliceous microalgae were used as biomarkers of geologycal, paleogeographycal and facial events. **Results:** the reasons for changing of the diatom composition in bottom sediments were determined; paleogeographic reconstraction and chronology of the Late Quarter paleoclimatic trends in the region were investigated. **Conclusions** of the main paleoclimatic events of the Late Quarter within the northwestern shelf and in the southern part of the Skotia Sea are made. Two climatic phases are identified: «Little Ice Age» (900-500 years ago) with moderate icy conditions and the next phase of rapid modern warming.

Key words: paleoclimate, South ocean, diatoms, Antarctic Peninsula.

ПОЗДНЕЧЕТВЕРТИЧНЫЕ КОЛЕБАНИЯ КЛИМАТА В ЗАПАДНОЙ АНТАРКТИКЕ И ИХ ВЛИЯНИЕ НА МОРСКИЕ КРЕМНИСТЫЕ МИКРОВОДОРОСЛИ

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Реферат. Цель работы – реконструкция позднечетвертичных климатических событий в районах северного и северо-западного шельфа Антарктического полуострова на основании изменения видового состава, численности и экологической структуры диатомовых ассоциаций в донных осадках. **Метод -** использование кремнистых микроводорослей в качестве биомаркеров геологических, палеогеографических и фациальных событий. **Результат:** установлены причины изменения состава диатомовых комплексов в толще осадков, выполнены палеогеографические реконструкции и прослежена хронология позднечетвертичных климатических трендов в регионе. Сделаны **выводы** об основных палеоклиматических событиях в пределах северо-западного шельфа и южной части моря Скоша. Выделены два климатических этапа: «малый ледниковый период» (900-500 лет назад) с умеренноледовыми условиями и последующий этап современного стремительного потепления.

Ключевые слова: палеоклимат, Южный океан, диатомовые водоросли, Антарктический полуостров.

ПІЗДНЬОЧЕТВЕРТИННІ КОЛИВАННЯ КЛІМАТУ В ЗАХІДНІЙ АНТАРКТИЦІ І ЇХ ВПЛИВ НА МОРСЬКІ КРЕМНИСТІ МІКРОВОДОРОСЛІ

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Реферат. Мета роботи - реконструкція пізньочетвертинних кліматичних подій у районах північного і північно-західного шельфу Антарктичного півострова за зміною видового складу, чисельності та екологічної структури діатомових асоціацій у донних відкладах**. Метод –** використання кременистих мікроводоростей в якості біомаркерів геологічних, палеографічних і фаціальних подій. **Результати:** встановлено причини зміни складу діатомових комплексів в товщі осадків, виконано палеогеографічні реконструкції та простежено хронологію пізньочетвертинних кліматичних трендів в регіоні. Зроблено **висновки** про основні палеокліматичні події в межах північно-західного шельфу і південної частини моря Скоша. Виділено два кліматичних етапи: «малий льодовиковий період» (900-500 років тому) з помірнольодовими умовами і наступний за ним етап сучасного стрімкого потепління.

Ключові слова: палеоклімат, Південний океан, діатомові водорості, Антарктичний півострів.

1. Introduction

The objective of the present contribution is the reconstruction of the late Quaternary climate in the western section of the Antarctic region and assessment of the feasibility of climatic trends prognosis based on the siliceous microflora study.

One of modern priorities, set forth by the Scientific Committee on Antarctic Research (Antarctic Climate Change and the Environment - 2016 Update, SCAR, IP35) is the analysis of trends of climatic changes on the Antarctic continent and in the Southern Ocean and assessment of their impact on the terrestrial and marine biota.

The geographic position of the Antarctic region makes it both crucial in the Earth's climatic system and oceanic circulation, and extremely sensitive to the climatic changes. The international Antarctic researches show that the major part of the West Antarctica, in particular, the Antarctic Peninsula as its most sensitive area, is subject to intense heating during several last decades (Etourneau et al., 2013). The modern global warming causes increased melting and thinning of ice shelves and controls the wind strength, as well as flow rates and directions of oceanic currents. At the same time the aquatic areas are characterized by the growth of the ice cover, inhibiting the passage of oceanic currents, thus causing the redistribution of the thermal potential in the region. This becomes especially important within the Drake Passage, which is a natural bottleneck on the way of the Antarctic Circumpolar Current (ACC) and in the region near South Orkney Islands, where confluence occurs of moderately warm ACC water and cold water mass of the Weddell Sea.

