Antarctic Glacial and Subglacial Topography

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Abstract : 1. The data is collected and generalized according to 48,000 km of surface traverses in Antarctica during the last 15 years. An evaluation is made of reliability of material and methods of study of the ice cover thickness, evaluation of precision of levelling methods and prospects of aeromagnetic, radar and electrical methods for the study of the ice cover thickness of Antarctica. Methods are suggested which allow to make indirect evaluation of the relief of the subglacial bed of Antarctica according to the relief and inclination of the sufrace, crevassing of the ice cover and geological structures.

2. By application of the material on subglacial bed relief YU. N. AVSYUK, L. I. IVASHUTINA, A. P. KAPITZA and O. G. SOROKHTIN compiled the map of subglacial bed relief of Antarctica. The horizontal contours are drawn every 500 m. In the process of Antarctic researches new large forms of sub-ice relief were revealed: Gamburtsev Mts., Vernadsky Mts., Golitsin Mts., Shchukin Mts., Schmidt Plateau, East Plateau, West Plateau. In the process of generalization of materials large faults were found in Antarctica: the Trans-Antarctic trough.

3. The map of the thickness of ice cover in Antarctica has been made by the method of graphical subtraction by using the map of subglacial relief of Antarctica and the map of ice cover surface. The amount of ice in Antarctica was estimated according to that map, which makes 24 million km^3 of ice.

4. On the basis of the analysis of the map of ice cover surface a map has been compiled of the lines of ice flow, and the main ice divides and centers of ice diffluence in Antarctica were determined.

5. Geophysical data testify that the earth's crust in Antarctica is in the state of isostatic equilibrium, while at the same time separate forms of the relief have deviations of mean values of the free air anomaly, which allow to propose a hypothesis about the general reduction of the ice cover of Antarctica in the Holocene. The general retreat of glaciers does not contradict the separate data about short-period (within tens or hundreds of years) advances of ice cover edge.

7. The analysis of data about the subglacial relief of Antarctica has been used in calculation of the uprising values of the earth's crust after deglaciation, and a map is compiled predicting contours of the continent in the Post-Glacial Period with compensational uprising.

8. Major trends are suggested of the study of subglacial bed of Antarctica and of the ice cover relief for the solution of the most important glaciological and geomorphological problems of Antarctica.

After many years of intense international Antarctic exploration, it is now possible to map the entire continent. The first attempt summarizing all pertinent data is made in the Soviet Atlas of the Antarctic, in which for the first time the principal features of Antarctic geography are given.

Studies of the Antarctic ice cap topography and its thickness were started 15 years ago with the beginning of the British-Norwegian-Swedish Expedition and French Polar Expedition in 1950. The expeditions of the U. S. S. R., U. S. A., Great Britain, Australia, France, Japan, and Belgium carried out extensive research with the objective of obtaining ice thickness and ice cap topography data, 48,000 kilometres of profiles being covered by 1965. Airborne measurements (radio barometric levelling) of ice surface elevations have been performed on vast Antarctic areas.

Figure 1 shows tracks of gravimetric and seismic traverses in Antarctica.

