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ANTARCTIC SUBGLACIAL AND SUBMARINE RELIEF: GEOMORPHOLOGICAL MAPPING OF PRE-GLACIAL RIVER VALLEYS

ABSTRACT

This pilot project was a part of a larger complex geomorphologic mapping of the entire Antarctic continent conducted by the team of researchers from St. Petersburg (Russia). Radar profiling data transformed into digital topographic models were utilized as raw materials for the research. Submarine and subglacial geomorphology is a scientific branch that could provide new findings while studying palaeogeographic environments of the Antarctic. River valleys are one of the clearest evidences of the pre-glacial development of territories. Researchers can initially investigate them using the system-morphological approach established and developed by A. N. Lastochkin. This clear methodological base and corresponding set of mapping methods – including creation of structural networks, compiling of difference maps, analysis of lineaments and vector fields – made it possible to map the main river basins, which are now buried under the ice sheet or represented by only detrital cones on the continental slopes. Such large drainage systems were identified and initially described within the entire Antarctic continent. They are, with no doubt, of pre-glacial age and have only fluvial nature. One of Antarctic regions – Lambert Graben – was studied more closely. We identified there two generations of valleys: river preglacial and pre-icecover ones. The latter are presumably associated with mountain glaciers preceding the formation of the ice sheet. Newer and more detailed profiling data passed through a prism of the system-morphological approach that can multiply our knowledge of subglacial topography as well as the past of Antarctica.

KEYWORDS:

the Antarctic, subglacial geomorphology, geomorphological mapping, pre-glacial river valleys

INTRODUCTION

The International Geophysical Year (1957-58) was a real starting point to study the submarine-subglacial relief of Antarctica. However, until the end of the twentieth century there was an obvious lack of data concerning basal topography [Barker *et al.,* 1999]. Radar profiling has made it possible to build the entire continent's models BEDMAP (2000) and BEDMAP-2 (2013). These have become a powerful incentive for further findings and developments. "Nevertheless, there are still many gaps in the study of the Antarctic subglacial relief and its development" [Ingólfsson, 2004]. This concerns also the pre-glacial history of Antarctica's topography. Now, we are at the

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very beginning of these studies. The study of pre-glacial environments could result in new knowledge about some global palaeoevents and trends, mineral resources allocation, modern dynamics of the ice sheet, etc.

This study of pre-glacial river valleys and palaeogeograpical environments of Antarctica was a part of the larger long-term project aimed at multi-level geomorphological mapping of the entire continent and some selected regions of Eastern Antarctica, which has so far received less scientific attention than the West Antarctic Ice Sheet [Bennett & Glasser, 2009]. The project was carried out by the team of geomorphologists from Saint-Petersburg State University (SPbSU), under the leadership of Alexander Lastochkin. The intermediary outcomes were published in Russian language in the two-volume monograph “Subglyazialnaja geomorfologija Antarktiki” [Lastochkin, 2006; Lastochkin, 2007] while the final ones appeared in the Geomorphologic Atlas of the Antarctic [Geomorfologicheskij atlas Antarktiki, 2011; The Antarctic. Geomorphologic Atlas 2013]. In addition, some results of this Antarctic project were presented in the collective monograph published by Cambridge University Press [Zwolinski, Boltramovich, Kejna, Lastochkin, Zhirov, 2016]. We are fully aware that these findings will be further specified in the continuing research of Antarctica’s subglacial topography.

The investigation of pre-glacial river valleys was based on a system-morphological study. This innovative approach provides a distinct understanding of relief morphology and development. It brings interesting results while studying not only the Earth’s surface but other geofaces and interfaces as well, including submarine and subglacial areas. From the clear allocation of morphologic elements and forms to the dynamics of processes – that is the paradigm. We believe that this method of morphological identifications and interpretations will be further developed and improved. Now we can say that it could be successfully utilized in different geostudies, for various theoretical and applied purposes.

METHODS AND MATERIALS OF RESEARCH

International BEDMAP data were the general base for the geomorphological mapping of Antarctica. The selected regions – Lambert Graben, Princess Elizabeth Land, and Vostok Lake area – were explored based on much more detailed radar profiling data obtained by the Polar Marine Geosurvey Expedition (PMGE), St. Petersburg, Russia. Namely radar studies, as emphasized by many researchers [Bingham *et al.*, 2010], have achieved the greatest progress in the study of subglacial environments and their past.

