Bollettino di Geofisica Teorica ed Applicata Vol. 40, n. 3-4, pp. 189-194; Sep.-Dec. 1999

Topographic mass density and gravimetric geoid modelling

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(Received October 4, 1998; accepted August 5, 1999)

Abstract. Current geoid modelling procedures assume an average density of 2.67 g/cm^3, which appears to be inadequate for geoid modelling at the centimetre level of accuracy. We have produced the topographic mass density map of Canada based on the digital geological map of the country and in-situ rock density values from various geological studies and actual rock samples. Representative density values of the rock types in Canada vary by as much as 13% when compared to the mean value of 2.67g/cm^3. In the Skeena region of British Columbia, Canada, the effect of the variable density on the terrain corrections to gravity ranges nearly three mGal, while in the rolling hills of Northern New Brunswick, Canada, the range is about 0.5 mGal. Consequently, the effect on the geoid ranges nearly 10 centimetres and seven millimetres respectively for the two test areas.

1. Introduction

Whilst there are many factors posing hurdles in an accurate geoid model determination, only the effect of variable topographic mass density is of concern in this paper. Martinec (1993, 1998) has shown theoretically that the lateral density variations of the topographical masses are large enough to introduce a sizeable effect on the gravity reductions, which, in turn, have an effect on the geoid model that can reach the decimetre level in mountainous areas. His study did not take into consideration the contribution from the primary, indirect terrain effect.

In early 1997, we initiated a study to develop a prototype system based on Geographical Information System (GIS) technology to assign rock density values to the rock types present in

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the Skeena region of British Columbia, an area of considerable varying relief and relatively complex geological structure (Fraser et al., 1998). This prototype system involved the integration of density values with bedrock geologic maps, digital terrain elevation data (DTED) and gravity observations in a GIS. Later, after the prototype system was tested and validated, we extended the study to include the whole Canadian landmass. In this latter effort, we used the digital geological map of Canada (Natural Resources Canada, 1997) as the base map, various detailed geological studies and in-situ rock density values from our National Gravity Database (NGDB).

2. Developing the prototype system - Design issues

1. *Selection of algorithm for terrain corrections:* We used the sloping-top triangular prism algorithm (Woodward, 1975) and modified the TRITER software (Geodetic Survey Division, 1996) to accept variable rock density. The Delauney triangulation and available DTED were used to create a Triangular Irregular Network (TIN) of prisms in the test area.
2. *Selection of the study area:* Large terrain corrections, representative geological structures and availability of adequate data were the basic criteria used for the selection of the study area. The selected study area is located in west central British Columbia, Canada, and is approximately 132 000 km^2. It is located within the coastal mountain range and is composed of Precambrian to Cenozoic sedimentary, igneous and metamorphic rocks (Fraser et al., 1998).
3. *Selection of the data sets for the study area:* Various problems and challenges were encountered in the compilation, such as the scale and projection of the available maps, the reliability/accuracy of the data, the lack of detailed description of bedrock geology, and processing time and cost.

Table 1 - Bedrock geology attribute data as used in the prototype system. "Unit" signifies the geological unit according to geological age and rock composition.

Unit	Type	Composition	Density g/cm^3
EBC	I	andesite: 2.75, basalt: 2.88, dacite: 2.70	2.78
Eg	I	granite:2.67, granodiorite:2.70	2.68
EG	I	quartz monzonite: 2.65, quartz monzonite: 2.64	2.65
Egd	I	biotite granodiorite: 2.67	2.67
EGI	I	syenite: 2.65	2.65
Egn	M	gneissic rocks: 2.74	2.74
EGV	I	trachyandesite: 2.70, trachyte: 2.57, basalt: 2.88	2.70
EJd	I	hornblende diorite: 2.83, tonalite: 2.75	2.81
EJT	I	granodiorite: 2.70, quartz diorite: 2.75, diorite: 2.80	2.74
EKgb	I	gabbro: 2.98	2.98
Ekgbdm	M	meta diorite: 2.80, gabbro: 2.98	2.85
EKqd	I	quartz diorite: 2.75	2.75
EKqm	I	quartz monzonite: 2.65	2.65
ET	I	granodiorite:2.70, quartz monzonite:2.65, tonalite: 2.75	2.70
ETg	I	granodiorite: 2.70, quartz monzonite: 2.65, granite: 2.67	2.68