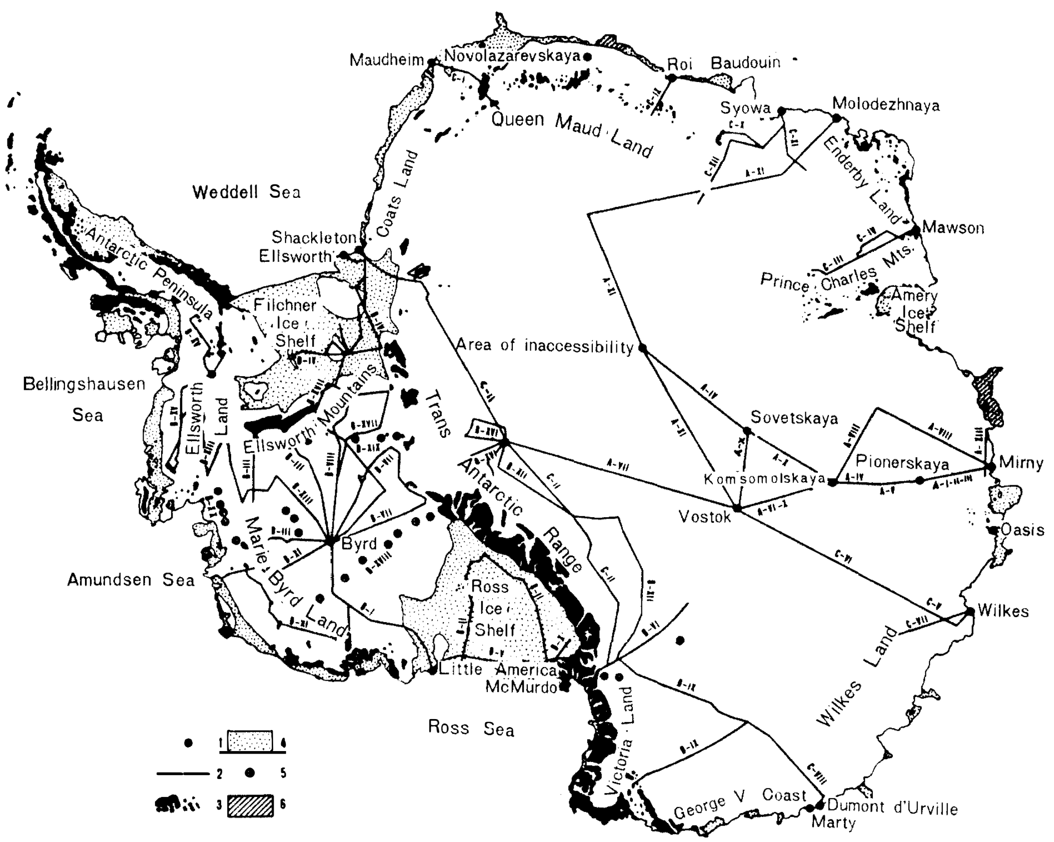


Fig. 1. Seismic gravity measurements in Antarctica. Symbols on traverses from AI to AXVI are traverses of the U.S.S.R teams, from BI to BXX are traverses of the U.S.A teams, CI–Norwegian-British-Swedish Expedition, CII–Commonwealth Expedition, from CIII to CVII–Australian team traverses, CVIII–French Expedition traverse, CIX–Belgium traverse, from CX to CXII–Japanese team traverses.

1. Scientific stations.	*4. Ice shelves.*
2. Seismic routs.	*5. Aircraft landing points.*
3. Mountainous areas, with rock outcrops.	*6. Aerial survey.*

Methods of barometric and geodetic levelling are now employed for the measurements of ice surface elevations. The former allow us to determine the elevations of glacial surface with mean square error of $\pm$20–30 metres, while the latter give the error of only $\pm$3–5 metres.

Using methods of geodetic levelling which imply the use of optic and radio distance instruments (tellurometer), the members of the Soviet Antarctic Expedition covered 3400 kilometres and the heights of all Soviet Intercontinental Stations were determined. Thus, precise vertical angle bench marks were used as a basis for the barometric levelling. On the average, heights of surface features were determined with the precision of the barometric levelling.

Subglacial relief is determined by geophysical techniques. These methods are seismic sounding, gravity measurements, magnetic and radar observations. The basic method of ice sheet thickness determination is seismic sounding which yields the ice thickness with the accuracy of 4–5 per cent. Gravity measurements permit one to determine subglacial relief on the basis of seismic data with the accuracy of 7–10 per cent, depending on the ice sheet elevations.