The system-morphological approach [Lastochkin, 2002; Lastochkin, 2011] has been used for the mapping of the Antarctic submarine-subglacial relief. First, we analyzed topography and fixed: 1) point, 2) linear, and 3) areal elements of the submarine-subglacial interface. All these elements were allocated by means of an analysis of four principal geomorphological functions: 1) altitude (or depth), 2) its first derivative (gradient), 3) its second derivative (vertical curvature), and 4) horizontal curvature.

The next step is to combine elements of abovementioned three kinds into single geomorphosystems (landforms) – using the method of extended symmetry. Finally, we combined structurally and originally similar landforms into larger areas and, thus, outlined the geomorphological provinces (regions) of Antarctica. That was the end of the general geomorphological mapping stage and, correspondingly, the beginning of the specific geomorphological studies.

The system-morphological approach, which is been developed by A.N. Lastochkin, is unfortunately little known outside Russia. Nevertheless, Russian researchers have successfully used it in the study of the northern continental shelf of Eurasia [Lastochkin, 1976], and then to study subglacial relief of Antarctica, submarine relief of Mid-Atlantic Ridge as well as for other not easily accessible areas.

Figure 1. *Vostok Lake basin. Ideal patterns of structural networks of subglacial and submarine relief*

1. Longitudinal lines of Y-system. 2. Cross lines of X-system.
3. Border lines of ideal patterns and their fragments. 4. Discontinuities of structural network.
5. Anomalous strikes of crest structural lines (a), keel structural lines (b).
6. Directions of the higher gradient of longitudinal and cross lines. 7. Index of pattern (see Figure 2)