The study of Quaternary changes in ice conditions, impacting the polar currents, is of crucial importance for understanding the role of the Southern Ocean in the development of modern climate (Lee. et al., 2012). Since causes and consequences of climate changes are immensely wide, adequately modeling all constituents of this process is a complicated challenge. The sequences of past climate changes are recorded in the bottom sediments, therefore modern reconstructions of paleoclimate trends in Antarctica are essentially based on the materials of marine geology studies. Versatile data on sediment composition and accumulation conditions in Antarctic basins yield important information for paleogeographic reconstructions, enable using past events logs for interpretation and assessment of future climatic trends and for long-range climate prognosis.

A wide variety of geological methods is involved for the reconstruction of climatic and oceanographic history of the Antarctic basin. These studies particularly include data on plankton groups of fossils, primarily on siliceous phytoplankton, dominating in the area. The most widespread group of microphytoplankton in Antarctic waters are diatom algae with siliceous skeleton, showing high sensitivity of cells towards changes in temperature, salinity, luminance, ice and hydrology conditions, and trophicity of the basin. The ecological composition and ratio of different taxa in assemblages markedly point at their optimal living environments. Due to their actuated response to the environmental factors, diatoms are reliable bioindicators for revealing the natural zonation of surface waters of the World ocean and facial zonation of the sea floor.

The diatom dominate in both biomass and taxonomic biodiversity in the phytoplankton of Argentine Islands Archipelago (Samyshev, 2009). Their abundant fossils are buried in the sea-floor sediments and provide the principal source of silicon dioxide in the disjunctive areas of pelagic biogenic silica accumulation. The marine sediments with diatoms present a continuous geological record, which allows to assess the paleoenvironmental changes. The successions of diatomic ecosystems, traced in the Quaternary sections, reflect principal climatic events of the geological history, related to the retreat and melting of the sea ice cover of the last Antarctic glaciation.

2. Materials and techniques

The study area covers the shelf zone of the north-western part of the Antarctic Peninsula, as southern part of the Drake Passage (region of Mordvinov Island, South Shetland Islands) and southern part of the Scotia Sea (South Orkney Islands) (Fig. 1).

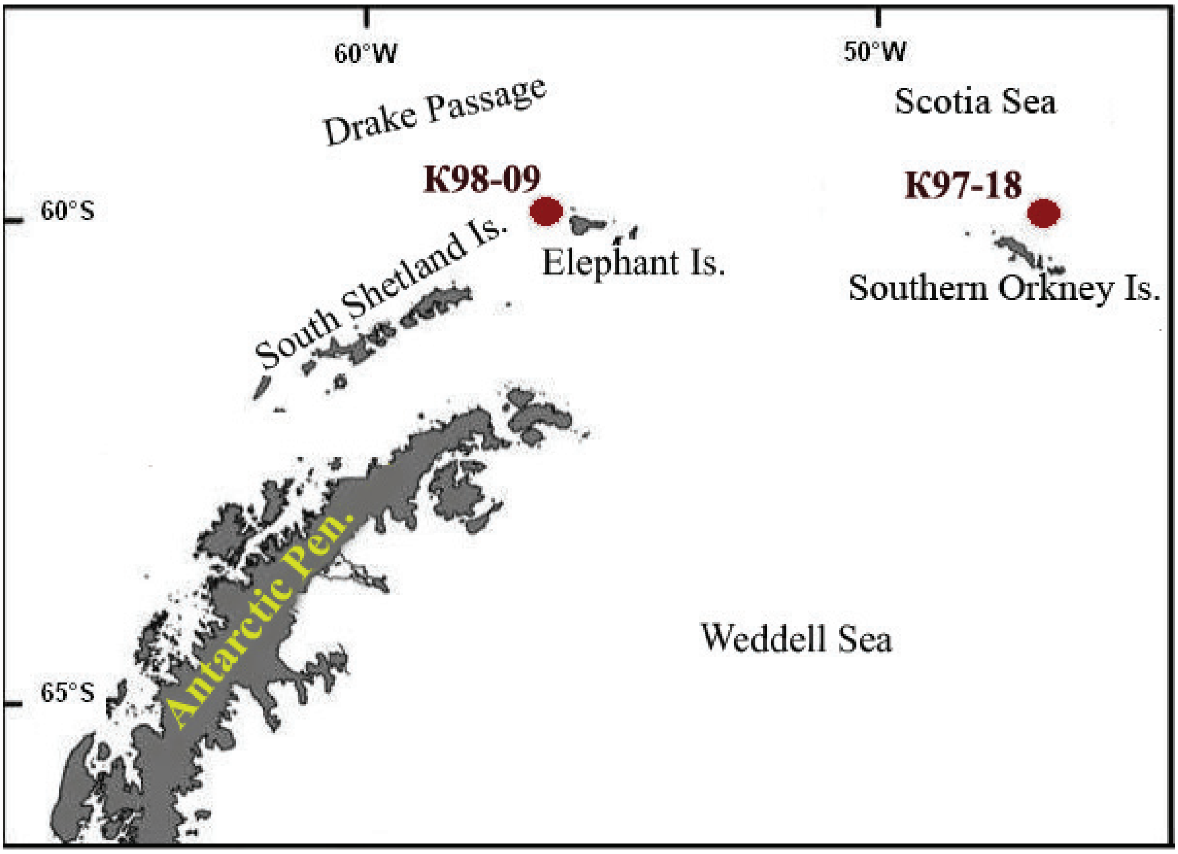

Fig. 1. Scheme-map of the investigated area.

