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# EXPLORATION OF GAMBURTSEV SUBGLACIAL MOUNTAINS (EAST ANTARCTICA): BACKGROUND AND PLANS FOR THE NEAR FUTURE

ABSTRACT. The Gamburtsev Subglacial Mountains (GSM), located in the central East Antarctica, were discovered by the Soviet team of the 3rd Complex Antarctic Expedition in 1958–1959. The GSM has highly dissected Alpine topography reaching maximum elevations of 3000 m. The mechanism driving uplift of the young-shaped GSM in the middle of the old East Antarctic Shield is unknown. With only limited constraints available on the topography, geology, and lithospheric structure, the origin of the GSM has been a matter of considerable speculation. The latest interpretation suggested that the GSM were formed during Permian and Cretaceous (roughly 250–100 Ma ago) due to the combination of rift-flank uplift, root buoyancy and the isostatic response. Later on the Antarctic Ice Sheet covered the range and protected it from erosion. However, this theory cannot explain lack of erosion process during many millions years in between uplifting and beginning of glaciation. The next step of the GSM exploration focuses on the direct observation of ice sheet bed by drilling. In order to penetrate into subglacial bedrock in the GSM region the development activity already has been started in China. It is proposed to use cable-suspended drilling technology and movable drilling shelter that can be transported to the chosen site with crawler-tractor. The first field tests of the drilling equipment are planned to carry out near Antarctic coast in season 2015–2016, and drilling to the bedrock would be finished during next two seasons.

KEY WORDS: subglacial environment, Antarctic tectonics, bedrock drilling

## INTRODUCTION

Covering nearly 14 million km$^2$, Antarctica is the coldest, driest, highest, and windiest continent on the Earth. While it is challenging to live and work in this extreme environment, this region offers many opportunities for scientific research. One of the most important frontiers of Antarctic exploration is study of subglacial topography and geology, which is less well known than the topography of Moon and Mars, obviously because of the thick ice sheet covered about 98% of the continent and extremely severe conditions.

The rocks of the Antarctic crust are exposed primarily on the Antarctic Peninsula, in the Transantarctic Mountains of East Antarctica, a major mountain belt some 3000 km in length that rises to over 4500 m in height, in the Ellsworth Mountains of West Antarctica, and in the extinct volcanoes of Marie Byrd Land (Fig. 1). In addition, small mountain ranges project through the East Antarctic ice sheet in Dronning Maud Land, in Enderby Land, in Mac. Robertson Land, and in a few places in Wilkes Land. The Sentinel Range of the Ellsworth Mountains in West Antarctica includes the Vinson Massif, which contains the highest peak in Antarctica at 4901 m a.s.l. [Stonehouse, 2002].

The present elevation of the bedrock surface of some parts of East and West Antarctica is actually below sea level (Fig. 2). For example, two large subglacial basins in Wilkes Land of East Antarctica lie below sea level. The bedrock surface of most of West Antarctica is also below sea level partly because