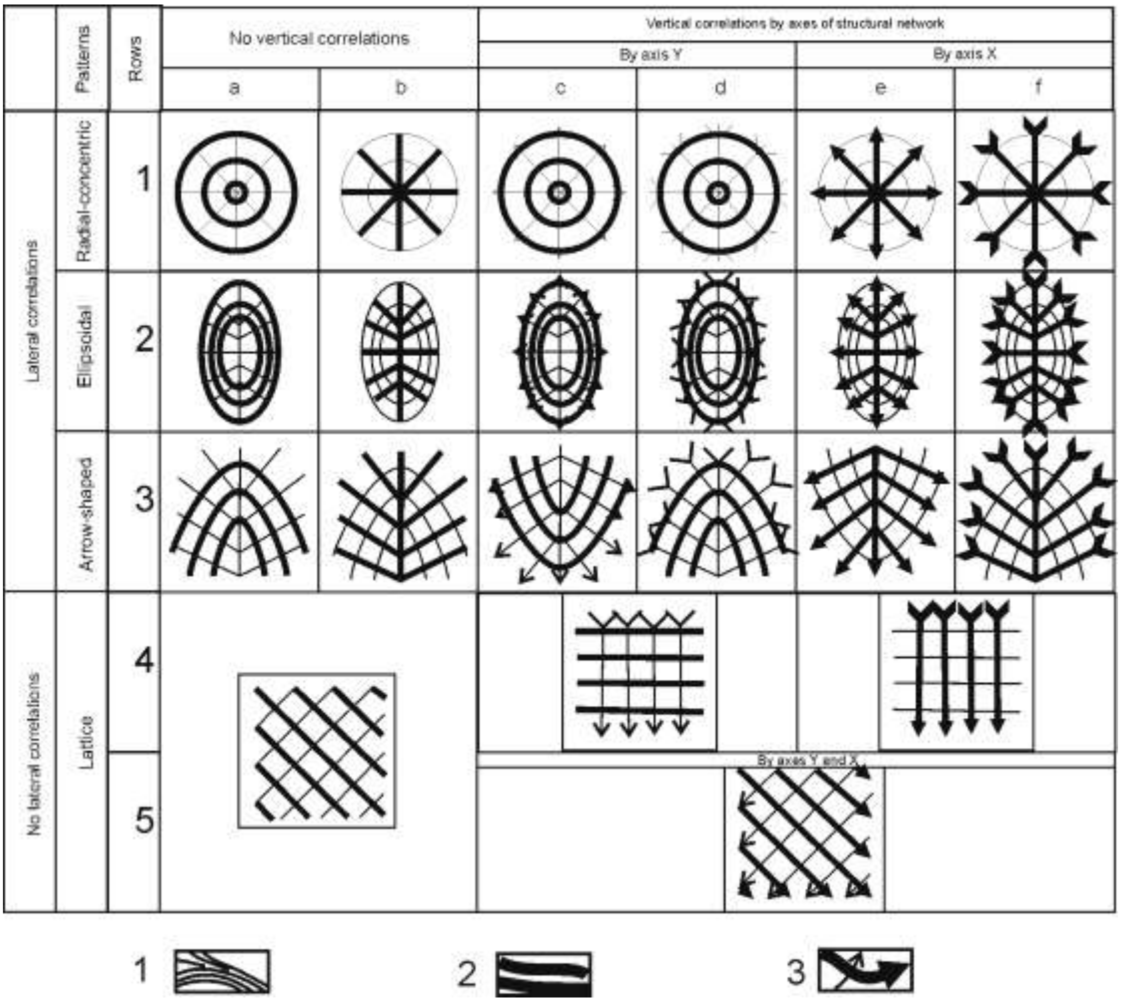

Figure 2. *Ideal patterns of structural networks*

1. Longitudinal lines of Y-system. 2. Cross lines of X-system.
3. Directions of the higher gradient of longitudinal and cross lines

The specific geomorphological studies included structural analysis that revealed areal and linear morphostructures – tectonically based landforms and groups of landforms. The study of linear morphostructures allowed drawing conclusions about the ancient pre-glacial river network of Antarctica.

When studying the subglacial topography we have to deal with the valleys that are barely reflected on radar profiles and grid-based hypsobathymetric maps. Methods of subaerial morphostructural studies are almost useless under the conditions of Antarctica. Nevertheless, there are several areas of analysis:

1) <u>Structural networks</u>

This is a new approach in morphology studies – structural networks. We compile them on the basis of crest (they connect apices and tops, i.e. maximum heights) and keel (they connect thalwegs and bottoms, i.e. minimum heights) structural lines, which form the backbone of relief. These networks reflect natural horizontal curvatures of the Earth's surface and interfaces, such as the submarine and subglacial ones. Symmetrical analysis of structural networks allows detecting various morphotectonic elements: circular, curvilinear, and rectilinear (Figures 1, 2). The latter are the most useful while allocating linear morphostructures. The map of the structural networks can also be utilized as an important source of information concerning Antarctic neotectonic uplifts and subsidences.

2) Lineament analysis

Tectonic faults are usually expressed in the relief because of fluvial erosion. This might be true also for the pre-glacial Antarctica – when the large transit river valleys were incised into the Mesozoic peneplain and oriented toward the seas of the Southern Ocean.

Given the ice sheet's existence and a still rather weak geophysical database, we must rely on the lineament analysis in order to identify linear morphostructures. The lineament analysis comprises the studies of orientation and density of lineaments. Lineaments concentrations provide us with valuable information about the position and characteristics of different linear morphostructures.

There are two morphological kinds of lineaments. The first of those are tied up to continuous disjunctive dislocations that are expressed through straight parts of valleys, rifts, and grabens. These are, for example, the subglacial valleys in the areas of Lambert Graben and Princess Elizabeth Land. The lineaments that are related to the subglacial valleys around Vostok Lake are not so clear. The second category of lineaments consists of morphologically discontinuous disjunctive elements that are marked through the zones of tectonic fractures. They are less expressed and much more difficult to be interpreted morphologically.

3) Morphosculptures

A third area to study Antarctic pre-glacial valleys is the analysis of morphosculptures. These are landforms created by above-the-surface (exogenous) forces but controlled by tectonic movements, which are of glacio-isostatic or other nature.

Direct investigation of subglacial morphosculptures needs a higher density of ground-based radar profiles. Only air-based radar profiling does not provide sufficient details. Within the project, the most valuable results were obtained for the area of Lambert Graben where we are now confident enough to outline a plurality of subglacial and submarine valleys of several categories (Figure 3).