We used the geological survey materials of seasonal Ukrainian Antarctic expeditions of 1997, 1998, 2004, acquired by the Institute of Geological Sciences, National Academy of Sciences of Ukraine in the southern part of the Scotia Sea. We studied the column cores of the sea-floor sediments from the southern part of the Drake Passage (station K98-09, column core length 0.45 m) and from the south-western part of the Scotia Sea (station K97-18, column core length 0.50 m, water depth ca. 1600 m), retrieved with a diameter 127 mm and length 1.5 m direct-flow gravity core sampler and "Ocean-15" clamshell bottom sampler.

The laboratory analysis of micropaleonthological samples was performed according to the routine procedure of diatomic study. The determination of taxa and morphology of diatoms was performed with optical microscope Olimpus CX4 and scanning electron microscope JEOL NeoScan JSM-5000.

3. Principal results and discussion

The base of our paleogeographic and paleoclimatic reconstructions is the relation of the dispersal of diatoms with their distribution in the modern sediments and determination of principal factors, impacting the species composition of their assemblages (Ogienko, 2015). The major part of marine diatoms is characterized by a clear expansion zonation, with reproduction boom areas, associated with geographic zones, where optimal living conditions for a species are encountered. The analysis of the species composition and environmental groups of diatom allows to determine the location of the ice edge, hydrodynamic conditions, sea water surface temperature in the algae vegetation period, presence of summer sailing ice, stratification of the water column during spring thaw of sea ice, water bioproductivity, location of upwelling zones at various stages of geological history.

The species, particularly sensitive to the changes in water salinity, temperature, depth, lightand hydrodynamical conditions, trophicity and other physical and chemical parameters, are indicator species of the environment, or biomarkers.The diatom groups identified in the bottom sedimentary cores were classified by their tolerance to the limiting environmental factors:

1. Group of Antarctic cold-water marine planktonic and cryophile with habitats, associated to the sea ice (Fig. 2). The representatives of this group live on the ice surface and inside ice pores, as well as in the ice saturated sea water under low temperatures. The optimal vegetation temperature range is from −1°C to +1.5°C (Armand et al.). They can be indicators of various ice conditions.

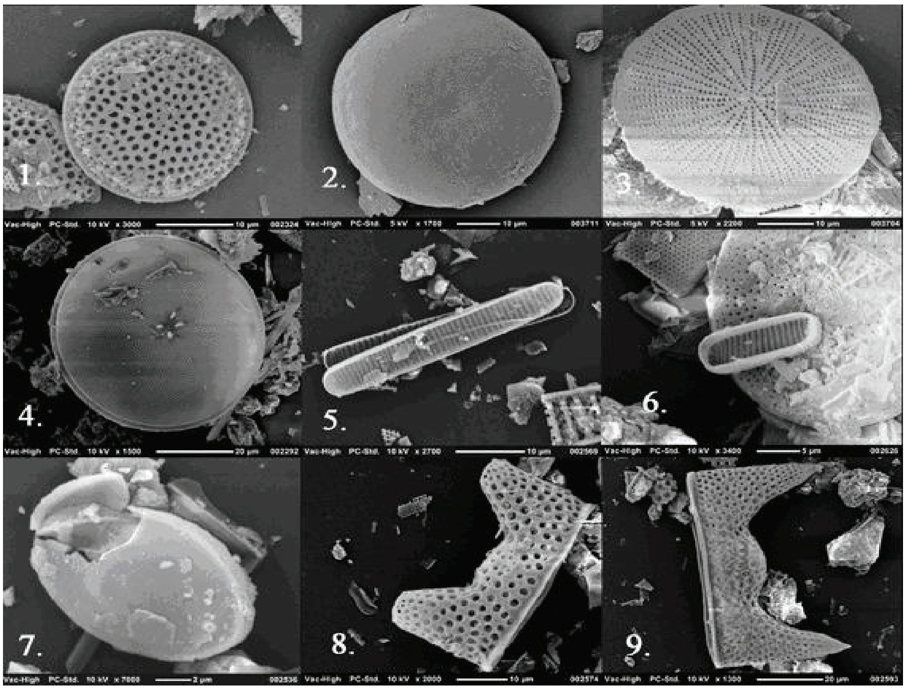

Fig. 2. Cold-water Antarctic marine planktonic and cryophile diatom species (SEM): *1 – Thalassiosira antarctica, 2 – Porosira glacialis, 3 – Actinocyclus actinochilus, 4 – Stellarima microtrias, 5 – Fragilariopsis cylindrus, 6 – F. curta,* 7 – *RS Chaetoceros sp*., 8 – *Eucampia antarctica var. recta, 9 – E. antarctica var. recta.*