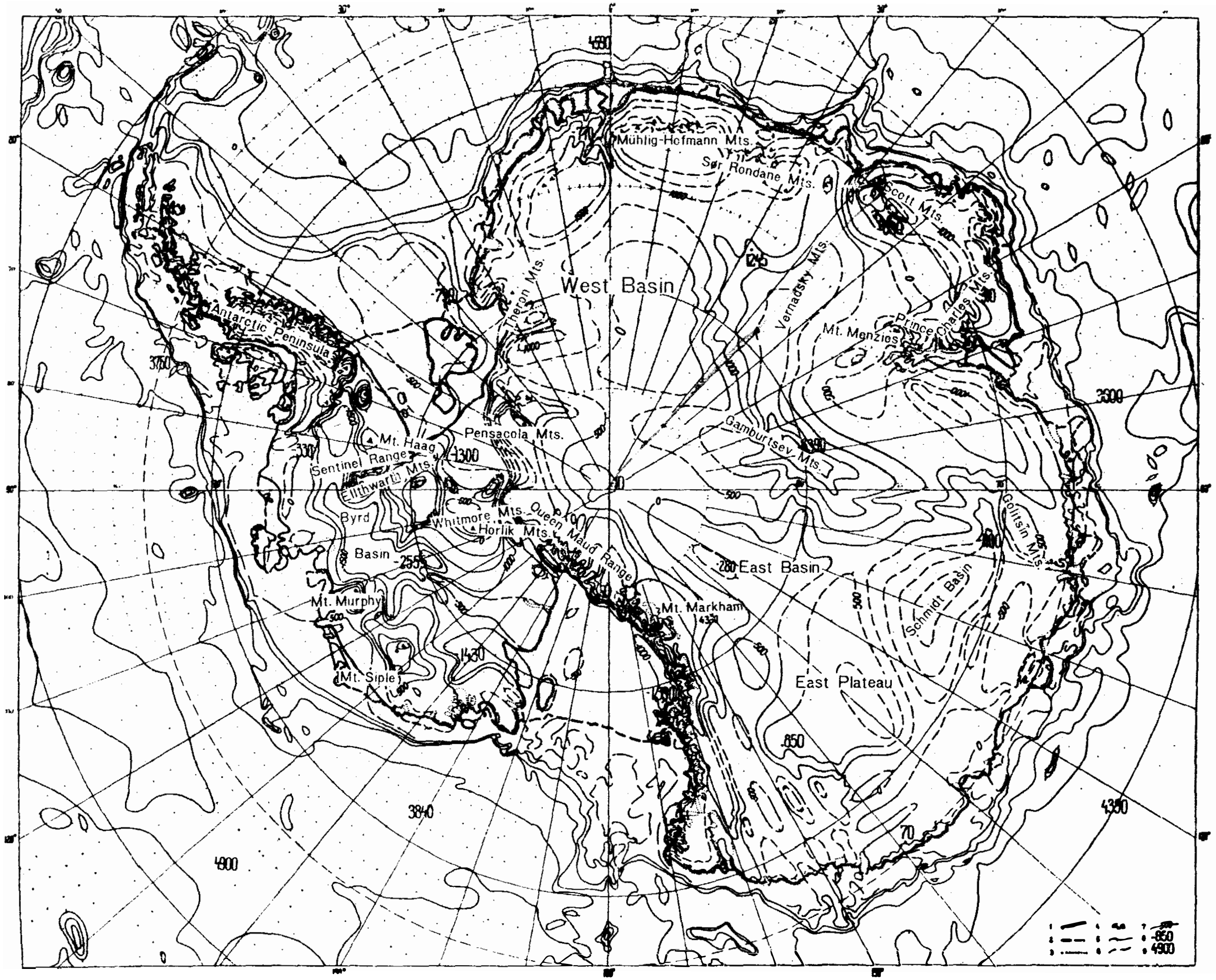
Routine seismic soundings are performed at 50–200 km intervals in traverses, whereas the intervals in gravity measurements are only 5–20 km, so as to make more detailed profiles. Results of ground and airborne magnetic measurements give poor accuracy mainly due to the diurnal variations of the magnetic field.

The method of the airborne magnetic measurements, in which the peculiarities of the Antarctic geological structure are considered, has been developed by the U. S. Antarctic Expedition scientists. It allows one to determine the ice thickness with an accuracy of 30–50 per cent. Radar technique for ice thickness measurements is very promising. First trials of this technique made in the Expeditions of the U.S.S.R., U.S.A., and United Kingdom were successful, and continuous measurements to the depth of 1500 metres were made en route of the vehicle. The development of this method with the use of an aircraft as a moving vehicle will help us to get a more detailed picture of the subglacial topography.