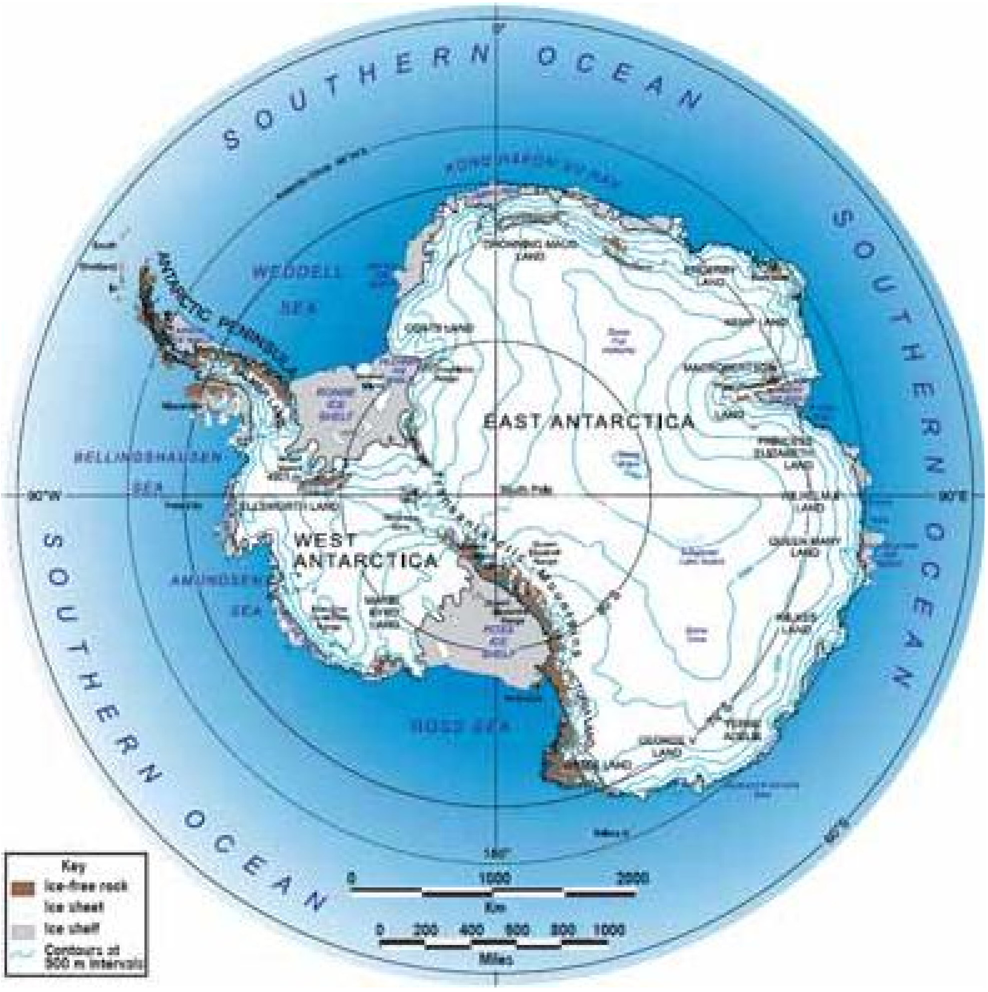

Fig. 1. Antarctic surface topography. Transantarctic Mountains divide Antarctica in two parts: West Antarctica and East Antarctica correspond roughly to the eastern and western hemispheres relative to the Greenwich meridian [http://geology.com/world/antarctica-satellite-image.shtml]

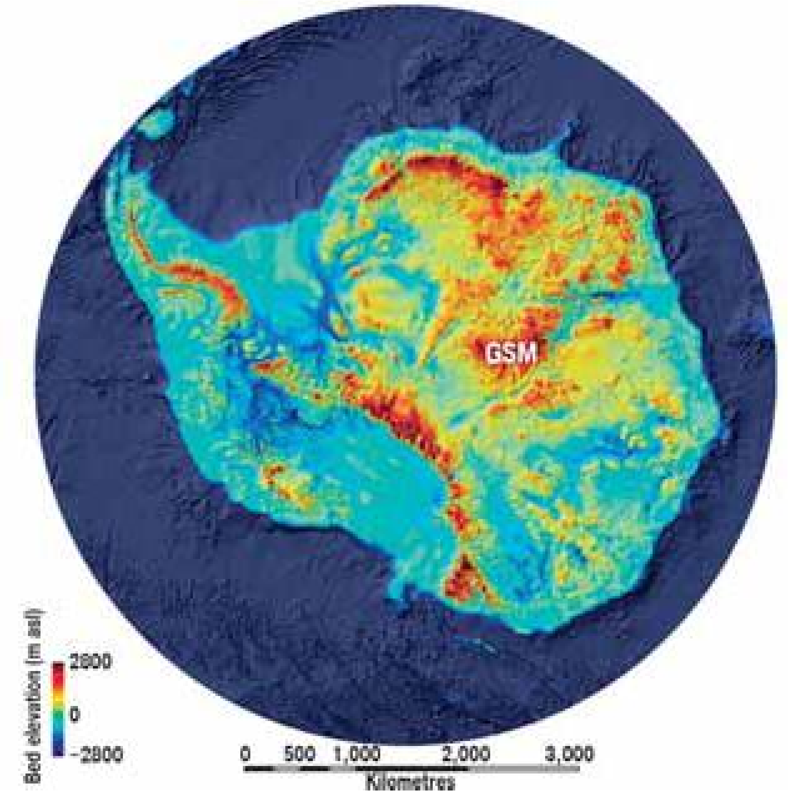

Fig. 2. Antarctic bedrock topography. Bedmap2 bed elevation grid is based on data from a variety of sources, including many substantial surveys undertaken over the past 50 years [Fretwell et al., 2013]

of the mass of the overlying ice sheet. The Gamburtsev Subglacial Mountains (GSM), located in central East Antarctica, has highly dissected Alpine topography reaching maximum elevations of 3000 m and a median elevation of about 1400 m in the north–south-trending [Ferraccioli et al., 2011].

