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INTERPRETATIONS OF COMPLICATED FOLDED STRUCTURES AT THE LOWER PARTS OF ANTARCTIC AND GREENLAND ICE SHEETS

ABSTRACT. Complicated folded structures were recently recorded by radar survey in the lower portions of the Antarctic and Greenland ice sheets. From a geological point of view the Antarctic and Greenland ice sheets are considered as geological features, while the ice is classified as sedimentary or metamorphic rock. In this regard the genesis of the ice sheets is analyzed from the perspective of geodynamics and metamorphism, and complicated folded structures on radar profiles are interpreted as tectonic and metamorphic structures. This study considers the processes of three kinds of tectonic structures: glacial diapirs, glacial diapir folds and glacial intrusions. Radar profiles not only capture ice flow structure but can also detect the thermobaric field in ice sheet, and in this case the complicated folded structures are interpreted as representative of recorded metastable boundaries of ice recrystallization.

KEY WORDS: evolution and dynamics of ice sheets; analogies of the glaciological, geological and atmospheric objects

INTRODUCTION

Recently the complicated folded structures were recorded at the lower part of the Antarctic and Greenland ice sheets within the frame of BEDMAP, ABRIS, RADARSAT, GAMBIT/AGAP and other projects. These structures are expanded in the bottom of the ice sheet (of 1/3 to 1/4 of total thickness) and have a complicated, irregular shape that cannot be explained by the isochronal genesis of ice sedimentary accumulation [Cavitte et al., 2013; Fujita et al., 1999; Popov et al., 2007]. Formation of such structures also cannot be explained by generally accepted ice flow laws [Budd, 1969; Cuffey and Paterson, 2010].

Bell [Bell et al., 2011] explained the formation of complicated folded structures as a process of freezing-on ice at the base of the ice sheet. According to this theory, water at the bottom of ice-filled valleys refreezes to the base of the ice sheet because of the water's close proximity to the overlying ice and fluid flow into the above ice matrix. Instead of melting the ice around it, the convective thermal transfer of energy, produced by the activity of water, results in water freezing and buoying up the ice sheet. This leads to bending and modifying of the layers to the point of top layer erosion. However, based on this theory impossible to explain when and why the accretion ice disappears beyond the area of its formation, and its long duration expansion over the whole ice sheet is not observed subsequently. Moreover, in the radar profile aqueous layers were not registered, ie there is no source of ice accretion.

NEEM community members suggest [NEEM, 2013] that folded structures appeared due to different rheological properties of ice near the base and overlying ice. Very large differences in ice rheological properties are documented between glacial ice (with crystal sizes of 1.5 mm and a strong preferred vertical c-axis orientation) and interglacial ice (with crystal sizes of 25 mm and multiple maxima fabrics). The viscosities of these two types of ice differ by a factor of 50–100, allowing glacial ice to deform very easily while the interglacial ice remains more rigid.

This paper displays alternative different visual logical interpretations on the origins of complicated folded structures as recorded on radar profiles of the Antarctic and Greenland ice sheets.

ICE SHEETS AS GEOLOGICAL OBJECTS

Antarctic and Greenland Ice sheets can be considered as geological formations when viewed in terms of continental changes and time scales, where ice is analogous to sedimentary and metamorphic rocks. From this standpoint, we can analyze the genesis of the ice sheets in terms of geodynamics whereby complicated folded ice sheet features, as captured in radar profiles, can be interpreted as glacial tectonic and metamorphic structures.

Ice has a natural tendency to operate like a plastic substance. Rocks also exhibit plastic properties. Applying analogies between the processes of ice flow in the Antarctic and Greenland ice sheets and tectonic processes in the metamorphic rocks of the lower Earth crust may offer additional or relevant clues in further interpreting the formation and processes of complicated shape structures within the ice sheet.

Analogies with the processes of geodynamics in other rocks that exhibit low viscosity and are capable of undergoing plastic deformation and flowing are also possible. These are salts [Alsop et al., 1996], anhydrite, gypsum, coals, and aqueous clays. Additionally, radar profiles may offer opportunities to detect the thermobaric field, and in that instance – complicated folded structures can be interpreted as the images of ice recrystallization boundaries.