RESULTS OF RESEARCH AND ITS DISCUSSION

Many scientists have emphasized that vast area under the ice sheet was preserved from erosion and, therefore, pre-glacial relief kept its main features [Kleman, 1994; Kleman & Hättestrand, 1994; Hättestrand & Stroeven, 2002]. This was confirmed by the dating by cosmogenic radionuclides of surface deposits [Fabel *et al.*, 2002; Stroeven *et al.*, 2002]. Deep and lasting preservation of subglacial relief provides excellent opportunities of palaeogeographical interpretation of morphology of the current subglacial-submarine interface both within the continent and on the continental margins.

The palaeogeographical reconstruction can be divided into two epochs – "pre-glacial" and "pre-icecover". The first is aimed at studying non-glacial (mainly fluvial) morphosculpture, and the second includes the studies of forms of the subglacial-submarine interface, which are associated with mountain glaciation, Alaskan type and other forms of glaciations preceding the formation of the ice sheet on the continent.

Identifications of the river flow in pre-glacial time were the result of detection of detrital cones on the continental slope of Antarctica. They were revealed in association with corresponding drainage basins and watersheds on analytic and orographic maps. Detrital cone identifications on the map of the pre-glacial fluvial morphosculpture (Figure 4) are based on the following morphological features:

- The majority of detrital cones protrude far into ocean as periclinal forms, complicating the morphology of the continental slopes. They can be traced to a maximum depth, covering the foot and the most of the slope above.
- The surface of detrital cones is formed by the divergence, including that of submarine canyons, which provided transit pathways for turbid runoffs with terrigenous material, as well as slurry watersheds dividing the canyons from the "point of delivery" above the shelf edge down the continental slope.

- Detrital cones on the continental slope having divergent (“fan”) keels and crest lines were the areas of accumulation of terrigenous material brought in to the edge of the shelf by river and fluvioglacial flows in pre-glacial or interglacial periods.
- Sometimes, there is a deep cut in the edge of the shelf above the canyon, extending to the continental edge and securing access of the main river valley to the slope during the maximum regression, which then transforms into the system of divergent submarine canyons.

Because of the ancient, pre-icecover age of detrital cones and submarine canyons they have lost their morphological manifestation due to the subsequent subaqueous erosion by ice water flows, which destroyed some cones either completely or only their flanks. Seasonal cold (as compared to warmer ocean water) melt water penetrates cones, flowing over the edge of the shelf along its entire width. Down the slope, these flows gradually concentrate and even form channels, joining into canyons.

Large detrital cones on the narrow parts of continental slope indicate that there was an extensive removal of terrigenous material during ocean regressions. Rivers must be responsible for that removal as is the case of modern Amazon, Congo, Ganges, etc.

There are clear differences in the structure of the capes (continental promontories) and the three types of continental slopes: centroclinal, periclinal, and monoclinal.

The detrital cones on the continental slopes are the least developed on the monocline ones. They correspond to the smallest catchment areas representing a narrow coastal zone. Those coastal zones are separated from the mainland by alongshore mountain ranges and swells. The widest detrital cones or their fragments correspond to the largest basins, including the highest orogens, which still exist in the form of mountain ranges and highlands (with the exception of Byrd Plain).

The connection between the land drainage basins and the canyons on the continental slope is often interrupted by a system of circumpolar uplifts and troughs, extending along almost the entire edge of the shelf. This system is a younger relative to the reconstructed system of channelized deliveries of materials from all over the continent to the edge of the shelf and beyond – even to the continental foot. It was a result of the pressure redistribution of the ice cover on the Earth's crust and of the bulge of mineral masses from under the cover on its periphery and coastal zone. In this case, many of the “points of delivery” of alluvium have lost their distinctive locations.

On the Figure 4 the assumed Antarctic deep-water detrital cones are numbered (Arabic numerals) in accordance with their associated drainage basins (Roman numerals).

One should take into account a common origin of neotectonic movements, which have controlled the structural plan of the continent since pre-glacial time – 34 million years ago ([Florindo *et al.*, 2003; Antarctic Climate Evolution, 2009; Barrett, 2009; Turner & Marshall, 2011]). Presumably, further transformations have taken place mostly in the direction of increase of the vertical contrast – without significant lateral changes. This provided a preservation of the entire orographic- and hydrographic plan, which is reflected in the current subglacial-submarine relief.

The maps of polybasic surface (Figure 5) and its vector lines (Figure 6) provide guidance on the direction of river runoff. Chains of identically oriented areas having merging stream lines reflect the direction of concentrated runoff in pre-glacial time.