Available data make it possible to map the subglacial Antarctic relief. Data on ice sheet thickness are obtained for 7600 points, 1000 of them being given by seismic soundings. This material should be supplemented by the indirect data on general character of Antarctic bedrock. These data imply:

1. The slope of the ice surface, which is represented by sastrugi, caused by catabatic winds;
2. Crevassed zone, formed by irregularities of sub-ice relief;
3. Nunataks;
4. Data on regularities of Antarctic geological structure, etc.

At present, the method of ice sheet thickness estimation according to data of ice surface elevation is being developed. As is known, the Antarctic ice sheet rests on a flat basement. It is fed regularly by precipitation and we may assume that it is in equilibrium. The surface of this ice sheet has a dome-like form, semi-elliptical in section. The deviations from this form might be attributed to



1. *Antarctic ice sheet limits.*
2. *Ice shelf limits.*
3. *Outlet glacier limits.*
4. *Outcrops.*
5. *Horizontal lines of sub-ice relief.*
6. *Hypothetical horizontal lines.*
7. *Numbers of horizontal lines.*
8. *Bedrock elevations in metres.*
9. *Sea depths in metres.*

Fig. 2. Subglacial topography. Cross section of subglacial bedrock floor with 500m intervals.

precipitation variations shown by stratification of the ice sheet surface. This dome-like form is also affected by irregularities of subglacial relief. At present, calculations on a digital computer are made so as to obtain a self consistent picture of the Antarctic large.

Regularities of ice sheet thickness depending on subglacial relief variations are analyzed and ice thickness for the sites where the surface elevation is unknown, are estimated by the computer. These calculations are performed according to the data of ice sheet thickness, precipitation accumulation and surface topography.

The direct and indirect data obtained on ice sheet thickness allowed us to compile the map of Antarctic subglacial relief (this map is included in the Soviet Atlas of the Antarctic, and its principal authors are YU. N. AVSYUK, L. I. IVASHUTINA, A. P. KAPITZA, O. G. SOROKHTIN, with the assistance of P. S. VORONOV and A. V. ZHIVAGO).

In the process of this work the following subglacial mountainous structures were discovered: Gamburtsev, Vernadsky, Golitsin, Shchukin, as well as the Schmidt Basin, and East and West Basins.

These features of subglacial relief shed a new light on East Antarctica bedrock structure (Fig. 2).

On the orographic map of the Continent, the following major elements are

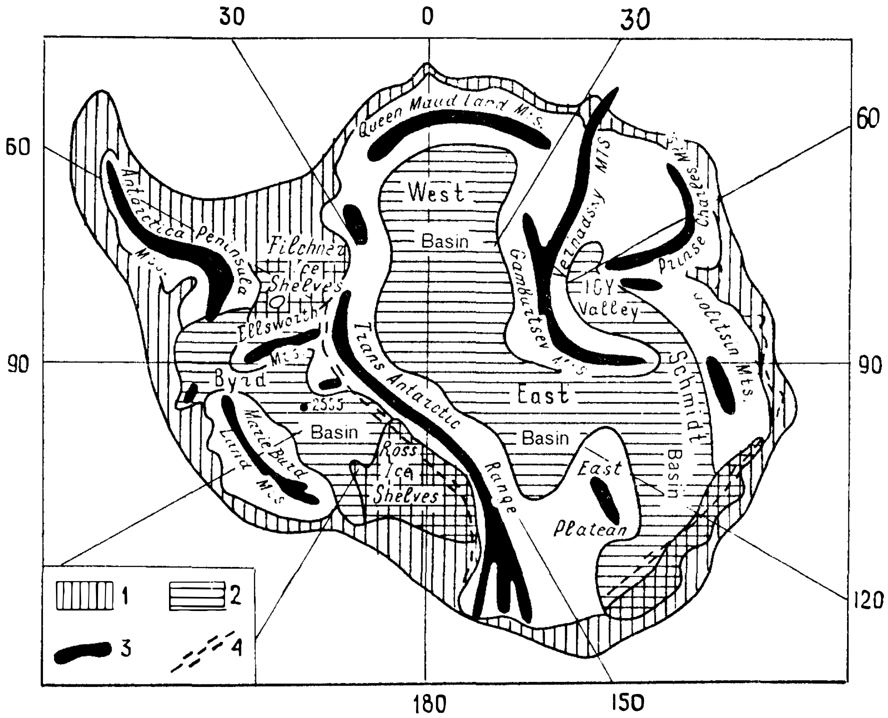


Fig. 3. Orographic scheme of Antarctica.