4. *Rock density assignment:* Density values were assigned to the geological units using existing studies of the test area and density information from other areas (e.g., Clark, 1966; Gibb, 1698; Hutchison and Roddick, 1969; Sobczak et al.,1970; Maxant, 1980). Table 1 shows a subset of the geological units in the study area, its rock type [i.e., igneous (I), and metamorphic (M)], its rock composition and the assigned density values. The density values of only the major rock constituents in a unit were used to determine its representative density.
5. *Development of quality control/assurance and processing methodology (data flow) procedures:* This step is particularly useful for the future expansion of the system, merging of new data sets, establishment of procedures for evaluating the quality of the data sets and conduct, and analysis and evaluation of the system tests vis-à-vis the design specifications.

3. The topographic mass density map of Canada

The digital geological map of Canada (Natural Resources Canada, 1997) contains 43 different categories of rocks based on sedimentary, metamorphic and volcanic processes. After the assignment of density values to the various rock categories, we imported the density tables to the polygon layer of the geological map, using the ArcView® software package. In a second stage,

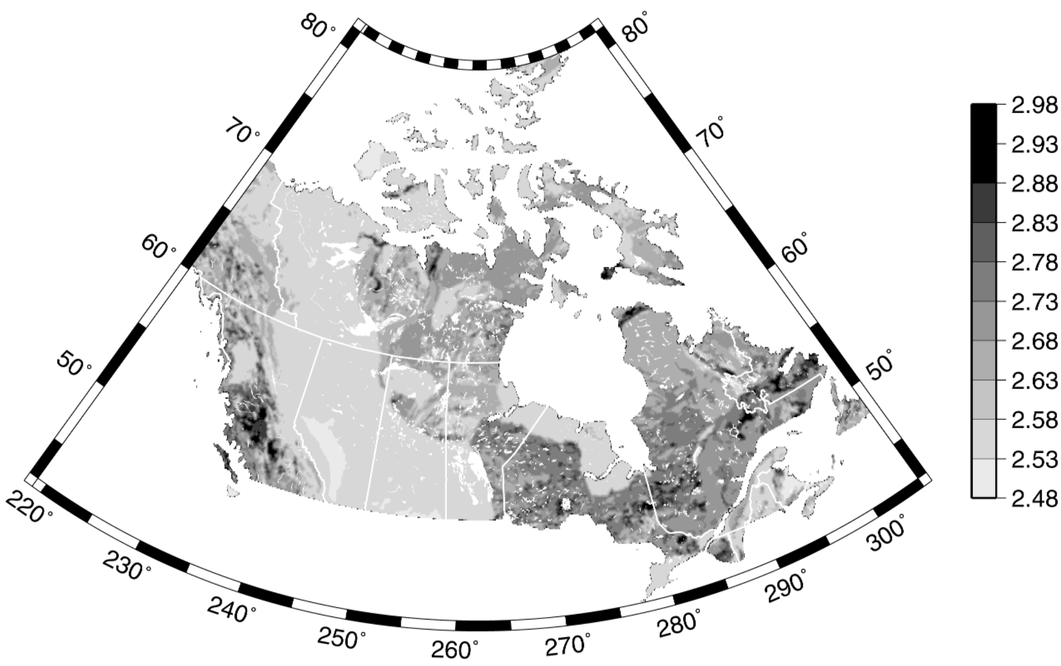

Fig. 1 - The topographic mass density map of Canada.