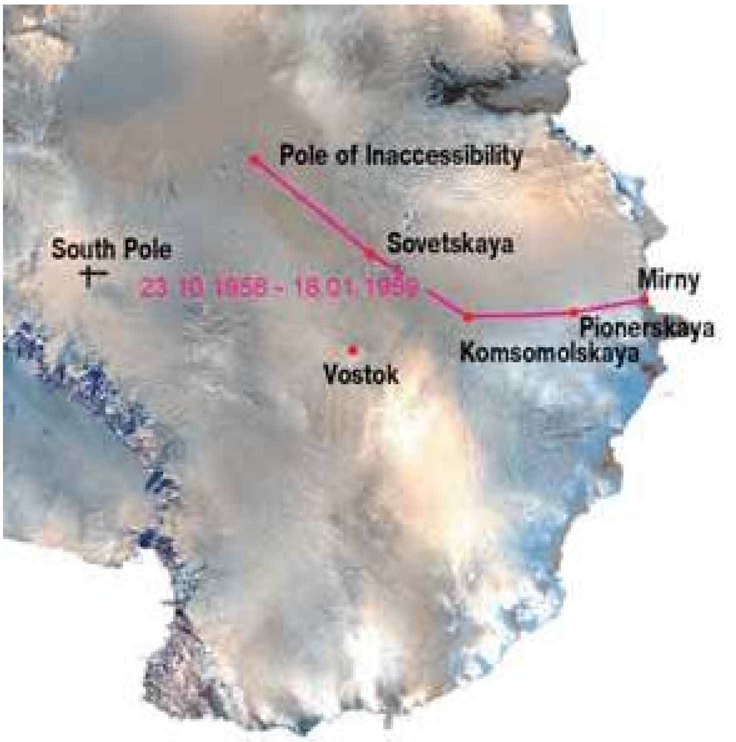

**Fig. 3. Traverse route of the 3rd Complex Antarctic Expedition (23.10.1958–18.01.1959)**

Among other subglacial objects the GSM are one of the most enigmatic features on the Earth. The range has become the subject of great scientific interest because the mechanism driving uplift of the young-shaped GSM in the middle of the old East Antarctic Shield is unknown [Talalay and Markov, 2012]. The GSM may have served as a nucleation point for the first large-scale ice sheet that formed in Antarctica as the Earth's climate cooled roughly 34 Ma ago [DeConto and Pollard, 2003]. The tectonic and glacial histories of Antarctica are tightly linked [Zapol, 2011]. Without its high topography, the history of the Antarctic ice sheet would have been quite different. Without the continental glaciation the subglacial mountains of Antarctica would have been quite different. Understanding the mechanisms and timing of the formation of the GSM is linked to the understanding of the changing climate of Antarctica and of the planet in the past.

## DISCOVERY

The GSM were discovered by the Soviet team of the 3rd Complex Antarctic Expedition[1] in 1958–1959. The unique traverse from Mirny station to the Pole of Inaccessibility was underway during 88 days and overcome about 4300 km (Fig. 3). As a result of seismic and gravimetric surveys the first profile of the East Antarctic Ice Sheet has been built (Fig. 4), and in the region of the highest point of the ice sheet a huge subglacial mountain range was discovered [Sorokhtin et al., 1960]. It was named as 'Gory Podlyednye Gamburtseva', for Soviet geophysicist Grigory Gamburtsev (1903–1955), one of the creators of modern seismology. The Advisory Committee on Antarctic Names (ACAN) accepted the English interpretation of this geographical feature 'Gamburtsev Subglacial Mountains' in 1975.

After the GSM discovery first geophysics appeared here only in 1974. The joint project of the airborne radio-echo sounding carried out by the Scott Polar Research Institute (Cambridge, UK), U.S. National Science Foundation and the Technical University of Denmark yielded multiple bedrock profiles in this region [Turchetti et al., 2008]. The presence of the GSM was confirmed, and the map of Antarctic bed topography issued in 1983 contained a quite detailed description of the GSM [Drewry, 1983].

Exploring the history of the East Antarctic ice sheet and lithospheric structure of the GSM were the primary goals of the Fourth International Polar Year (2007–2009). At that time multi-national and multi-disciplinary Antarctica's Gamburtsev Province (AGAP)

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[1] Complex Antarctic Expedition, USSR (the 1st CAE was formed in 1956); later, the expeditions were referred to as Soviet Antarctic Expeditions (SAE) and Russian Antarctic Expeditions (RAE).

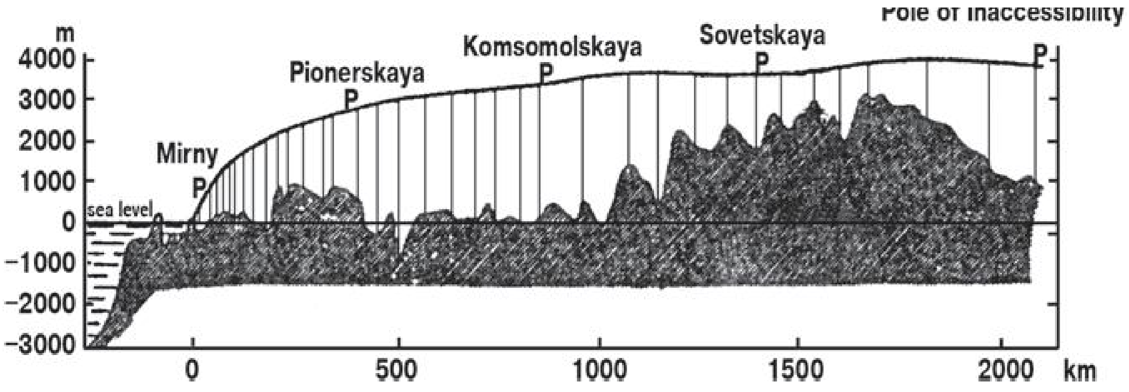

**Fig. 4. First profile of East Antarctica: vertical lines indicate the points of joint seismic and gravimetric observations, between which the profile was built according to the gravity survey [Sorokhtin et al., 1960]**

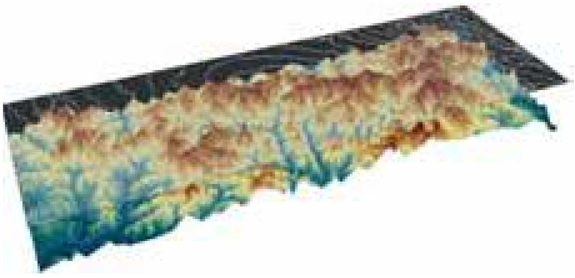

**Fig. 5. 3D-modell of the GSM built up according with results of AGAP geophysical survey (Credit: T. Creyts, Lamont-Doherty Earth Observatory of Columbia University, USA)**

project was founded by 7 countries: Australia, Canada, China, Germany, Japan, the United Kingdom, and the United States [Bell, 2008]. Unfortunately, Russian scientists, discoverers of the GSM, did not attend this project. The AGAP partnership included aerogeophysics, traverse programs, passive seismic experiments and shallow ice core drilling. The surveys were targeted at understanding the tectonic origin of these enigmatic mountains to provide crucial new inputs into ice sheet and climate models. The modern-day remote-sensing technology and 3D-modelling revealed a very jagged landscape of the GSM (Fig. 5).