1. Continental shelf. *3. Mountain ridges.*

2. Subglacial plains. *4. Deep trenches.*

clearly seen (Fig. 3): East, West, Schmidt, Byrd Basins, vast shelf areas under the Ross and Filchner Ice Shelves and the mountainous structures of Trans Antarctic Range, partly under the ice sheet, partly above it, mountainous areas of Marie Byrd Land, Queen Maud Land, merging in the east with Prince Charles Mountains, supposed highland areas of Wilhelm II Land, merging with Golitsin Mts. and with the supposed East Plateau.

Trans-Antarctic Trench, Lazarev Trench, found partly on the shelf of the Davis Sea and on the east portion of Indian Ocean Coast are also noteworthy. The latter is supposed to submerge under the ice sheet, since the maximum depth of the bedrock floor being 2500 metres, is found in the area of Wilkes Base.

By superimposing the map of the sheet elevations on the map of bedrock topography, a map of the Antarctic ice sheet thickness has been prepared (Fig. 4). The maximum ice thickness is found in two major Antarctic Plains, namely, East and West Basins, where this thickness reaches 4000 metres. In the highland

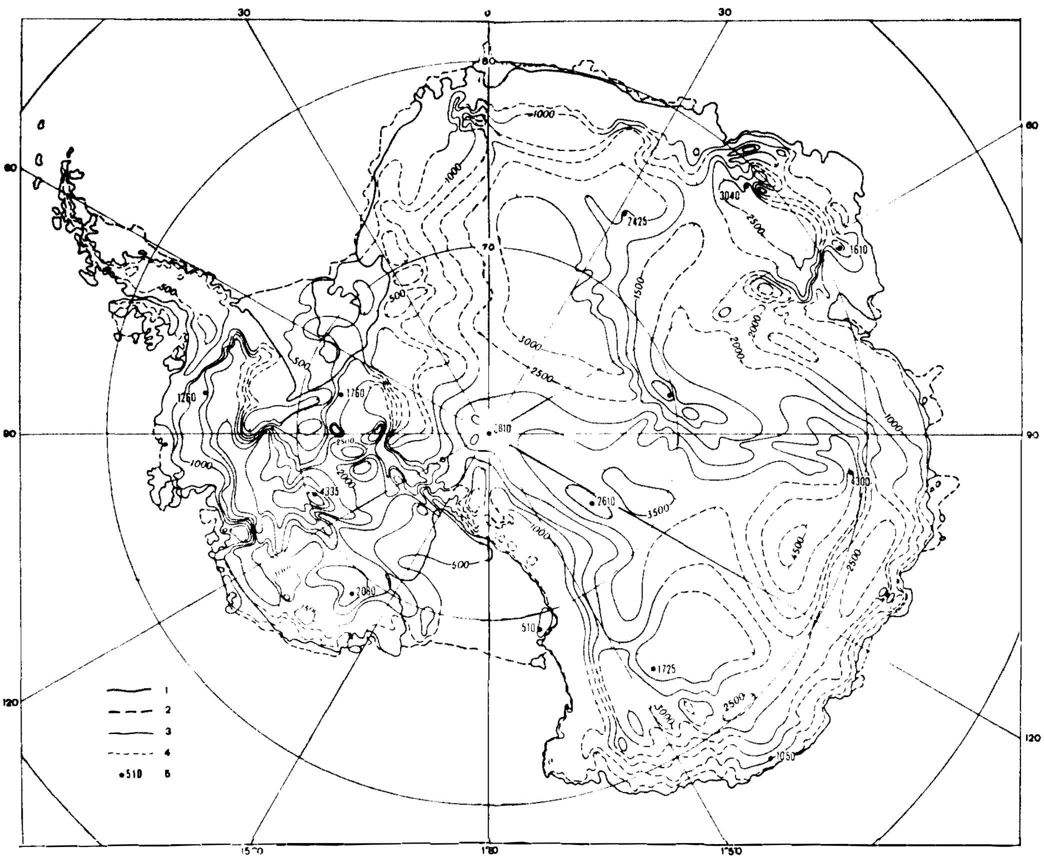


Fig. 4. Antarctic ice sheet thickness map.