GLACIAL DIAPIRS INTERPRPETATION

Diapirs structures

The occurrence mode of the complicated folded ice structures can be characterized as follows:

- They occur at the boundary of ice sheets with the bed and expand to heights of 1/3 to 1/4 of total ice sheet thickness;
- Pressure levels are some of the highest found in natural conditions of the ice on the Earth;
- Temperature is close to pressure melting point;
- Metamorphic intensity can reach the highest levels found in the natural conditions of ice on Earth. Similar conditions exist in the rocks with high metamorphic intensity (e.g. granulites);
- They occur in the lower Earth crust at the boundary with the upper mantle;
- Pressure is the highest one for the crust rocks under the natural conditions on the Earth;
- Temperature is the limit one for a solid phase of the Earth crust rocks close to melting temperature and the phase transformation to liquid mantle state;
- Metamorphic intensity is the highest one for the Earth crust rocks under the natural conditions on the Earth.

The diapir, similar to a granulite, is one of the typical geological structures in plastic rocks. It is a type of intrusion in which a more mobile and deformable material is forced into brittle overlying rocks [Serpukhov et al., 1976]. The diapir structures in the rocks

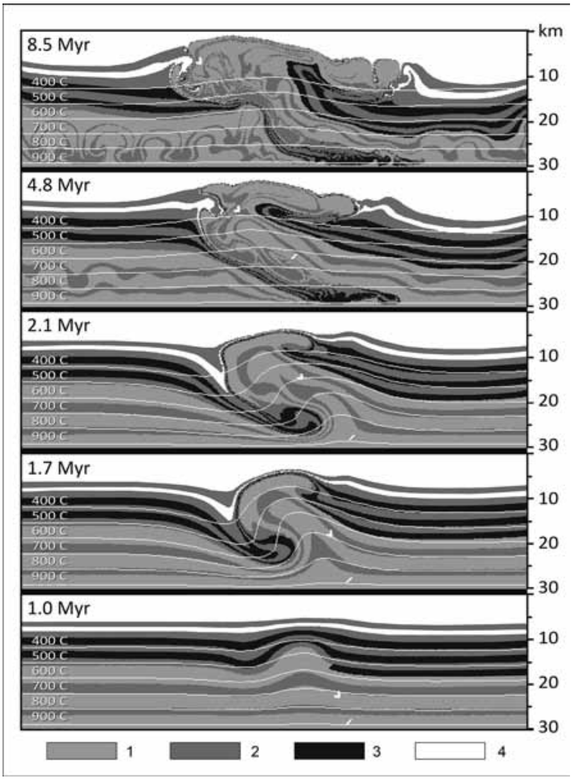


Fig. 1. Computational simulation of granulite diapir formation in the lower Earth crust:

1 – granulites; 2 – metabasalts; 3 – metasomatites; 4 – sedimentary rocks. The left-hand and right-hand scales are for temperature and depth in the Earth crust, accordingly [Gerya et al., 2000]

have been thoroughly studied under the natural conditions, and the processes of their formation have been simulated computationally (Fig. 1).

In accordance with morphological geotectonic geology [Khain and Lomize, 1995; Chorley et al., 1984; Scheidegger, 2004] the complicated structures in the lower part of the Antarctic and Greenland ice sheets may be identified as "glacial diapirs". This classification explains not only the shape, but also the genesis of these structures.

Glacial diapirs in the Antarctic ice sheet

A complicated folded ice structure, measuring ~15 km wide and ~600 m high, and surveyed using radar over Gamburtsev Subglacial Mountains in the East Antarctic region [Bell et al., 2011], was selected below as the first example of a glacial diapir (Fig. 2).

Generally in this region ice is flowing from area of Dome A. At that point the highest plastic deformations occur in the lower ice sheet layer [Budd, 1969; Cuffey and Paterson, 2010; Zotikov, 1963]. As appears evident in the bedrock topography, the lower layer flows within local combe and is overlapped by the less plastic ice sheet layer. The ice flow runs into a subglacial mountain ridge with a relatively high surface slope of about 15 degrees. This obstacle builds up excess pressure in the ice flow, forming the diapir core. The lower, most plastic ice is squeezed up from the high pressure area in front of the mountain slope to the area with less pressure above mountain peaks where thickness of the overlying ice is less. As may be supposed, this diapir core could break through to the surface, but it is protected by an overlying ice layer, with less plasticity. Moreover, in ice sheet the flow of the overlying layer entrains glacial diapir in further overcoming of the mountain ridge and flowing behind it.