2. Subantarctic oceanic planktonic group (Fig. 3.). These are apparently warm-water open sea and oceanic planktonic diatom species, which survive at essentially higher temperatures in the ice-free water. They are suppressed under ice conditions and are merely antagonists of such conditions, being indicators of ice-free environments. The optimal temperature range for most of them is from +1°C to +8°C (Crosta et al., 2005).

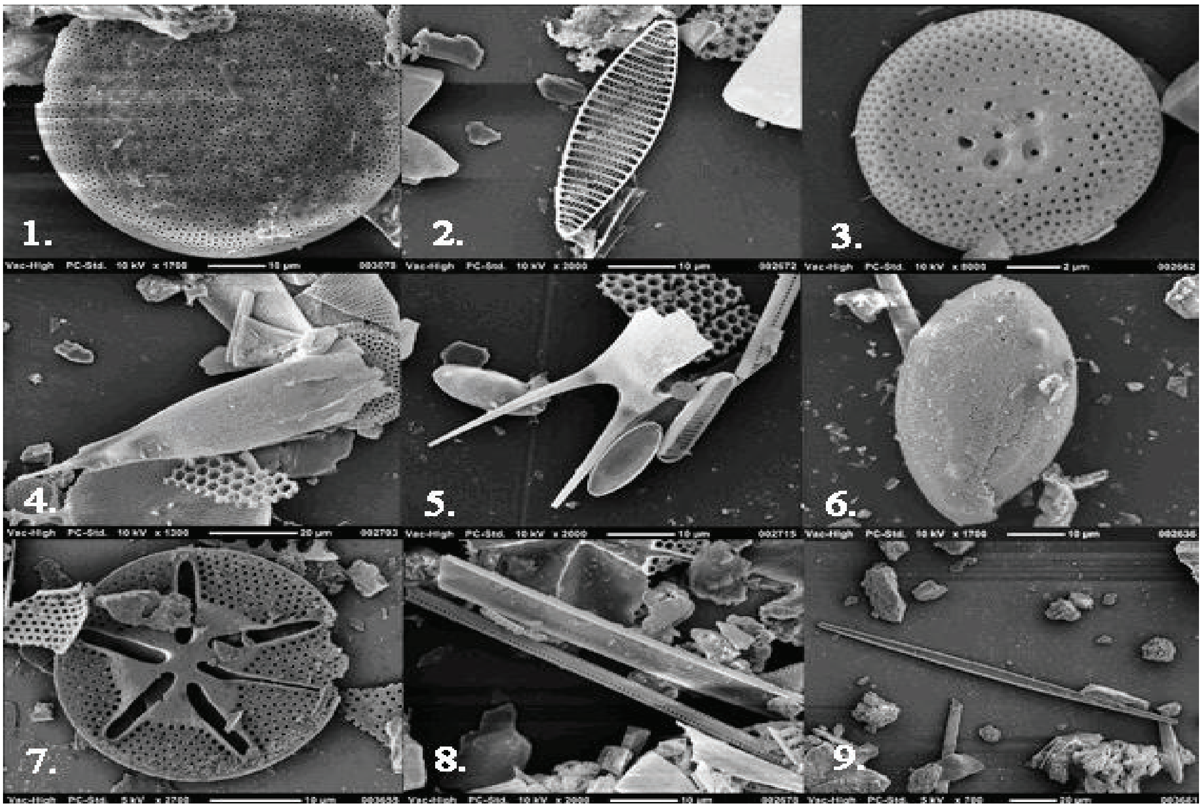

Fig. 3. Open-water and oceanic diatoms (SEM):
1 – Thalassiosira lentiginosa, 2 – Fragilariopsis kerguelensis, 3 – T. gracilis var. gracilis, 4 – Rhizosolenia styliformis, 5 – R. antenatta f. antenatta, 6 – Odontella weisflogii, 7 – Asteromphalus sp., 8 – Thalassiothrix antarctica, 9 – Thalassionema nitzschioides.

3. Tychopelagic species and epiphytes group, or marine semi-benthic diatoms (Fig. 4). Tychopelagic species need a substrate for reproduction, however they live as planktonsc organisms. They are epiphytic forms an integral part of benthos associations, however, they can encounter in plankton as sessile forms on macroalgae.