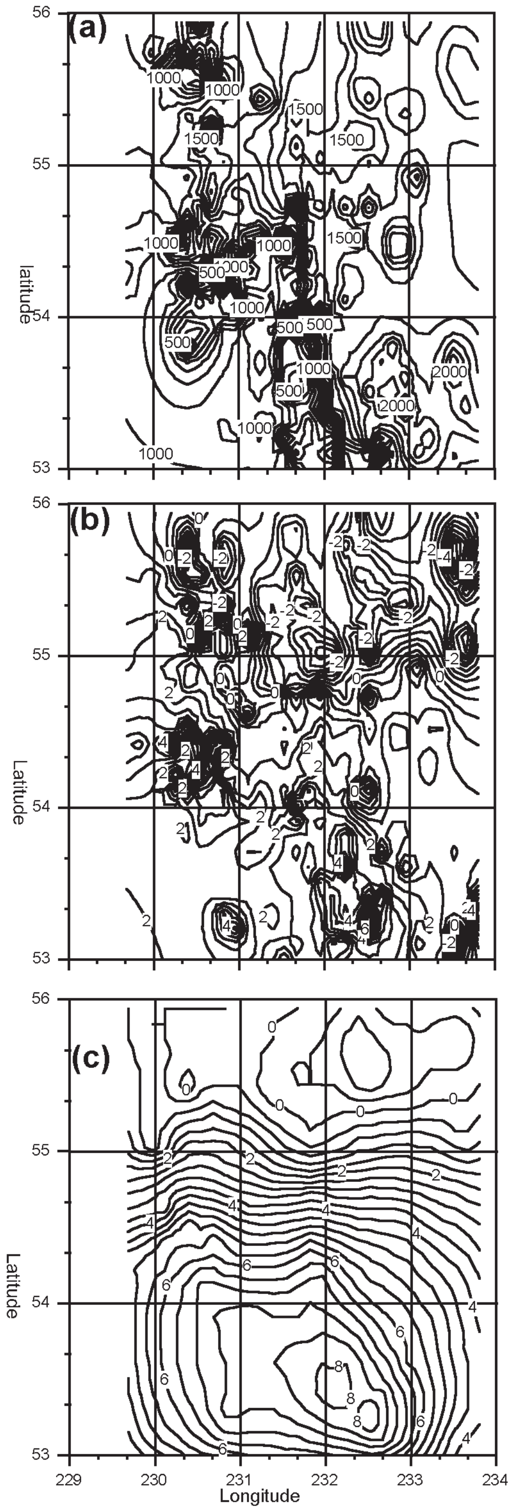

Fig. 2 - Topography (m) of the Skeena region (a); change in % of the mass density with respect to the mean value (b); effect of lateral density variations on the geoid (cm) (c).

we overlayed over 14 000-point-density values, determined from actual rock samples. The comparison of the point densities with the assigned values was realised with a *point-in-polygon* analysis for all geological structures and showed a good agreement in spite of the fact that the assigned densities (first step) referred to general rock types. The topographic mass density map of Canada is shown in Fig. 1.

4. Discussion

The main subject in this paper was the preliminary evaluation of the effect of varying mass density of the topographic masses on a geoid model and in particular, on the Canadian geoid model. In this effort, we avoided any complex formulation regarding the regularisation of the topographic masses; rather, we followed a simplistic approach by calculating the effect of variable mass density on the terrain corrections (planar approximation) and then convolving them with the Stokes function to get the desired result.

Two study areas were selected: the Skeena region (British Columbia) and Northern New Brunswick. The former possesses a rugged topography that is rather typical in western North America, where it is expected that the effect of variable density will be significant. The latter area has rolling hills with elevations reaching a few to several hundred metres.

In the Skeena region, the effect of variable density on the terrain corrections is significant and ranges three mGal, while in New Brunswick it ranges only 0.5 mGal. In the geoid space, (indirect effect was not considered) this translates to about eight centimetres in the Skeena region (Fig. 2c), while in New Brunswick the effect on the geoid is of the order of several millimetres. The spatial wavelength of this effect may vary from tens to a few hundreds of kilometres and it is the subject of further investigations.

It appears that the lateral variations of mass density introduce a sizeable effect on the geoid. The indirect effect with variable density is expected to have minimal effect on the geoid in respect of the Stokes-Helmert scheme. In the Skeena region, the effect of the density anomaly on the indirect effect reaches a maximum magnitude of 1 centimetre. Investigations with more complex models are continuing.

In this paper we have also touched, marginally, the usefulness of a Geographical Information System (GIS) in the access, retrieval, processing, integration and modelling of large and heterogeneous data sets, such as the geological map of the vast Canadian landmass and rock densities. This approach was proven to be very effective in the design of our prototype system (Fraser et al., 1998) and later when composing the density map of Canada (this study). Further details on the use of a GIS in geoid modelling can be found in Pagiatakis and Armenakis, (1999).

Acknowledgments: D. Fraser and K. McEwen were financially supported by the Earth Sciences Sector of the Department of Natural Resources Canada, through the Geomatics Professional Development Program (GPDP). We wish to thank Dr. Carmel Lowe, of the Pacific Geoscience Centre of the Geological Survey of Canada, for providing rock density measurements for the Skeena region. Bryne Hearty of the Geodetic Survey Division provided all point density values from the archived density tables.

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