It was found that the GSM have about the same size as the European Alps, and very sharp peaks and valleys are remarkably similar to the Alps themselves. It should be noted that Alps were formed as a result of the collision of the European and African tectonic plates and uplifted during the Paleogene and Neogene periods (i.e., about 65 to 2,6 Ma ago). It all adds to the mystery from the tectonic perspective of how the GSM were created in the central part of East Antarctic Shield, where such processes do not occur, at least in the last 100 million years.

In this connection one of the scientists joked: "It is like opening the door of an Egyptian pyramid and finding an astronaut inside". There is no good reason for an astronaut to be inside an Egyptian pyramid just as there is no good reason for a major mountain range in the middle of the East Antarctica.

## ORIGIN

Even the intensive research of the GSM was carried out within AGAP project, only limited constraints on the topography, geology, and lithospheric structure are still available, and the origin of the GSM has been a matter of considerable speculation [Hansen et al., 2010]. Some studies have suggested that the GSM were uplifted by a mantle plume, forming a volcano-capped dome, similar to the Hoggar massif in Africa [Sleep, 2006]. Other studies have suggested that the GSM developed through multiple Proterozoic or early Paleozoic orogenic events associated with the assembly of Gondwana [Fitzsimons, 2000, 2003]. Alternatively, the GSM may have resulted from far-field compression associated with the formation of Pangaea during the late Carboniferous–early Permian [Veevers, 1994].

The latest conception [Ferraccioli et al., 2011] proposed that the root formed during the Proterozoic assembly of interior East

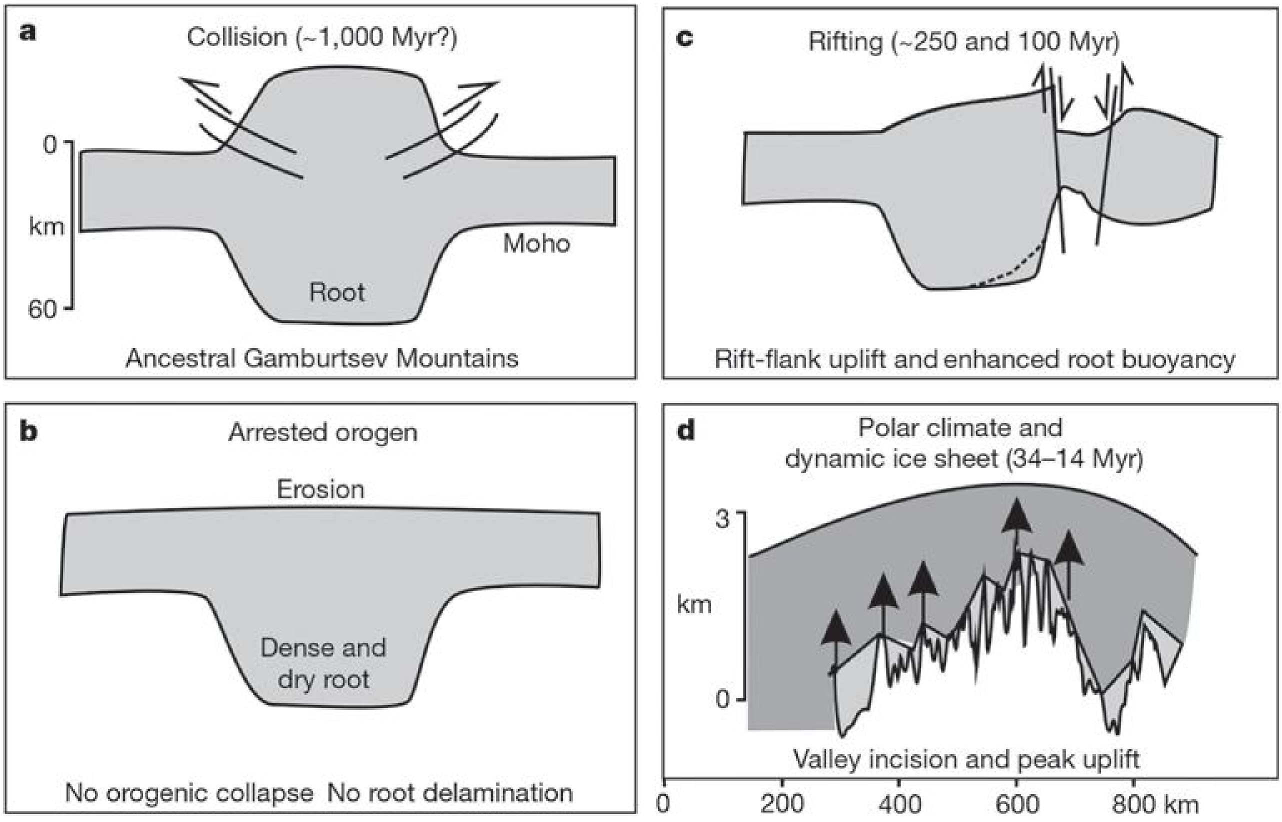

**Fig. 6. Schematic of the elements contributing to the GSM uplift – explanations are given in the text [Ferraccioli et al., 2011]**