In this way, for example, consensus was reached on the issue of main runoff directions, leading to the Filchner Ice Shelf, the least explored of the Western Plain of Antarctica (basin XI on Figure 4). The first channel is represented by the submountain trough that is positioned to the south of the Range of Dronning Maud Land. The second one is occupied by the valleys on the piedmont plain separating this range from the lowest southern part of Western Antarctic Plain. The last channel is the valley that drained this part of the plain.

It might be noted the longtime evolution and conservatism in the position of some of the river valleys and their fragments. They were preserved in geological sections, even during the alternation of periods of regressions with repeated transgressions. The stability of the river valleys is determined by their disjunctive predetermination.

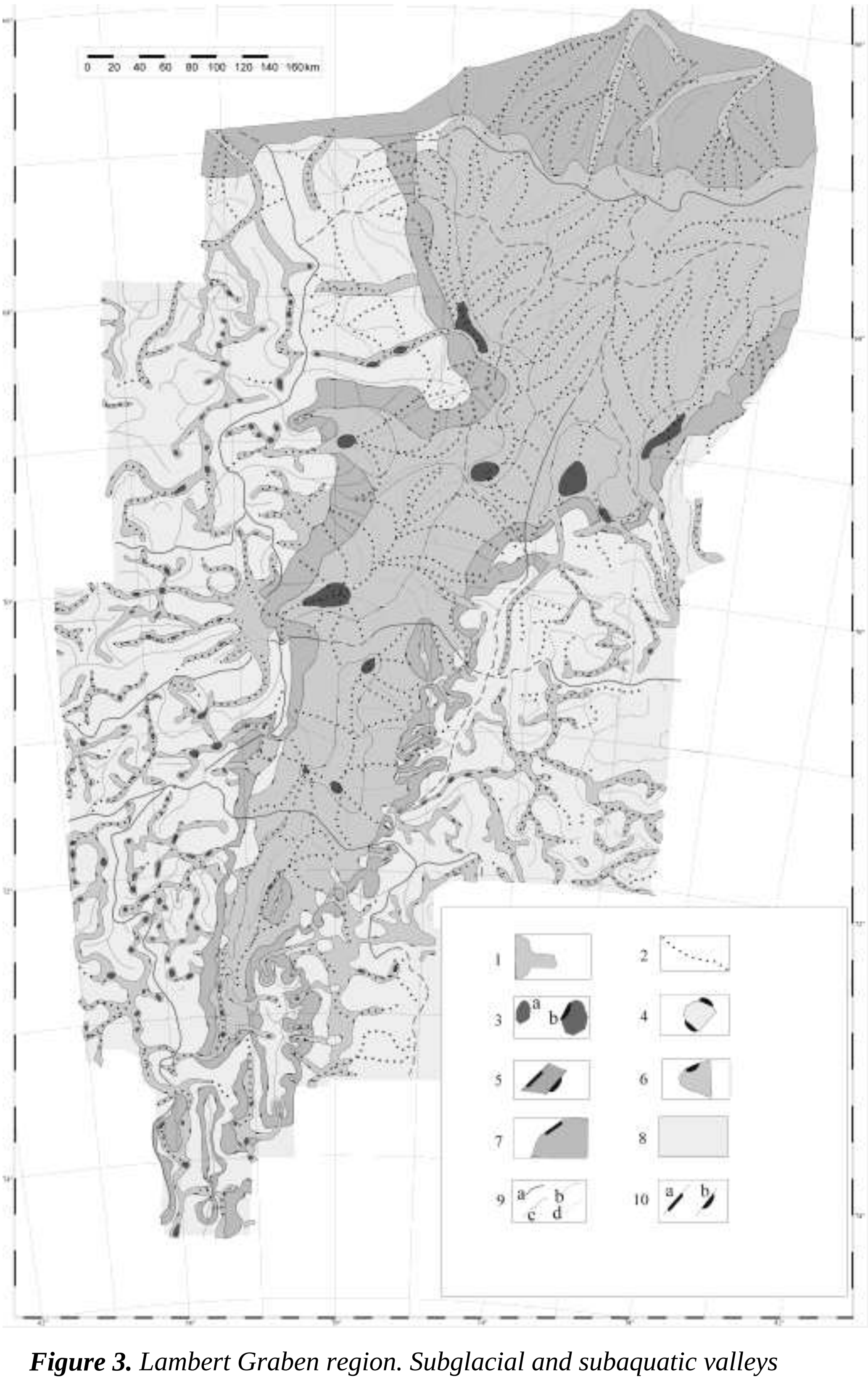

Figure 3. *Lambert Graben region. Subglacial and subaquatic valleys*

1. Subglacial and subaquatic valleys and glacier lake basins;
2. Thalwegs of valleys, drainage hollows and submarine canyons; 3. Depressions inside valleys (a), basins (b);
4. Assumed end moraines and (or) detrital cones**;** 5. Lambert Graben sides and main continental cliffs;
6. Bottom of Lambert Graben and adjacent part of Cooperation Sea;
7. Shelf edge and continental slopes; 8. Above-the-valleys relief;
9. Major (a, c) and minor (b, d) iceshed and watershed lines that are identified reliably (a, b) and presumably (c, d);
10. Convex (a) and concave (b) bends lines