Glacial diapirs in the Greenland ice sheet

Similar complicated folded ice structures were found in Greenland, and features identified in the region of the North Greenland Eemian Ice Drilling [NEEM] base are selected as an example (Fig. 3). From the perspective of structural geology, these structures correspond not to a stand-alone glacial diapir but to a system of glacial diapir folds. These are anticlinal, dome shaped folds, characterized by a heavily folded core which consists of older high plasticity ice. The diapir core is bounded by more gently dipping layers of the fold flanks.

The genesis of these glacial structures may be identical to diapir folds given how similar they are to the sedimentary cover of the Earth's crust. Such anticlinal structures

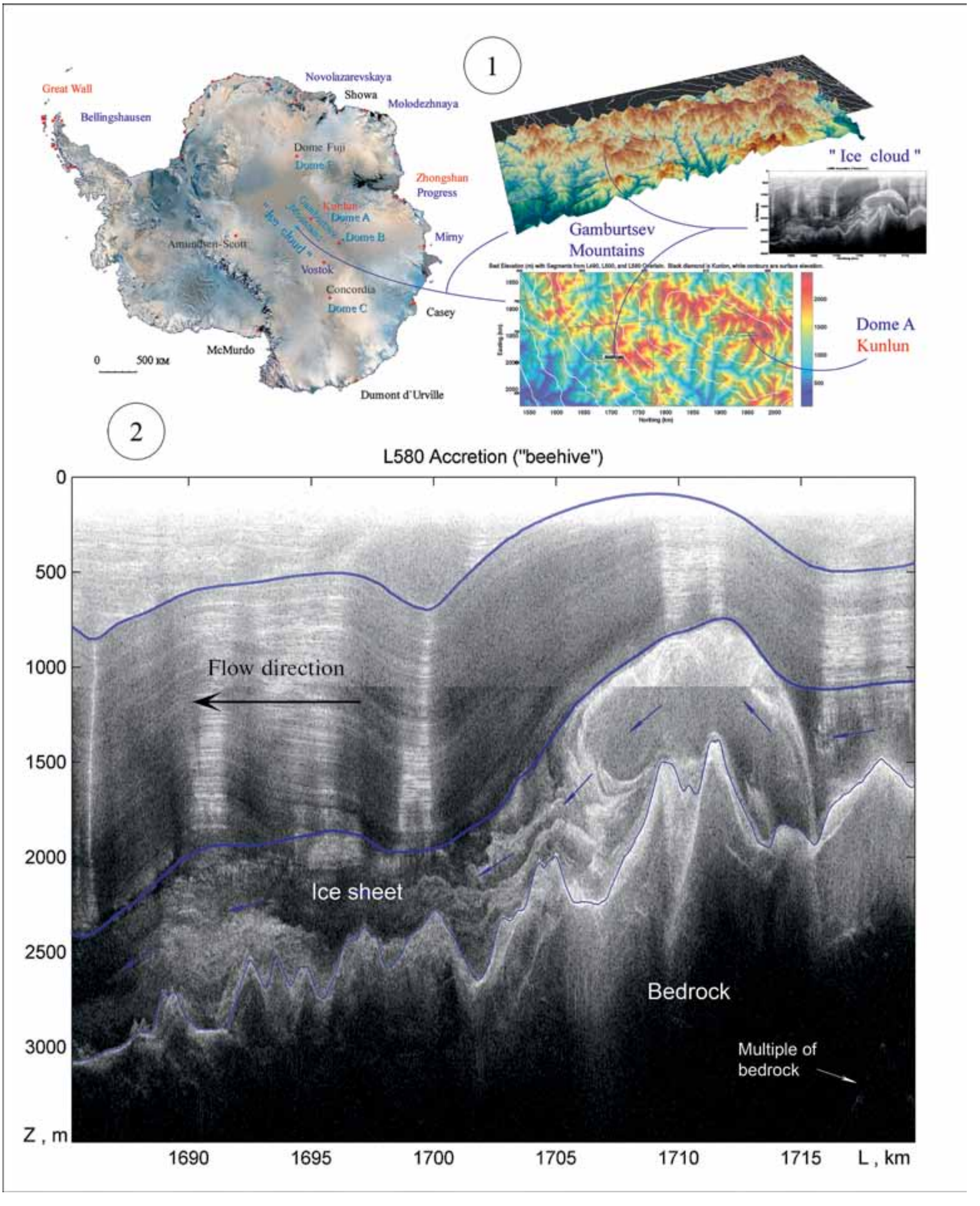


Fig. 2. Complicated folded structure in the region of Gamburtsev Subglacial Mountains, East Antarctica:

1. Location; 2. Radar profile: the lines mark boundaries between main flow layers
[Profile provided by M. Wolovick, Lamont-Doherty Earth Observatory, Columbia University, USA]

originate in the layered formations during intrusion of low-viscous rocks (e.g. in salts, anhydrites, gypsum, coals, and aqueous clays), which are able to deform plastically and to flow towards lower pressure areas.