Antarctica (about 1 Ga ago) was preserved as in some old orogens (Fig. 6, a), and post-collisional orogenic collapse and major Moho re-equilibration did not occur, preserving a dry and dense root like that in the Trans-Hudson orogen and the Urals (Fig. 6, b). Permian and Cretaceous (roughly 250–100 Ma ago) rifting drove flexural uplift and, through possible heating and/or depressurization, reduced the density of the root and released its latent buoyancy, to help produce the broad GSM rift-flank (Fig. 6, c). Fluvial and glacial erosion in the valleys uplifted the peaks, creating the modern high-relief Alpine topography of the GSM. The East Antarctic Ice Sheet has preserved the rugged topography of the GSM for at least 14 million years (Fig. 6, d).

So, according to the most of the interpretations while the mountains may look young, the evidence would suggest they must be quite old. The main problem of such standpoint is that it cannot explain lack of erosion process during many millions years in between the GSM uplift and beginning of glaciation that protected mountains from weathering. With no rock samples available, geochronologic constraints on the age of the GSM have not been acquired. The only one way to clear up the GSM age and origin is direct observation of ice sheet bed by drilling.

## PLANS FOR THE NEAR FUTURE

Drilling operations in Antarctica are complicated by extremely low temperature at the surface and within ice sheet, by ice flow, the absence of roads and infrastructures, storms, winds, snowfalls, etc. All those are the reasons that up to the present moment bedrock cores were never obtained at inland of Antarctica. To recover subglacial bedrock samples, two types of subglacial drilling technologies might be considered [Talalay, 2013]: (1) commercial drill rigs with conventional core barrel, or wire-line core barrel, or coiled tubing, and (2) electromechanical cable-suspended drilling with near-bottom fluid circulation. These drilling technologies have different concepts, limits, performance, and applicable scopes.

To use commercial drill rigs in these heavy conditions, many components such as hydraulic system, fluid processing system and some others should be principally redesigned as they are not able to work at low-temperatures. Commercial drill rigs operate as outdoor machines, use tents, or primitive shelters that are not enough at extremely low temperatures and storm winds in Antarctica. In addition, commercial drill rigs are still very heavy and power consuming. They require a large logistical load to move and support, so that using in Antarctica not only disadvantageously but also in some cases impossible.

In our opinion, the most effective method to penetrate subglacial bedrocks is electromechanical cable-suspended drilling technology. This was confirmed by five successful projects carried out by U.S. and Russian specialists in the past (Table 1). The main feature of the electromechanical cable-suspended drills is that an armored cable with a winch is used instead of a pipe-string to provide power to the down-hole motor system and to retrieve the down-hole unit. The use of armored cable allows a significant reduction in power and material consumption, a decrease in the time of round-trip operations, and a simplification in the cleaning of the hole from the cuttings.

In order to penetrate through the Antarctic Ice Sheet in the GSM region the development activity already has been started in Jilin University, China. It is assumed to choose the drill site with the ice thickness at most of 1000 m (ideally 600–800 m) and to pierce into the mountain slope to a depth of few meters (Fig. 7). The expected average daily production of ice drilling would be not less than 25 m/day.

All drilling equipment (two 50-kW diesel generators, winch, control desk, etc.) will be installed inside a movable sledge-mounted

**Table 1. Subglacial drilling experience with electromechanical cable-suspended drills**

| Years | Till & bedrock interval (core length) | Location | References |
|---|---|---|---|
| 1966 | 1387.5–1391 m (3.5 m) | Camp Century, Greenland | Ueda and Garfield, 1968 |
| 1988 | 457–461.6 m (4.6 m) | Vavilov Glacier, Severnaya Zemlya | Vasiliev and Talalay, 2010 |
| 1994 | 3051.5–3053 m (1.5 m) | Summit (GISP2), Greenland | Gow and Meese, 1996 |
| 1994 | 554 m (0,1 m) | Taylor Dome, Antarctica | Steig et al., 2000 |
| 2001 | 722–724 m (2.0 m) | Akademiya Nauk Glacier, Severnaya Zemlya | Vasiliev and Talalay, 2010 |