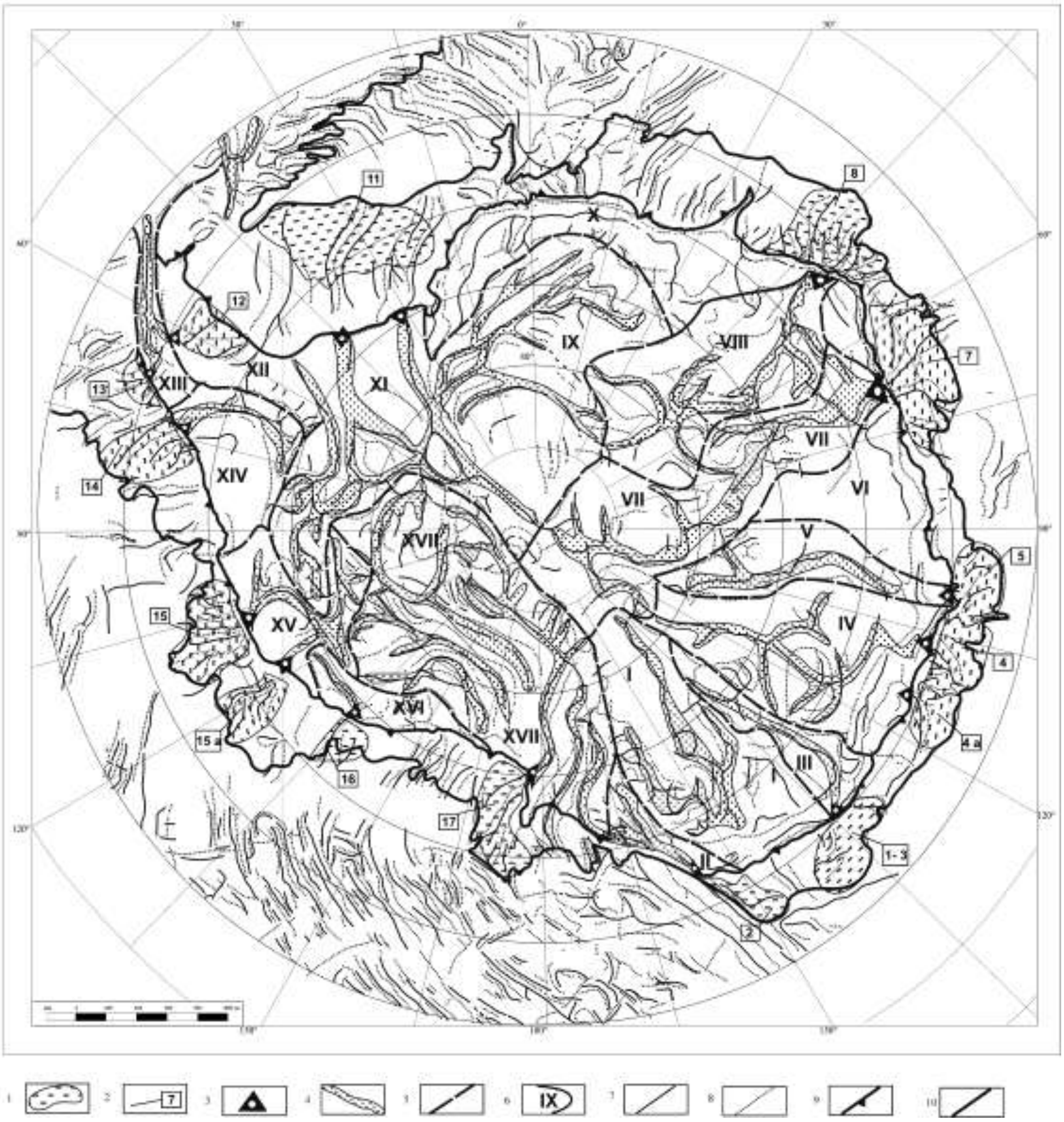

Figure 4. *The Antarctic. Main pre-glacial fluvial landforms and elements*
1. Detrital cones on continental slopes; 2. Numbers of detrital cones;
3. Points of alluvium delivery by rivers to the edge of the shelf; 4. Largest valleys;
5. Main watershed lines, border lines of drainage basins; 6. Drainage basins
Structural lines: 7. Keel lines; 8. Crest lines; 9. Edge of the shelf;
10. Lower border line of continental slopes

CONCLUSIONS

General features of the pre-glacial palaeogeographical environment of Antarctica (Figure 4) were reconstructed with the account of the origin of the morphotectonic and orohydrographic plans, and the long-term development and the history of the river valleys.

Contours of ancient Antarctic watershed spaces can be identified also despite the lack of data about hypsobathymetry of the subglacial-submarine interface and its development during ice-sheet existence. This development can be attributed to mostly vertical high-amplitude neotectonic and glacio-isostatic movements, which lasted tens of million years.

One can speak about the long-term lateral stability of watershed spaces also because of the presence of ancient, even pre-Mesozoic, peneplains with preserved weathering crusts within the present surface outcrops. Geological and geophysical data of the distribution of the sedimentary basins in Antarctica with mainly Upper Mesozoic-Cenozoic strata and alluvial deposits, also contributes to the reconstruction of ancient fluvial landforms.

Figure 5. *Antarctica. Polybasic surface of subglacial and subaquatic relief*
1. Isobases in 200 m

