# ISOSTASY OF ANTARCTICA

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## Abstract

## Full Text

## GEOPHYSICS

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# ISOSTASY OF ANTARCTICA

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The conclusion regarding the isostatic state of Antarctica, owing to the difficulty of calculating isostatic anomalies, was originally obtained from mean free-air anomalies ([1]). It was assumed that the mean values of free-air anomalies over areas of considerable size are close to isostatic anomalies. However, B. A. Andreev ([2]), on the basis of the empirical dependence of topographic-isostatic reductions on station elevations, came to the conclusion that in the center of Antarctica one may expect intense negative isostatic anomalies of the order of 80 mgal. Discussion of this question ([3–6]) showed that there is no unified opinion concerning the isostasy of Antarctica. The authors, independently and by different paths, undertook an attempt to answer the questions posed.

At the present time more than 3000 gravimetric stations have been determined in Antarctica. Their accuracy varies and depends mainly on errors in determining the elevations of the glacier surface. The elevations of most Soviet gravimetric stations in the interior regions of Antarctica have been determined by geodetic leveling. Errors in determining Faye anomalies at these stations and at stations of the coastal zone do not exceed $±$5 mgal. In the remaining investigated regions of Antarctica, whose elevations were determined by barometric leveling, the value of the mean square error is apparently about $±9—±$10 mgal.*

Isostatic anomalies were computed by A. I. Frolov according to two models (Pratt–Hayford and Vening–Meinesz) at 73 stations, uniformly distributed over all the investigated areas of the continent ([7]). The computations were performed according to the tables of S. V. Evseev ([8]).

However, the process of computing topographic-isostatic reductions according to any of the known models of isostasy is very laborious. Since the accuracy of gravimetric determinations in Antarctica is not high, S. A. Ushakov applied a method of approximate estimation of isostasy, the essence of which is as follows. The disturbance of gravity by a geomorphological element that can be approximated by a spherical function of order $n$, $S_n$, is due to the influence of two layers (the surface layer, having density $\sigma S_n$, and the compensating layer, situated at depth $T_n$, having density $k_n \sigma S_n$), and on the Earth' s surface is equal, according to ([9]), to:

$$\Delta g_n = 4\pi f \frac{n-1}{2n+1} \sigma S_n \left[ 1 + k_n \left( \frac{R - T_n}{R} \right)^{n+2} \right],$$

where $\sigma$ is the density, taken as equal to 2.67 g/cm$^3$; $k_n$ is the compensation coefficient of the given geomorphological element; $R$ is the mean radius of the Earth. In the general case $k_n$ may vary from 0 (absence of compensation) to $-[R/R-T_n]$ (complete compensation, taking account of the difference in areas). For $k_n = 0$ we have

$$\Delta g_n = 4\pi f \frac{n-1}{2n+1} \sigma S_n;$$

* All gravimetric data are expressed in the system of American base stations. The anomalies were computed by the international formula.

for $k = -[R/R - T_n^2]$

$$\Delta g_n = 4\pi f \frac{n-1}{2n+1} \sigma S_n \left[ 1 - \left( \frac{R - T}{R} \right)^{n} \right].$$

Knowing $p(n, T_n) = \Delta g_n / 2\pi f \sigma S_n$ for $k = 0$ and $k = -[R/(R - T_n)]^2$, and approximating the relief by spherical functions, one can calculate the anomaly produced by any geomorphological element, both in the presence of isostasy and in its complete absence. Comparison of theoretical anomalies with observed ones makes it possible to obtain an idea of the isostatic state of the region.

To apply this method to Antarctica, all the studied areas were divided into cells with an area of about 40 thousand km$^2$. Within such a cell, the thickness of the ice, the elevation or depth of the occurrence of bedrock, and the free-air anomalies were averaged. In order to use a single density ($\sigma = 2.67$ g/cm$^3$) when computing theoretical anomalies with free-air reduction, the Antarctic ice ($\sigma = 0.9$ g/cm$^3$) and the thickness of the water surrounding the continent ($\sigma = 1.03$ g/cm$^3$) were "condensed" to a density of 2.67 g/cm$^3$. Owing to the central position of the Antarctic continent within the basin of the Southern Ocean, the principal relief pattern after condensation was obtained by approximation with the Legendre polynomial $P_6(\cos\theta)$ up to the second zero, with a coefficient of 2.9 km and a center at the point $\varphi = 85°$ S and $\lambda = 85°$ E. The approximation of local relief elements of the continent was carried out with Legendre polynomials of higher order only up to the first zero. In this procedure each element is approximated separately. These assumptions cause an error in the theoretical free-air anomalies of $\pm 10$–$\pm 12$ mgal, which is commensurate with the accuracy of the observed values. Comparison of the topographic-isostatic corrections calculated by the approximate method with corrections obtained from tables showed that the root-mean-square discrepancy is $\pm 14$ mgal. An exception is

Fig. 1. Schematic map of isostatic anomalies of Antarctica.