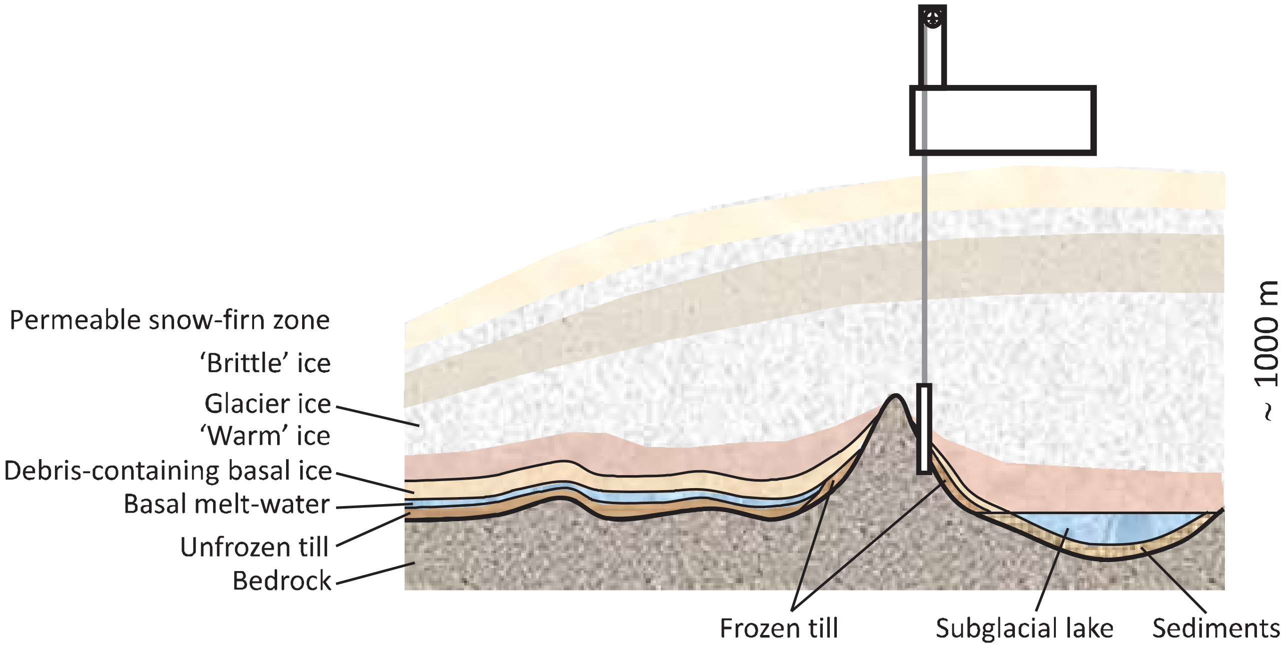

**Fig. 7. Schematic layering inside and beneath ice sheet: due to modelling, water on the base of the ice sheet is observed if thickness of ice sheet is more than 2000 m, and over the mountain ridge the bed should be frozen**