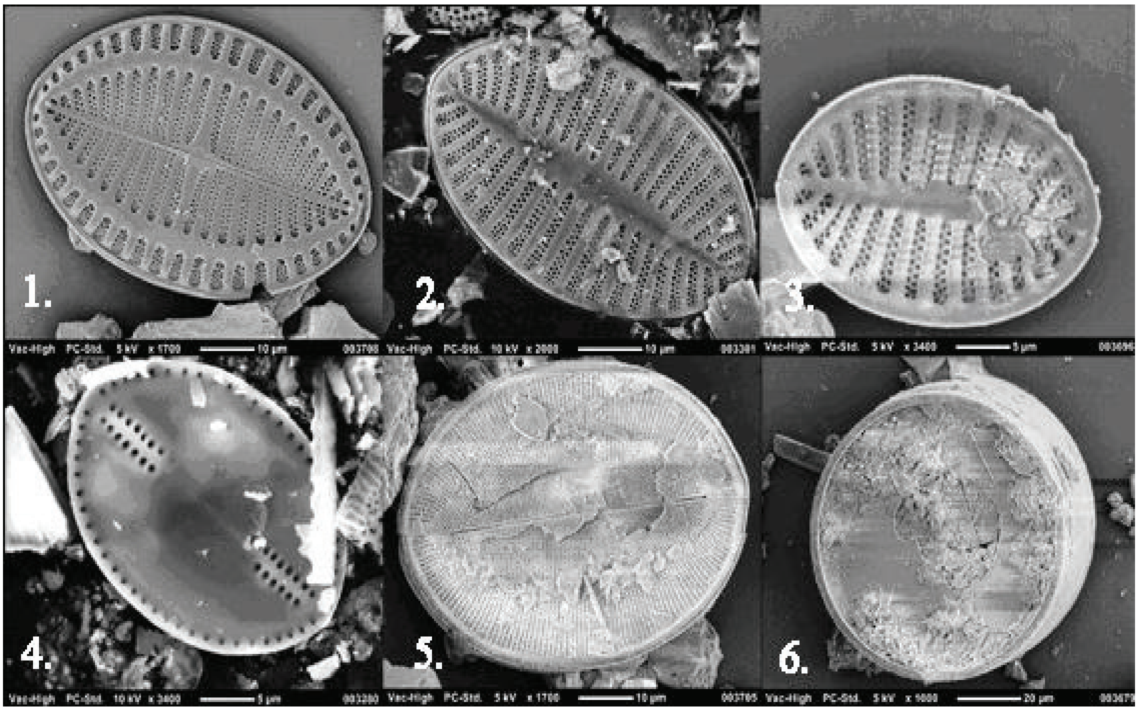

Fig. 4. Epiphytic and tychopelagic diatom species (SEM): *1 – Cocconeis fasciolata, 2 – C. fasciolata, 3 – C. costata, 4 – C. californica var. kerguelensis, 5 – C. infirmata, 6 – Paralia sol.*

4. Sea benthic group (Fig. 5). The expansion of these organisms directly depends on the basin depth. Their optimal habitat is the photic zone with the sea depth up to 50 m.