The glacial diapir folds in the Greenland ice sheet do not coincide with the bedrock topography as it has been recorded for similar structures in the Antarctic ice sheet. They occur on the flat-bottom land which has slight slope of 3–5 degrees and cannot be considered as barrier, which initiates formation of the diapir core. The reason for the diapir folds formation in the Greenland ice sheets may be as a result of the squeezing-

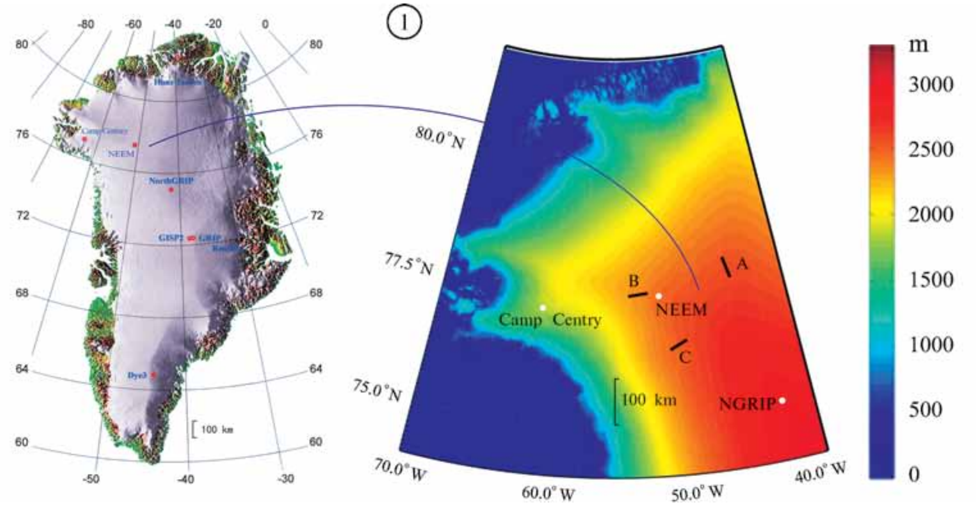


Fig. 3. Complicated folded structure in North Greenland in the region of NEEM base:

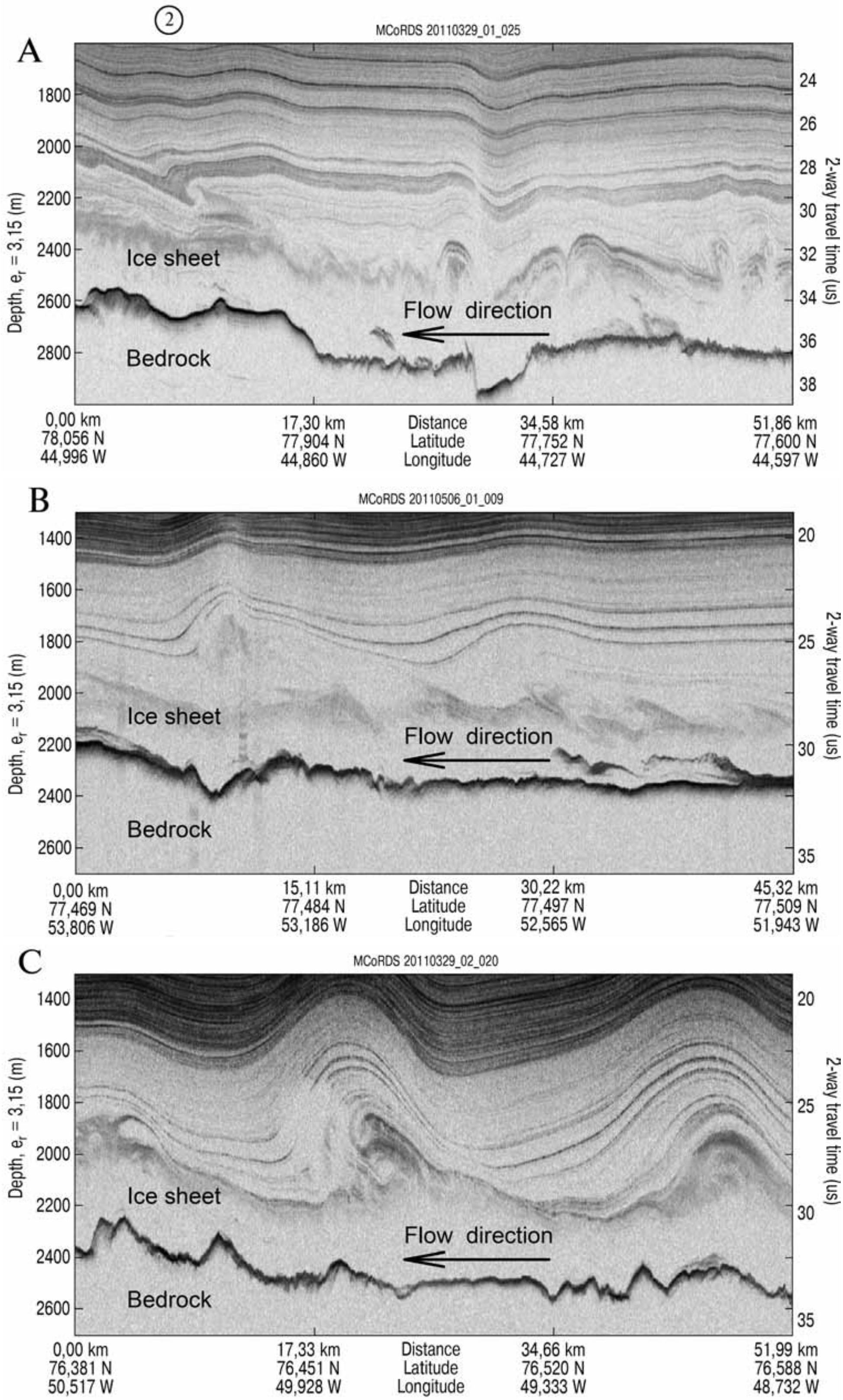
1. Location; 2. Radar profiles (see next page) [ftp://data.cresis.ku.edu/data/rds/]

up of the more plastic lower ice mass due to the vertical pressure gradient. In that case the intrusion of diapirs takes place towards the overlying formation with low pressure which can be caused not only by the thinner ice sheet areas but also by tectonic deformations and structural failures. Such areas may coincide with deflections downward into the local basins, which are seen in Fig. 3, as well as with areas of alternating forms of subglacial topography. The glacial diapir folds in the Greenland ice sheet are approximately the same sizes as glacial diapirs in the Antarctic ice sheet, measuring ~25 km wide and ~200–300 m high.

Thus, the complicated folded structures at the lower parts of Antarctic and Greenland ice sheets may be interpreted as diapirs or diapir folds, which are formed by the squeezing-up of the most plastic ice from the lower layer to the upper one. The squeezing-up process can be caused either by ice running into obstacles like subglacial mountain ridges or by the action of vertical pressure gradients in the overlying glacial mass. Regions of complicated folded structures are associated with ice sheet weakness in areas of ice thinning, local mounds, basins and alternating sign variations of subglacial topography.

INTERPRETATION OF GLACIAL INTRUSIONS

From a geotectonic aspect the complicated folded structures at the lower parts of the Antarctic and Greenland ice sheets can be also interpreted as glacial plutonic intrusion. The process of their formation is similar to the intrusion of molten magma (as a water analogue) to the Earth crust (as an ice sheet analogue). It is generally recognized that vast networks of lakes, rivers, and streams exist thousands of meters beneath the Antarctic and Greenland ice sheets [Box and Ski, 2007; Wright and Siegert, 2011; Wolovick et al., 2013 and others]. Under high pressure the subglacial water can cause hydraulic fracturing at the base of ice sheet bed. The phenomenon of hydraulic fracturing in ice was observed in a deep, overpressure borehole at Vostok Station, East Antarctica; Kudryashov et al., 2002. Lavryushin (1976) was supposedly the first to describe the mechanism of squeezing subglacial substrate into the cracks of the weakened zones at the lower glacier layers. He called such bodies "glacial dikes". Subglacial water layers may be a source of intruded ice, not over localized areas but over vast areas similar to the Earth's crust plutonic intrusions where the upper mantle is a source of magma invasion.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Ice sheet
Flow direction
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77,904 N
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77,752 N
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Ice sheet
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50,517 W
17,33 km
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METAMORHIC INTERPRETATION