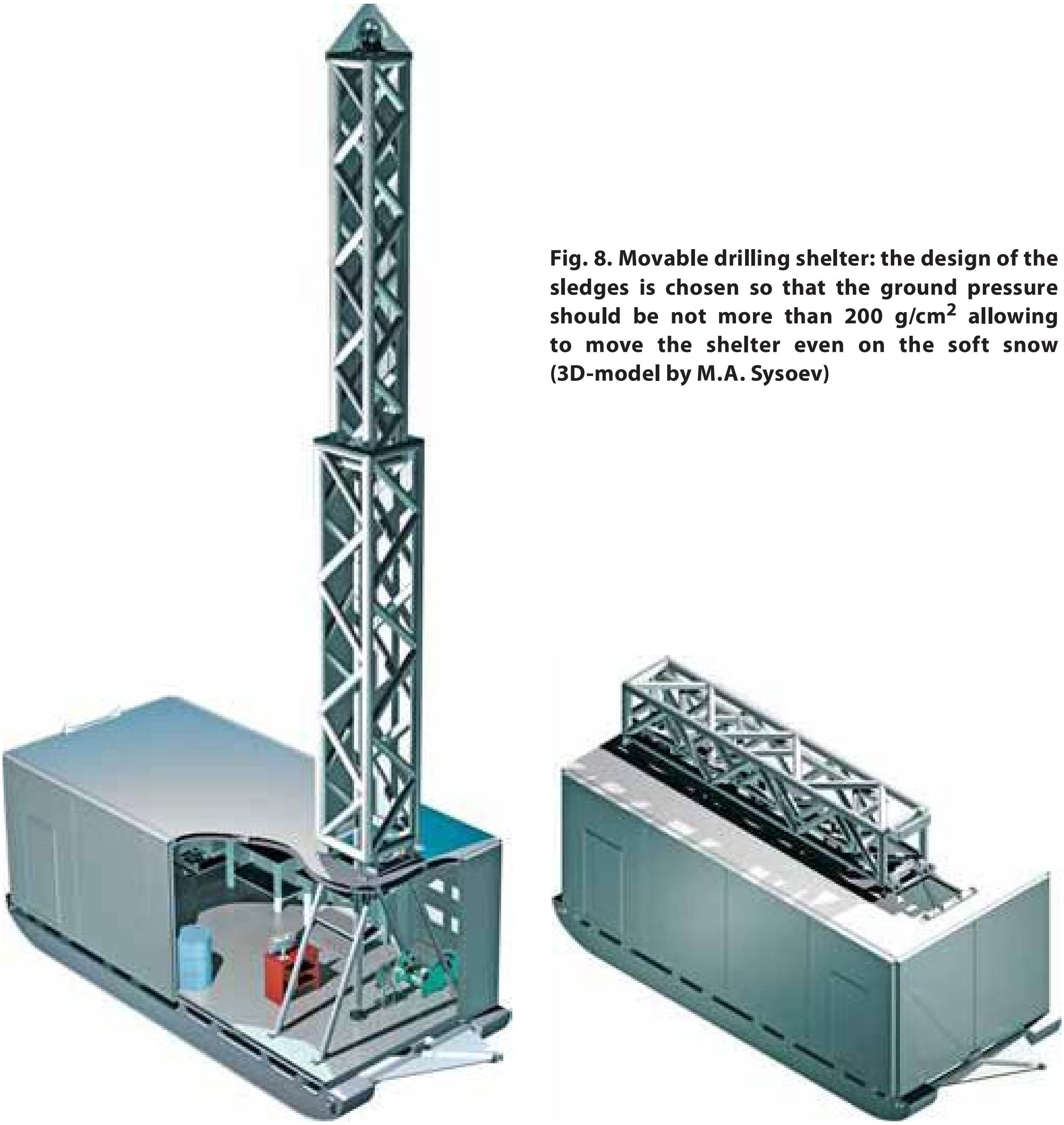

**Fig. 8. Movable drilling shelter: the design of the sledges is chosen so that the ground pressure should be not more than 200 g/cm$^2$ allowing to move the shelter even on the soft snow (3D-model by M.A. Sysoev)**

warm-keeping and wind-protecting drilling shelter that has dimensions of 7,5×4,0×3,0 m. Mast has two positions: horizontal for transportation and vertical working position (Fig. 8). Mast height is 12 m from the floor of the shelter. Total weight of drilling equipment (without drilling fluid) is near 20 tons. Drilling shelter is transported to the chosen site with crawler-tractor, and all equipment is ready to start drilling immediately upon arrival to the site.

Proposed borehole construction includes five following steps (Fig. 9):

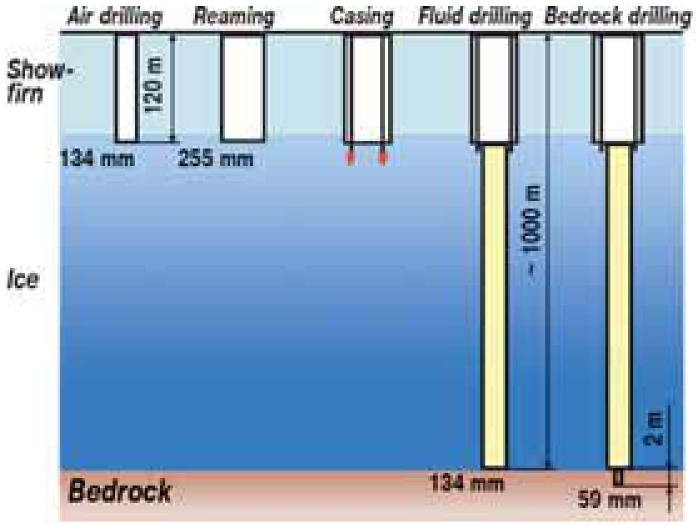

**Fig. 9. Proposed borehole construction and drilling technology**

(1) dry core drilling of upper permeable snow-firn layer with bottom-air reverse circulation; (2) reaming; (3) casing installation with thermal casing shoe; (4) fluid core drilling of glacial ice with bottom-fluid reverse circulation; (5) bedrock core drilling.

To drill through ice and bedrock a new multipurpose cable-suspended Ice and Bedrock Electromechanical Drill 'IBED' is designed with modulus structure in order to solve three different tasks (Fig. 10): (1) modulus A + B + E for dry core drilling with