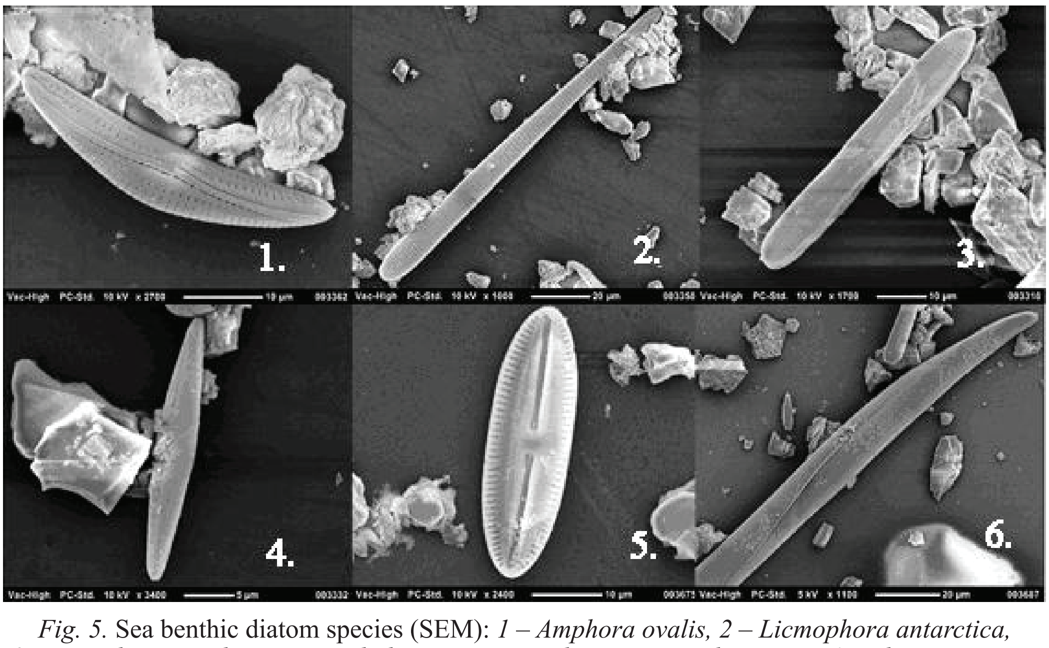

Fig. 5. Sea benthic diatom species (SEM): *1 – Amphora ovalis, 2 – Licmophora antarctica, 3 – Pinnularia quadratarea var. baltica, 4 – Navicula sp., 5 – Diploneis sp., 6 – Pleurosigma sp.*

The study of lateral distribution of these groups allows to identify 5 biofacies in the study area, to determine their habitats and to describe the shelf facial zones, existing during Holocene (Ogienko, 2015).

The study of vertical succession of diatom assemblages in the sections of bottom sediments presented a base for performing the paleoclimatic interpretation.

Three principal Holocene climatic phases are known in the western sector of Antarctica (Bak et al., 2007) (Fig. 6):

1 - Last Glacial Maximum, early Holocene (~ 23.40-8.3 ky BP), characterized by dense ice cover and decreased water bioproductivity.

2 - Climatic optimum, mid-Holocene (8.3-2.4 ky BP) with open water conditions and increased bioproductivity of siliceous plankton.

3 - Neoglacial event, upper Holocene (<2.4 ky BP) is characterized by partially open water conditions.

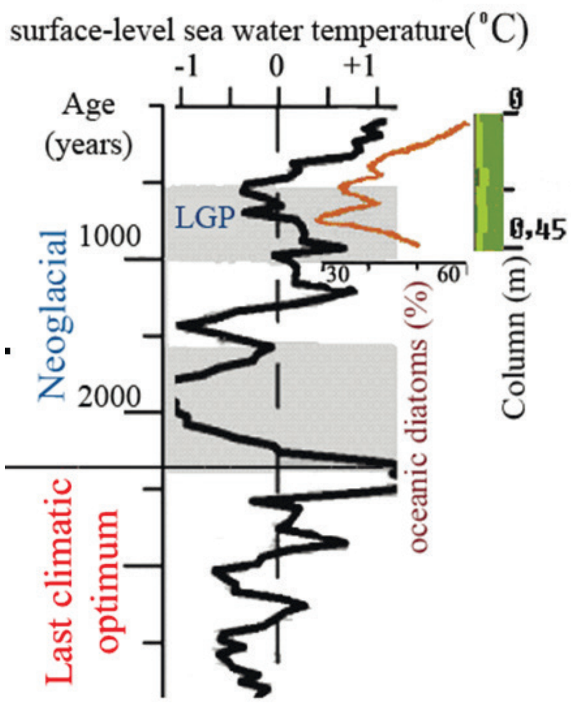

Fig. 6. Comparison of midyear surface-level sea water temperature changes during the Late Holocene, the Atlantic section of the Antarctica (Nielsen, 2004) is shown as a black line. A red line shows the subantarctic species amount in diatom assemblages in Site K98-09, LGP, Little Glacial Period.

Each of these phases is distinguished by a specific diatom assemblage with characteristic species composition and relation of antarctic vs subantarctic diatom groups content. The sequences of principal paleoclimatic events of the late Quaternary in the western sector of Antarctica were traced by core columns K97-18 from the south-western part of the Scotia Sea and K98-09 from the southern part of Drake Passage (area of Mordvinov Island, South Shetland Islands).

Furthermore, similar temperature fluctuations were identified on the base of O^{18} data and CO_2 variations from ice core, ice conditions, marine glacial deposits, and Holocene sea-level changes near Antarctic Peninsula, etc. (Stenni et al., 2017, Mulvaney et al., 2012, Bockheim et al., 2013) (Fig. 7).