Figure 1: Fig. 1. Schematic map of isostatic anomalies of Antarctica.

the region of the Gamburtsev Mountains, where there is a systematic difference of about 20 mgal. However, in this area the bedrock relief is very complex and poorly studied. Therefore the difference of 20 mgal lies within the limits of the possible error of extrapolating the relief of the Gamburtsev mountain massif westward from the area studied. We adopted the correction values obtained from the tables.

For the interpolation of isostatic anomalies to intermediate points along all gravimetric profiles, A. I. Frolov established the dependence of topographic-isostatic reductions on point elevations. On the basis of the map of the subglacial relief of Antarctica compiled by us and the map of isostatic anomalies, it proved possible to distinguish three areas with different correlation dependence:

1. Western Antarctica
   $\Delta g_I - \Delta g_F = -60\overline{H}$.
2. Marginal zone of Eastern Antarctica
   $\Delta g_I - \Delta g_F = +6 - 51\overline{H}$.
3. Central zone of Eastern Antarctica

$$\Delta g_I - \Delta g_F = +24 - 38\overline{H}.$$

Here $\Delta g_I$ is the isostatic anomaly; $\Delta g_F$ is the free-air anomaly; $\overline{H}$ is the point elevation obtained after condensing the ice layer to a density of 2.67 g/cm$^3$.

The resulting correlation formulas were used for an approximate calculation of isostatic anomalies along all studied routes, at more than 600 points. The error of the anomalies interpolated by these formulas relative to those calculated from the tables is $\pm 11$ mgal.

All the data obtained by the authors made it possible to compile a schematic map of isostatic anomalies for the regions of Antarctica studied up to the present time (Fig. 1). The mean value of the isostatic anomaly in these regions is negative, but in absolute value less than 10 mgal. The experience of Soviet

determinations of the elevations of intracontinental stations makes it possible to assume that the barometric elevations have a systematic error of $-20 \div -30$ m. Taking this circumstance into account, it may be supposed that in reality the mean value of the isostatic anomaly is close to zero. Consequently, the load of the external masses as a whole is very fully balanced.

However, the values of the isostatic anomalies in the studied regions of Antarctica vary from $+60$ to $-85$ mGal, which indicates a significant

**Fig. 1.** Schematic map of isostatic anomalies of Antarctica. **1**—coastline of the continent, **2**—ice shelves, **3**—isoanomalies, **4**—zero isoanomaly, **5**—stations at which the isostatic correction was calculated from tables

deviation of individual areas from the state of equilibrium. As a rule, isostatic anomalies are associated with certain large elements of the bedrock relief. Significant positive anomalies, exceeding +50 mGal, characterize some young block mountains in the marginal part of East Antarctica (the Enderby Land region, the Golitsyn Mountains). Some researchers (10) associate the presence of uncompensated block mountains in the marginal part of the continent with dynamic processes in the mantle, caused by the spreading of the asthenosphere from beneath the central regions of the continent, which undergo vertical displacement under the influence of the load of the continental glaciation. In our opinion, such an explanation, although possible, is not the only one. Directly south of the Golitsyn Mountains, in the bedrock relief, there is a depression up to 1000 m deep, characterized by negative isostatic anomalies of about 50 mGal. The region between the Golitsyn Mountains and the depression is characterized by the largest in Antarct—

···type by a horizontal gradient of isostatic anomalies (over 20 eotvos) and by vertical motion of blocks of the Earth' s crust directed against the establishment of equilibrium.

The Gamburtsev Mountains are characterized by small isostatic anomalies, averaging about −30 mgal.* In individual areas, however, their magnitude reaches −50 mgal. Since this very complex region has been studied very poorly, the conclusion that it is somewhat overcompensated should be regarded as preliminary. If it is correct, then one of the probable explanations of the negative anomalies is the existence beneath the Gamburtsev Mountains of a lighter substrate. However, the possibility cannot be excluded that the anomaly is due to a considerable extent to errors in allowing for the influence of relief and to a difference between the real distribution of densities in the Earth' s crust and that adopted in the isostatic model.

Significant negative isostatic anomalies, down to −80 mgal, characterize the depression extending in the region of Victoria Land west of the Antarctic Horst. The latter, so far as can be judged from the very scanty factual data, is essentially balanced. The studied regions of West Antarctica are close to isostasy.

Thus, all the available data make it possible to confirm the conclusion drawn earlier (1) that the excess load of the continental glaciation of Antarctica as a whole is compensated by subsidence of the crust and, probably, by flow of subcrustal material. In addition, it may be considered established that individual large blocks of the Earth' s crust are far from isostasy. These blocks have experienced and, probably, are experiencing vertical displacements directed contrary to isostasy and caused by processes occurring in the upper mantle. It seems likely to us that, as a result of these processes, which were already taking place during the period of continental glaciation, the structure of individual blocks of the Earth' s crust changed substantially, which led to a substantial change in the relief of the bedrock. It may be supposed that confirmation of this is provided by the deep subglacial depressions, which could have been formed in Quaternary time in the process of restructuring of the Earth' s crust, but because of the ice-sheet glaciation have not yet been filled with sediments.

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* As already noted, an approximate calculation gave anomalies of about −10 mgal.

*Note: Figure translations are in progress. See original paper for figures.*

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