Theory and experiments have shown that metamorphic transformations in the ice sheet lead to ice structure changes, and anisotropy, orientation of c-axes of crystals, and the influence of crystals size on relative dielectric permeability of the ice [Fujita, 1993, 2000; Matcheret, 2006]. If these changes have a high gradient, then they may be recorded as boundaries of radar signal reflections [Matsuoka et al., 2003]. Therefore, the radar profiles of the Antarctic and the Greenland ice sheets may display the structures of metamorphic ice transformations, and their interpretation can be made by analogy with the geologic structures and levels of metamorphic intensity.

The following types of metamorphism that may occur in the ice sheets and factors predetermining them (in brackets) were well known in rocks [Afanas'yeva et al., 2001; Bucher, 2011]:

- Pressure metamorphism (increasing of geostatic pressure);
- Thermal metamorphism (rise of temperature);
- Hydration metamorphism (interaction of rocks with water solutions);
- Dynamic metamorphism (tectonic deformations).

In addition, the rock metamorphism is subdivided to low, average and high intensity. Analogous to rock metamorphism, the complicated folded structures at the lower parts of the Antarctic and Greenland ice sheets can be interpreted as follows in the next sections.

Pressure and thermal metamorphism

From a metamorphic point of view, structure changes inside nontrivial bodies in the lower part of the ice sheets should be much higher than in surrounding ice, and these features may be interpreted as "relict ice domes" – ancient ice caps, which have undergone high intensity metamorphic changes – similar to the ancient platforms of the Earth's crust and overlapped by younger ice accumulations.

Local thermal metamorphism

Local geological processes in the Earth crust, such as hydrothermal vents, fumaroles, deep fault zones, as well as frictional heating of ice sheet are sources of intensive local thermal fields [Pattyn, 2010] that can produce thermal metamorphism in the lower part of the ice sheets.

Hydration metamorphism

Ice temperature at the lower part of the ice sheets is close to the pressure melting point, and therefore the hydration metamorphism can take place at the boundary with subglacial water. In light of this, the complicated folded structures on radar profiles may be interpreted as structures of intrusion and interaction of subglacial water and ice. This process is different from freeze-on of ice from subglacial water. In case of hydration metamorphism the structures may have complicated "nonlaminated" shapes that are common in fluid mechanics at the boundary of a nonlaminated flow (moving ice sheet) with a stationary medium (bedrock).

Dynamic metamorphism

The pressure-temperature changes of ice flow may cause dynamic metamorphism, and folded structures on radar profiles can be interpreted not only as the structures of ice flow but also as the distribution of "nontrivial" thermobaric fields, initiated by interaction of ice flow with bedrock.

Migration of the moisture saturated air layers over dominant obstacles may be considered as a similar process but not the geological one (Fig. 4 A, B). In this example, the cloud hanging around the obstacle represents the visual image of thermobaric field distribution of air flow.

By analogy, the structures on radar profiles of the ice sheets (Fig. 4 C) may be not an image