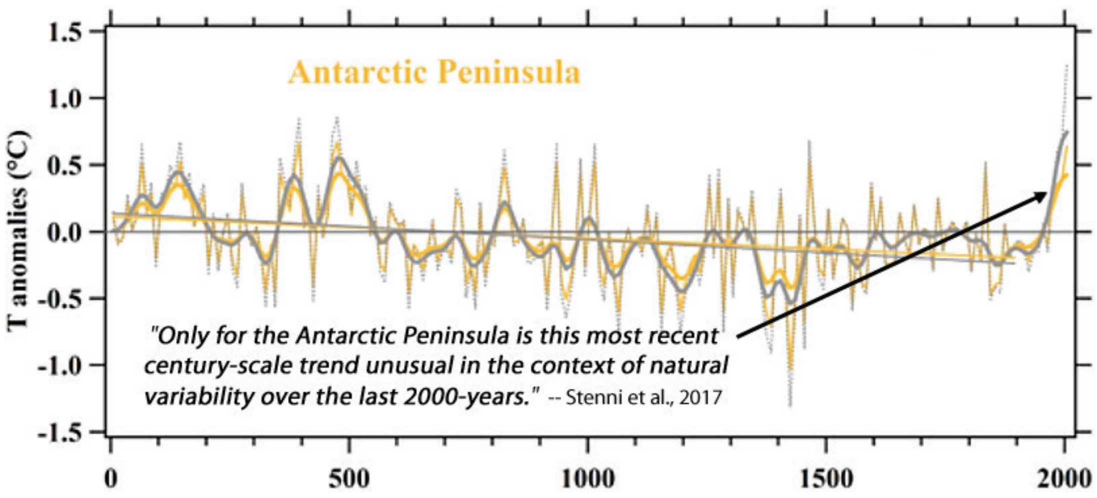

Fig. 7. Only for the Antarctic Peninsula this is the most recent century-scale trend in the context of natural variability over the last 2000 years (Stenni et al., 2017).

The Scotia Sea as a part of the oceanic basin has been formed in the late Paleogene as a result of separation of the Antarctic Peninsula from the South America. The sea occupies the area between the Drake Passage and South Sandwich Islands arc and is limited by the North Shetland Ridge in the north and South Shetland Ridge in the south. The major part of the basin floor is a flat bottom land with depths 3000-4500 m, lying far from the principal sources of clastic material deposition. The principal part in the transportation of the sedimentary material is played by icebergs (Lisicyn, 1994). The water circulation in the southern part of the sea is caused by the interplay of the cold undercurrent of the Weddell sea and the relatively warmer Antarctic Circumpolar Current (ACC). Low temperatures of near-surface water near South Orkney Islands in summer are controlled by the water supply from the Weddell Sea.

From the studies of sediment lithology and diatom taxonomy in the core K97-18 cross-section, taken in the south-western part of the Scotia Sea, two age intervals were identified, corresponding to two different climatic events.

The interval 0.5-0.38 m (>8.3 ky ago, late Pleistocene) corresponds to the final phase of the last peak of the Antarctic glaciation. To that time, the area was characterized by severe ice conditions with dense sea ice cover and iceberg drift with dominating ice-driven sedimentation. The sediments are represented by the lumpy gray siltstone with low clay content and considerable admixture of psammitic and gravel material. The ice-driven sedimentation was accompanied by the redeposition of earlier accumulated material of mid-Miocene diatoms.

The interval 0.38-0 m (from 8.3 ky ago till present) corresponds to the modern Interglacial period. The environmental condition in the area is close to the modern one: deep sea basin with strong oceanic impact and dense ice cover in winter, rapid thaw of sea ice in spring with formation of stratified water masses, short summer and the presence of drifting ice. The surface water temperature ranges from –1°C to +3°C, occasionally up to +4°C (average values from –0.5°C till +1.5°C). The diatoms are represented by almost equally proportioned modern antarctic and subantarctic plankton species. The sedimentation rate at this period is 4.6 cm/ky. The sediments are formed by the greyish-green siltstone with high clay content and admixture of psammitic and fine gravel material.

The Drake Passage (820 km width) is a significant constriction along the path of the ACC flow. According to various estimates, the opening of the Drake Passage began about 35 MA ago and had a global climatic impact not only for the Southern Ocean, but on the planetary scale (Lee et al., 2012). This event resulted in the formation of the modern ocean circulation pattern, triggering cyclic Antarctic glaciations and emergence of climatic environments, close to modern ones. Even the slightest increase in the ice density in the southern part of the Passage would constrain the water turnover between ACC and Weddell Sea and produce a dramatic impact on the eco-environments in the northern and north-western parts of the Antarctic Peninsula. During glaciations, the dense sea ice limited the transportation of ACC waters through the Passage, thus increasing the supply of the surface and middle-depth water masses of the northern ACC branch into the southern part of the Pacific and constraining water exchange between Pacific and Atlantic oceans. Thawing ice shelves and formation of open water environment resulted in both increased water exchange with the relatively warm ACC and cold water supply from the Weddell Sea to the embankment of the north-western part of the Antarctic Peninsula. As a result, certain areas underwent the lowering of surface water temperature together with general deglaciation.