BEDMAP offers a good but still insufficient database. Pre-glacial valleys can be defined with confidence against highlands and ridges. We associate these valleys with grabens and intermountain troughs, which are occupied in modern humid regions by persistent river valleys. Frequent restructurings of the river network are more common for the lower platform plains. This can be seen in obvious angulations and bifurcations.

We have to emphasize the fact that despite a number of new breakthrough works in the sphere of glacial geology the interaction mechanisms between the ice sheet and its bed are still arguable [Bennett & Glasser, 2009; Anderson, 1999; Benn & Evans, 2010; Guffey & Patterson, 2010; Marshall, 2012; Remote Sensing of the Cryosphere, 2015]. These mechanisms vary from the frozen and preserved bed to fast ice streams that influence the bed to a high extent.

Reconstructions of palaeorelief and landscapes based on studies of ice-free areas and shelves are common in recent times [Stokes & Clark, 1999; Stokes & Clark, 2002; Glacial Landsystems, 2003; Ó Cofaigh *et al.*, 2008; Chiverrell, 2013]. However, reconstructions of pre-glacial relief within subglacial areas are so far rare and controversial because of lack of data and impossibility of dating. Our reconstruction also suffers from these disadvantages.

Apart from the restructuring of the morphology, there are several difficult additional questions to answer. We cannot accurately determine the valleys of different generations. Other confounding factors from pre-glacial time also can hardly be reliably estimated at this stage of the research.

Currently, firm conclusions based on the accuracy of radar materials can only be achieved in some areas where ground-based profiling was performed. Therefore, a reliable identification of the subglacial valleys takes place in the areas of Vostok Lake, Lambert Graben, and Princess Elizabeth Land.