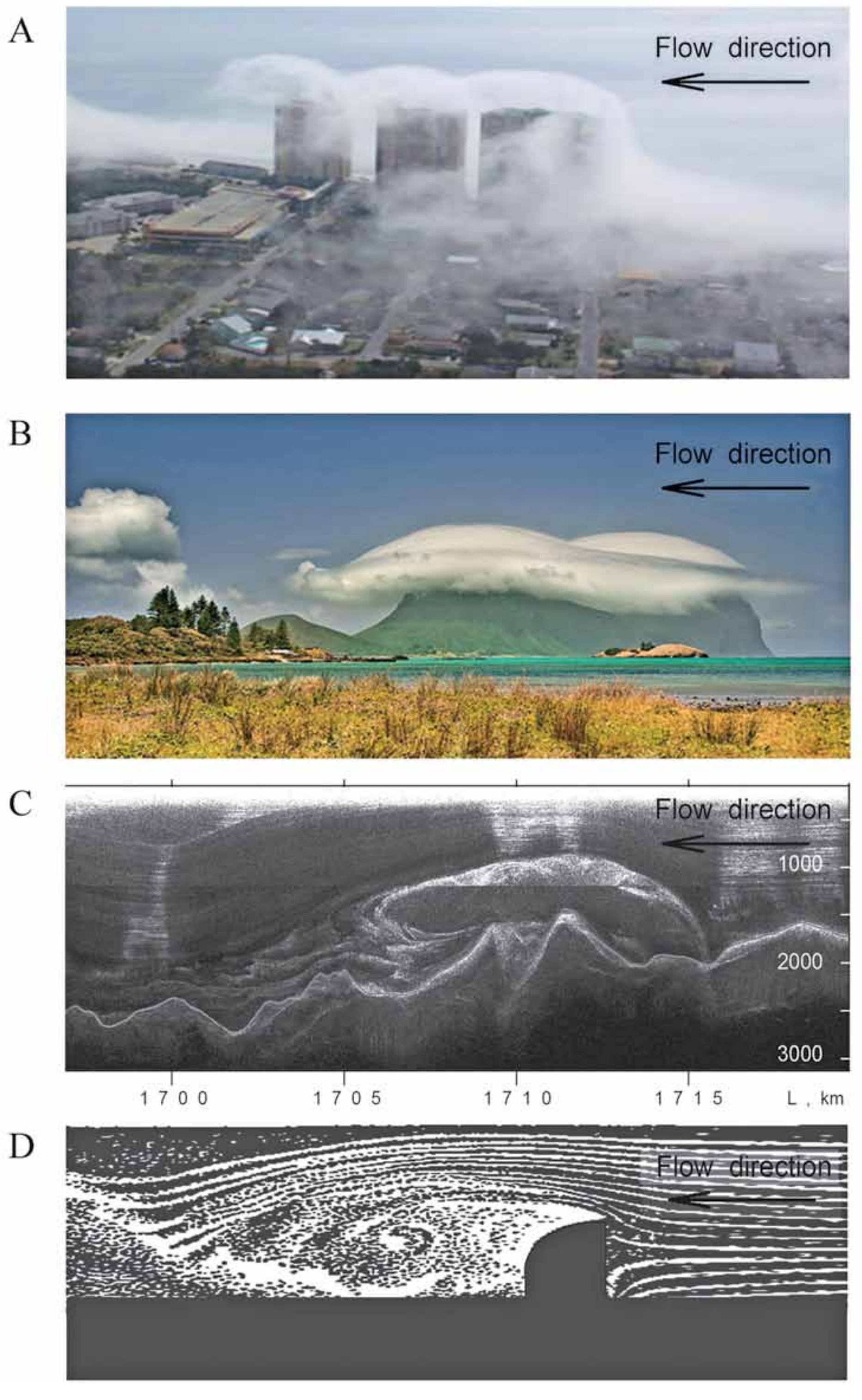

Fig. 4. Images of thermobaric field distribution in substance flow over barrier:

A, B – Metastable cloud structures over dominant obstacle; C – Nontrivial structure on radar profile in the region of Gamburtsev Subglacial Mountains, Antarctica; D – Typical flow structure of gas or liquid over barrier of ice volume but the image of recorded metastable boundaries of ice recrystallization. No matter how paradoxical it looks it appears feasible that the thermobaric filed distribution associated with ice recrystallization may have a nonlaminated shape close to the flow structure of gas or liquid over barrier (Fig. 4 D).

CONCLUSIONS

If the Antarctic and Greenland ice sheets are considered as the geological objects and ice as the rock, then the complicated folded structures reordered on radar profiles may be interpreted as results of tectonic and metamorphic processes of different types similar to processes in the Earth crust. According with the tectonic analogies complicated folded structures at the lower parts of the Antarctic and the Greenland ice sheets may be interpreted as glacial diapirs, glacial diapir folds and glacial intrusions. The other probable reason of the forming of nontrivial structures is metamorphic changes in the certain areas of ice sheets under the action of geostatic pressure, temperature and subglacial water. Radar profiles may also detect thermobaric fields, and in this case the complicated folded structures can be interpreted as the images of recorded metastable boundaries of ice recrystallization. The real situation at the lower part of ice sheets can be investigated only by in situ sampling using core drilling methods with the following comprehensive analysis of the ice structure and composition. ■

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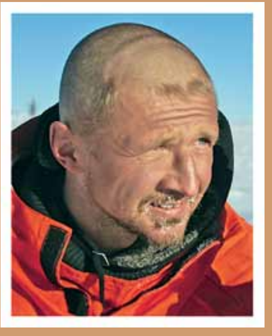

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