Along the whole length of the K98-09 core column, taken in the southern part of the Drake Passage (area of Mordvinov Island, South Shetland Islands), the diatom assemblages of upper Quaternary close in composition and consist mostly of planktonic antarctic marine species (30-60% in assemblages) and subantarctic oceanic species (30-60%). About 10% is represented by the cosmopolitan species. Benthic and semi-benthic fauna is almost absent. The ecological structure of the assemblages points at the environment, which is in general close to the actual situation: an open sea basin with dense ice coverage in winter and drifting ice in summer, with essential heavy currents impact. In the vegetation season of diatomic algae the surface temperature of the water mass changes from –1.5°C to +4°C, the average summer temperatures range from –0.5°C to + 1.5°, the water column is poorly stratified.

According to the analysis of the content of antarctic vs subantarctic species in diatom assemblages and by the presence of indicator species the age of the core was determined in general to be Late Holocene, corresponding to the “Neoglacial” event (<2 400 years) (Bak et al., 2007). More accurate information can be retrieved from the comparison of variations of the sea surface mean temperature in the area (Nielsen et al., 2004) and content of oceanic diatoms in the sediment core. This allows to conclude, that the sediments of the core K98-09 were accumulated during last 900 years.

From the lithology of sediments and ratio between cold water antarctic species and relatively thermophile diatomic groups in assemblages, two different intervals of the core column were identified, which correspond to two climatic stages.

1. The interval 0.45-0.18 m corresponds to the time range 900-500 years ago and shows a remarkable coincidence with the so called “Little Ice Age” event. The environment to that period was determined by the moderate ice abundance, complicating the ACC circulation. The diatom species are dominated by cold water antarctic marine plankton. The sediments consist of noncalcareous greyish brown siltstone with low clay content and admixture of sand and gravel material. The sedimentation rate is 67.5 cm/ky.

2. The interval 0.18-0 m (from 500 years ago till present) corresponds to the modern warming phase. To that period the restoration of circulation of the oceanic water took place due to the increase of the surface water temperature and degradation of ice environment. Oceanic subantarctic species dominate among diatomic biota. The sediments are represented by the siltstone with moderate up to high clay content and admixture of sand and gravel material. The sedimentation rate is 36 cm/ky. The ongoing character of the modern warming is evidenced by the activation of carbonaceous organisms (most likely foraminifera): upper 3 cm of the sedimentary column (corresponding to last 80 years) contain the admixture of biogenic carbonate as an indicator of the warming trend. The carbonate sediments of the Drake Passage are known in its northern areas only and are controlled by the carbonate nanoplankton.

4. Conclusions

Based on the geology of late Quaternary bottom sediments in the Western sector of the Antarctic shelf, paleogeographic reconstruction of the late Quaternary environments, sedimentation patterns in water areas with distinct facial composition, and stratification of sea-floor sediments by the diatomic analysis. We done next conclusions.

Within the north-western shelf of the Antarctic Peninsula the accumulation environments for the veneer sediments were close to the modern environment, corresponding to the marine conditions of the continental shelf. According to characteristic features of silicate microalgae associations five biofacies were identified.

In the southern part of the Scotia Sea (South Orkney Islands) two different stages of veneer layer (50 cm thick) formation of sea-floor sediments Based on the ~~of~~ geology of late Quaternary bottom sediments in the Western sector of the Antarctic shelf, paleogeographic reconstruction of the late Quaternary environments close to sedimentation patterns in water areas with distinct facial composition, and stratification of sea-floor sediments by the diatomic analysis. We done next conclusions: the peak of the latest Pleistocene glaciation (>8.3 ky BC), characterized by severe ice conditions; and a Holocene postglacial stage with environments, close to modern ones and sedimentation rate about 4.6 cm/ky.

The analysis of the biosiliceous pattern of bottom sediments in the southern part of the Drake Passage shows, that the accumulation time of the 45 cm thick layer of sediments does not exceed 900 years. The paleogeographic environments in the study area are traced for this time period. Two climatic stages were identified: "Little Ice Age" (900-500 years ago) with moderate ice conditions and constricted circulation of surface water, sediment accumulation rate being 67.5 cm/ky; and the stage of rapid modern warming (from 500 years ago till now), which is characterized by the increase in surface water temperature and development of open water oceanic environments. The sedimentation rate for this period is 36 cm/ky. Upper 3 cm of sediment, corresponding to last 80 years, show the appearance of biogenic carbonate which is an indicator of global warming tendency.

The study of siliceous microalgae in the bottom sediments in the northern and north-western parts of the Antarctic Peninsula shelf has pointed at a wide range of possibilities for using the diatomic algae as reliable biomarkers for identification and characterization of facial zones in the basin, revealing the natural zonation of surface water, paleogeographic reconstruction and determining the chronology of Quaternary climatic events in polar latitudes.

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