1. *Antarctic ice sheet limits.*
2. *Ice shelf limits.*
3. *Thickness contours (with 500 m intervals).*
4. *Hypothetic contcurs.*
5. *Thickness in metres.*

area of East Antarctica (Gamburtsev Mts.) the ice sheet thickness decreases to 600–1000 metres.

The total volume of the Antarctic ice sheet is estimated to be 24,000,000 km^3, this is equivalent to the rise of the World Ocean Sea level by 56 metres (in present boundaries).

There exist four ice divides or the centres of ice sheet movement, namely, East Antarctic Ice Divide, coinciding with subglacial mountainous structure of Gamburtsev-Vernadsky Mountains, Mid-West Antarctic Ice Dome, west of Ellsworth Mts., Marie Byrd Land Dome and Ice Dome or rather Ice Rampart of the Antarctic Peninsula. On the scheme of the Antarctic ice sheet movement (Fig. 5) the arrows show ice flow directions, determined according to the gradient and ice surface elevation data.

Unlike Greenland, where the maximum ice thickness coincides with the line of ice divide, in Antarctica ice divides fall on bedrock elevations. Ice flows from some fronts of Drainage, the most interesting is the northern front of the East Antarctic Ice Divide where these flows merge into a single flow forming the upper portion of Lambert Glacier which then turns into the Amery Ice Shelf. The south slope of the East Antarctic Ice Divide yields two main flows one of

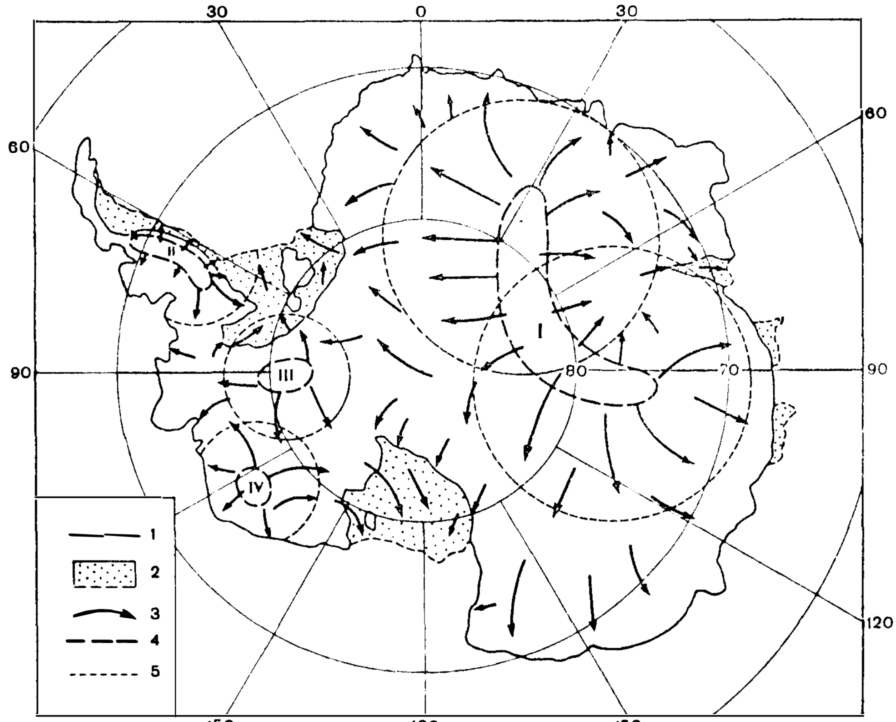


Fig. 5. The map of theoretical Antarctic glacier flows.