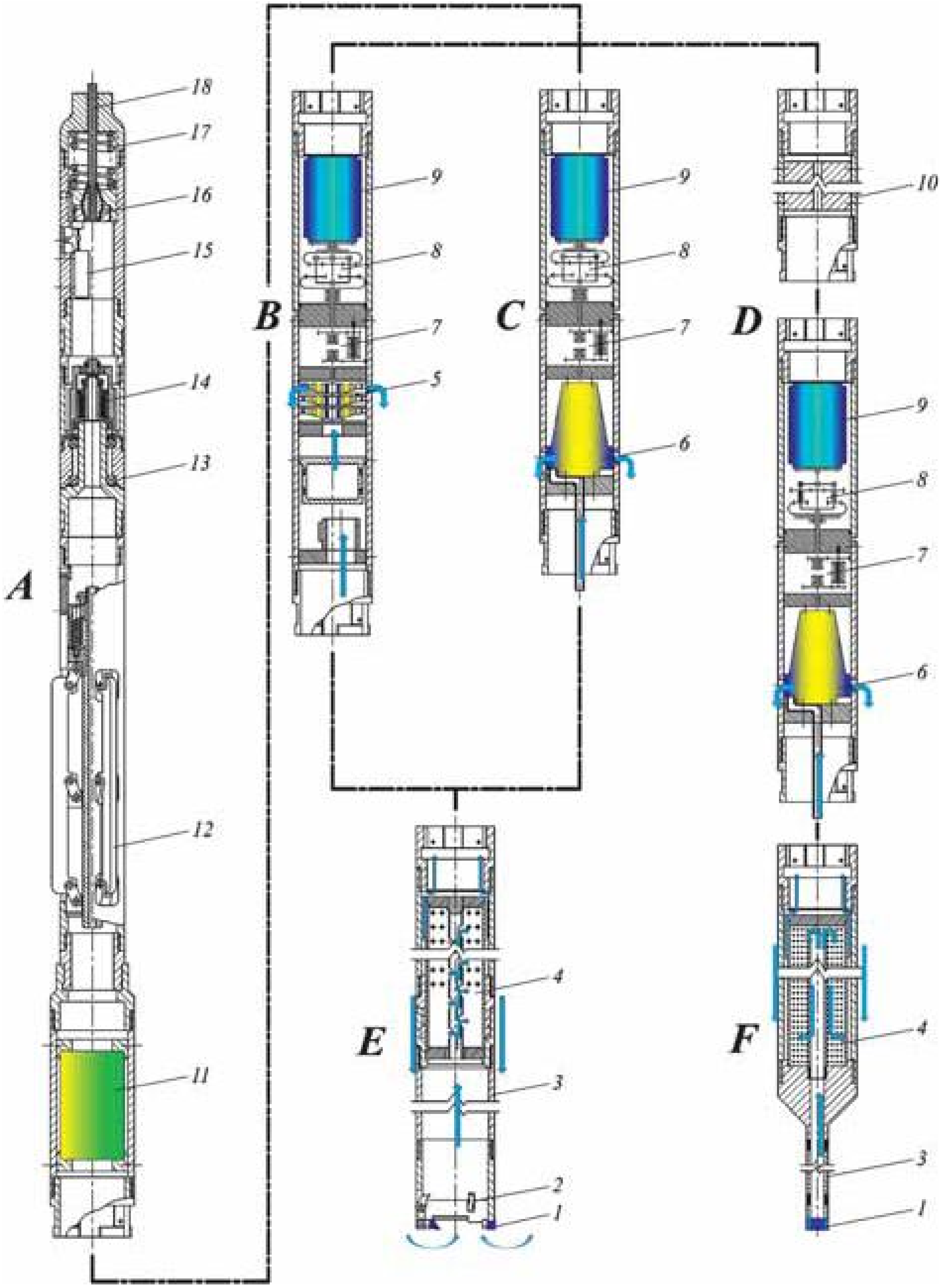

**Fig. 10. General schematic of electromechanical IBED drill:**

*1 – drill bit; 2 – core catcher; 3 – core barrel; 4 – chips chamber; 5 – air pump; 6 – fluid pump; 7, 8 – gear reducer; 9 – electric motor; 10 – dead weight; 11 – pressure chamber; 12 – antitorque section; 13 – bearing assembly; 14 – slip rings; 15 – load sensor; 16 – cable termination; 17 – spring; 18 – armored cable* bottom-air reverse circulation; (2) modulus A + C + E for fluid ice core drilling; (3) modulus A + D + F for bedrock core drilling. Different sections of the drill are easily replaced as all of them have the same bayonet joint.

The upper part is the same for all variants; it includes four sections: cable termination, slip rings section, antitorque system, electronic pressure chamber. The motor-gear sections are differed by rotation speed of the output shaft of the gear-reducer. All modulus contain 3 kW AC3×380 V submersible motor of Grundfos MS4000 type. The motor is pre-lubricated and can keep outer pressure up to 15 MPa. Gear-reducer for drilling in ice lowers the drill bit rotation speed to 100 rpm; gear reducer for subglacial drilling lowers the drill bit rotation speed to 500 rpm. In addition, module for dry core drilling contains vacuum pump for near bottom air reverse circulation instead of liquid-driven pump that is installed into other two variants. The rotation speed of air-driven pump is increased by the gear to 6000 rpm.

In modules for drilling with liquid the shaft from the motor connects with two gear-reduces: one for rotation of the core barrel and drill bit, and another one for driving of the pump. The pump is the Rotan CD33EM-3U332 pump with an internal idler gear. The capacity of the pump is 38–41 L/min with maximal pumping pressure of 0,2 MPa.

IBED lower part for drilling in ice consists from two parts: chip chamber for filtration of drilling fluid and collecting chips, and core barrel with the drill bit. The outer/inner diameter of the ice core drill bit is 134/110 mm. Length of the core barrel is 2,5 m. Lower part of the bedrock variant is adapted for coring bedrock using special teeth diamond bit and contains standard 2-m length core barrel borrowed from conventional diamond drill string, chip chamber for gravity separation of rock cuttings and dead weights (appr. 200 kg) for increasing of the load on the diamond drill bit. The outer/inner diameters of the diamond bit are 57/41 mm. To test shortened version of IBED drill the special stand has been built that can simulate borehole conditions (Fig. 11). The preliminary tests showed that teeth diamond drill bit could penetrate into the granite with average rate of 3,18 m/h at low load (3 kN) and torque (28,8 N m).

**Fig. 11. Stand for testing electromechanical IBED drill (Chungchun-city, China, 2013)**

The new approaches of subglacial bedrock drilling technology are connected with utilization of environmental friendly, low-toxic drilling fluids, e.g. low-molecular dimethyl siloxane oils or ester type. They have suitable density-viscosity properties, and can be consider as a viable alternative for drilling in glacial ice and subglacial bedrock.

According to approved schedule, the first field tests are planned to carry out just outside Zhongshan Station near Antarctic coast in season 2015–2016. Next season 2016–2017 the movable drilling shelter is planned to be transported to the chosen drilling site in the GSM region, and drilling to the bedrock would be finished during two seasons.

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