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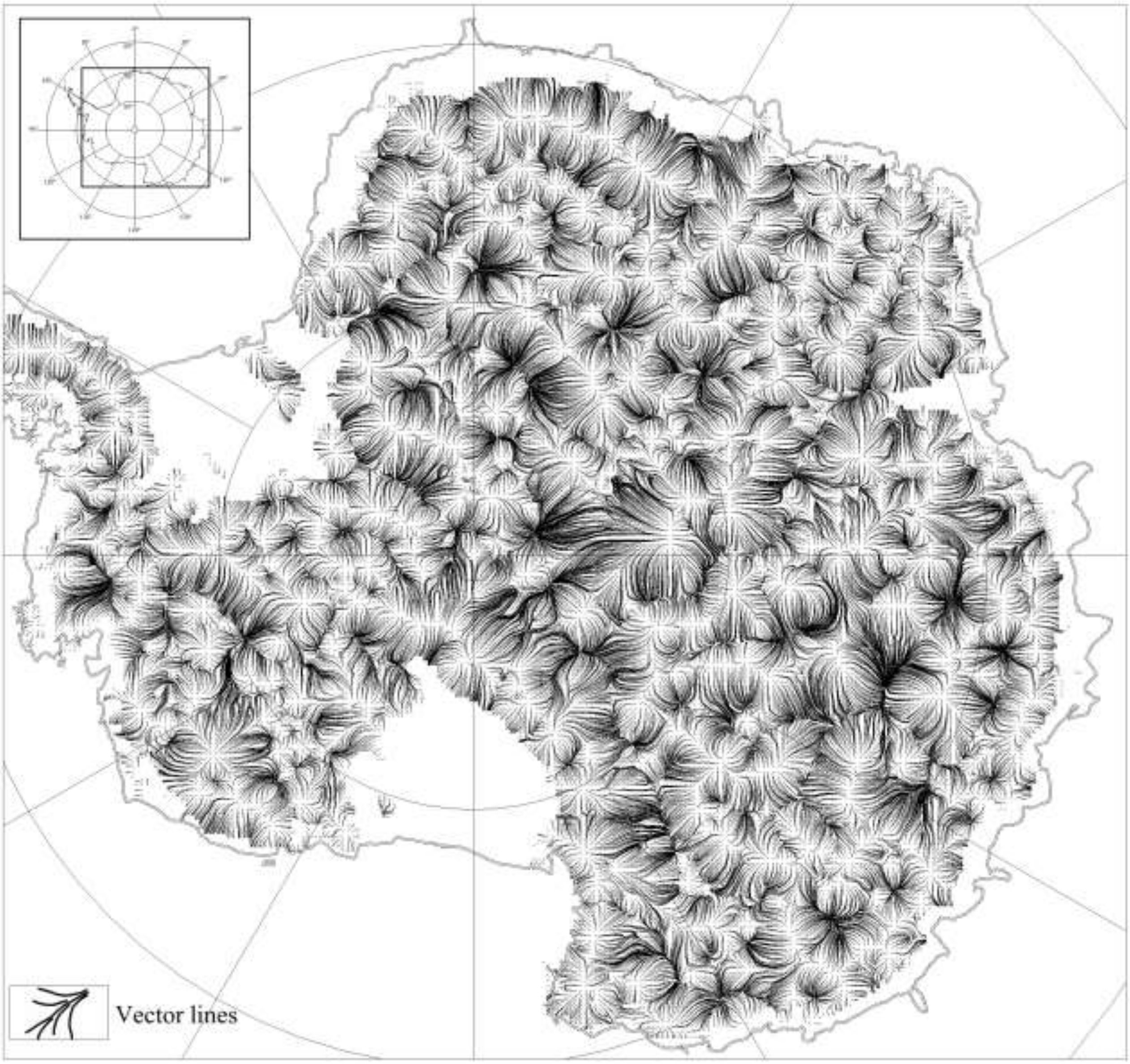

Figure 6. *Antarctica. Vector field of polybasic surface*
1. Vector lines

Our results were obtained based on the BEDMAP data. No doubt, the new data from the BEDMAP-2 project will help to get a more detailed picture of the pre-glacial palaeogeographical environments of Antarctica. Some valuable discoveries concerning the subglacial-submarine relief have already been made in Western Antarctica. For example, Gales *et al.* [2013] made a substantial contribution to the understanding of morphology of the shelves, upper continental slope, and sub-marine canyons. The "discovery of a subglacial basin under Ferrigno Ice Stream up to 1.5 kilometers deep that connects the ice-sheet interior to the Bellingshausen Sea margin and whose existence profoundly affects ice loss" by Bingham *et al.* [2012] is the result of detailed ground-based radar and seismic profiling. These researchers and others agree that the modeling of Antarctica and its separate regions, unfortunately, up to the present time is restricted "by lack of knowledge of basal topography and subglacial geology".

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