1. *Limits of glacier ice.*
2. *Limits of ice shelf.*
3. *Flow direction.*
4. *Limits of central zones of ice movement.*
5. *Theoretical limits of ice movement zones.*

them turns in the direction of Adelie Land and Victoria Land, and the other is in the direction of the Filchner Ice Shelf. The ice sheet between these two flows moves to the Antarctic Range and finds its way through it in the form of large outlet glaciers discharging into the Ross Ice Shelf.

The Ross Ice Shelf is nourished largely by the ice draining from the ice cap of Marie Byrd Land, and from Mid Dome of West Antarctica. These three flows merging together from drainage front in the direction of the Bellingshausen Sea Coast.

The ice drainage from the Mid Antarctic Dome, Antarctic Peninsula Rampart and East Antarctic Ice Divide nourishes the Filchner Ice Shelf.

To simplify the general picture, we may accept the existence of five centres of ice movement in Antarctica, these zones are superimposed on each other and the main flow is distorted by the irregularities of sub-ice terrain.

Dashed line on Fig. 5 shows these five zones.

The diameter of two centres (zones) in East Antarctica equals 2000 km, whereas that of three West Antarctica centres is only 1000 km. Now the isostatic depression of the earth's crust is finally proved. The estimation of Faye anomaly shows that its value for Antarctica, on the average, approaches zero. While morphological regions show variations of this anomaly. Mountain terrain (Vernadsky and Gamburtsev Mts.) is characterized by positive value of Faye anomaly. This anomaly for plains has on the average negative values (East Basin, Byrd Basin). Thus, large Antarctic basins are underloaded by the same order of magnitude. O. G. SOROKHTIN, on the basis of his earlier studies along a radial profile, made the inference on the positive characteristics of Faye anomaly and on the overloaded state of Antarctica. On these grounds he believes that Antarctic ice sheet is growing. But since that time a large amount of new data has been obtained, which permits us to differentiate the values of average Faye anomaly and make a conclusion that the whole Antarctic Continent is depressed on the average by 510 metres (according to SUYETOVA's data).

It is absolutely necessary to bear in mind that this overlying load of ice is not equal everywhere by its area, that is the ice sheet thickness is much larger on the valleys than on highlands and therefore the earth's crust depression and the ice load show variations. The load effect on the valleys was more continuous. If we consider the viscosity of the under-crust substance and the existence of inertia in the process of earth's crust response to the ice load, the average value of Faye anomaly will be indicative of the direction of the present-day process. In this respect the existence of underload testifies to the process of unloading, when the earth's crust lags behind in compensation uplift. It is difficult now to determine what time period is covered by unloading process since the estimation of viscosity value of undercrust substance show considerable variations. Rough approximation calculations allow us to suggest that valleys are subjected to regular unloading processes during last 10,000 years and thus, the Antarctic ice sheet is regularly shrinking, the load removal speed exceeds that of the compensating rebound of the earth's crust. This does not exclude the possibility of short period variations of ice balance.

Positive Faye anomalies under the mountainous structures of Antarctica may have two explanations. First, mountainous structures on the platforms which are characterized by positive Faye anomaly values. Second, in the process of ice sheet growth the valleys were submerging and the under-crust substance, moving to the mountain ridge areas, caused their compensation uplift. This process gives rise to positive Faye anomalies, which in the subsequent increase of the ice sheet could not disappear, when mountainous structures were covered by the ice.

It is necessary to bear in mind that mountainous structures in the process of glacial development are covered by ice during a shorter period of time as compared with other parts of the Continent.

In this respect, there is virtue in analyzing negative Faye anomalies found under the Ross Ice Shelf and under the Filchner Ice Shelf. These vast ice shelves are afloat and they practically do not add load to the earth's crust. The variations of the ice shelf thickness, while they are afloat and exert no influence on the earth's crust. Usually, continental shelf as transitional zone, is characterized by positive values of Faye anomaly. While the existence of negative values of this anomaly is indicative of the fact that ice in the areas of the Ross and Filchner Ice Shelves rested on the bed floor in the not remoted past and this ice develops according to the regularities of glacier ice and not according to that of the shelf ice.

If we analyze the transition of the Ross Ice Shelf into the glacier ice in the area of Byrd Valley (Fig. 5), we shall notice the depression of the bedrock and increase of the height of the ice cover. The inference can be made, if this ice were to recede in the area of Byrd Basin, then we may expect to see the unloading of the earth's crust and transition of the ice sheet into the ice shelf. This means that bay ice shelf is a transitional form from the glacier ice during deglaciation to the free ice continent provided that the bedrock is on a considerable depth below sea level as it is observed in West Antarctica. The inverse conclusion can be made, that is during the growth of glaciers on the islands of archipelago divided by rather wide and deep straits (up to 500–1000 m), first the ice shelf forms which growing will become grounded and turn into the ice shelf, change of ice sheet movement centres location appears to be possible, these being displaced to the area of bedrock depression.

The sign of the anomaly value under the ice sheet indicates the process whether the ice sheet grows or shrinks.

The inference on the transition stage of the ice shelf might appear important in the reconstruction of Quaternary Glaciers, located at the continental shelves of the Northern Eurasia and America.

Differentiated movements of the earth's crust will give rise to Antarctica contour variations in the Pre-Glaciation and Post-Glaciation Period after full isostatic compensation uplift of the earth's crust.

Figure 6 shows scheme of Antarctica contour reconstruction after deglaciation and full compensation.

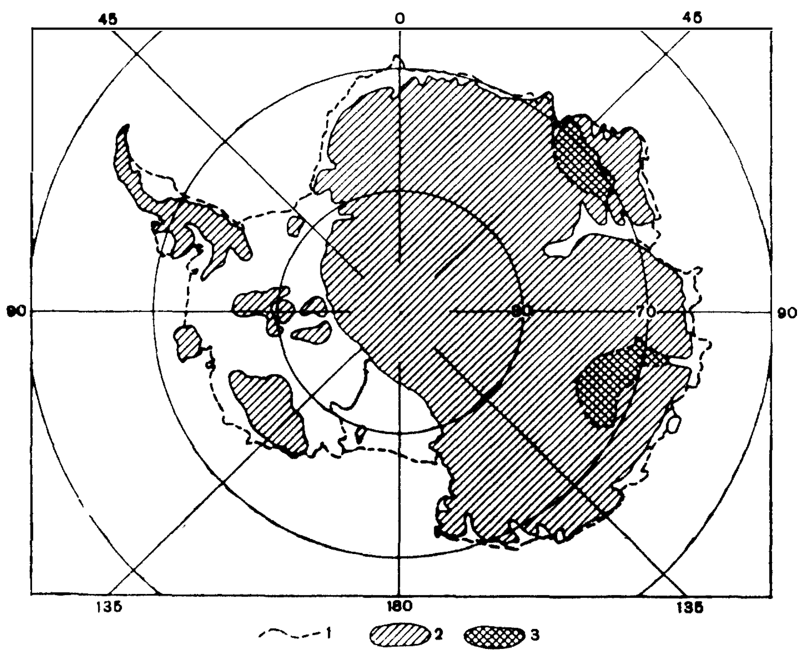


Fig. 6. Scheme of continent and archipelago contours after deglaciation and isostatic uplift of Antarctica.
1. Present contours of the Continent.
2. Contours after deglaciation.
3. Limits of theoretical interior basins after deglaciation.

Monolith of East Antarctica may have one or two deep straits or isolated interior basins. West Antarctica would most probably emerge as an acrhipelago of islands, separated by wide straits (500–1000 m).

Of prime importance to the Antarctic ice sheet exploration which actually has just been started is the method of airborne radar observations, which permits the glaciologists to cover vast Antarctic territories with dense measurements network in a short period of time. The resulting data may yield quite different map of Antarctic subglacial relief.

The second aspect of Antarctic exploration is aerial photo survey of interior ice sheet. It seems desirable to use in future both methods concurrently. Without exact data of Antarctic ice cap elevation, we cannot widen our understanding of the development regularities of the ice sheet. Only if we have at our disposal the exact data on bedrock relief and ice surface topography we shall be able to select proper sites for our glaciological experiments.