A STUDY OF INHERENT NOISE IN GRAVITY SURVEYS OF MOUNTAINOUS AREAS

R. M. WHITE* AND K. DUCKWORTH**

ABSTRACT

The level of noise inherent to a gravity survey of a mountainous area was evaluated by comparison of field observations with three dimensional modelling of an area of extreme topographic relief.

The study indicates that even with the most careful control of topographic effects the noise component due to incomplete control of these effects may be as large as 10 μm/sec^2 (1 mgl) and is probably no smaller than 2 μm/sec^2.

INTRODUCTION

Structural information derived from gravity surveys usually declines in quality as the topographic severity of the survey area increases. This decline is, in part, a result of cost compromises which must be made but it is also caused by inherent problems in controlling the effects of topography even if cost is no problem.

In an effort to evaluate the limitations which these inherent problems impose on gravity surveys in mountainous terrain, we undertook what can be described as a worst case study. This involved applying a gravity survey to an area which contained the worst terrain conditions available. It was hoped that if the area provided good enough independent structural information the inherent noise effects due to incomplete control of topography could be recognized after the effects of structure had been removed by numerical modelling of the known structure. The approach required that all topographic and known structural features be modelled in three dimensions and that the topographic surface be defined with more than usual accuracy. The complete removal of structural effects from observed data is, of course, never possible but it was hoped that effects due to unknown structure could be reduced to a level such that noise effects due to topography would dominate the final result.

We attempted to use all available technology at the limit of its capabilities.

The choice of area for this evaluation was easily made. The location was Mt. Yamnuska which is situated on the front range of the Rocky Mountains of Alberta just north of the Trans Canada Highway. This area has been studied by a number of investigators, notably Bally *et al.* (1966), Beach (1943), Fitzgerald (1962), Haman and Ozsezginer (1967), and Price and Mountjoy (1970). Thus the independent control on the structures in the area is unusually good. The location is illustrated in Figure 1. The prominent cliff which forms the south east face of Mt. Yamnuska has an elevation extent of 300 metres at its highest point and it is vertical to overhanging. The base of the cliff is the outcrop of the McConnell thrust fault. From the base of the cliff the talus slope has an additional elevation extent of about 500 metres. Hence it may be appreciated that this location provides an example of topographic severity which would rarely be equalled in exploration survey areas.

The gravity survey consisted of a single traverse down the talus slope from the base of the cliff, extending a distance of 2.5 kilometres along a south easterly heading perpendicular to the cliff face. This carried the traverse well out onto the plain in front of the mountain range.

* Texaco Exploration

**University of Calgary

Fig. 1. Mount Yamnuska viewed from the south. The gravity traverse met the cliff below the prominent peak which is emphasized by shadow.

The numerical modelling of the topographic and structural effects was treated by means of an algorithm due to Talwani and Ewing (1960). This permits the treatment of three dimensional masses which are defined by means of horizontal contours so that it is ideally suited to the treatment of topographic maps and of contoured structures within the topography.

Details of all the procedures employed in this study were provided by White (1976) and only the essential features are described here. The measures which were taken to control topographic effects were extended well beyond what would be economically feasible in an exploration survey. Our aim was to determine what was possible if the minimum amount of compromise was allowed to influence the result.

Topographic Maps

Four topographic maps were used in computing the effects of topographic masses. These were the 1:250,000 and 1:50,000 maps which are published by the government plus a 1:7200 map produced by photogrammetry for this project and a 1:480 map of the immediate area around the traverse which was produced by plane table. The limits to the lateral extent of the use of each map were largely controlled by practical considerations and some compromise was forced on us at this stage. The 1:480 map extended no more than 60 metres on each side of the traverse while the 1:250,000 map was used out to 65 kilometres, beyond which distance the influence of terrain was found to be insignificant.

The contour intervals were made progressively smaller for zones approaching the traverse, with a 1.5 metre interval being the smallest used. The contour accuracy close to the traverse was ±0.15 metres.

Gravity Observations

The difficulty of moving the gravimeter safely on the talus slope caused us to establish a string of secondary base stations before attempting the detailed survey of that slope. This allowed us to minimize the amount of movement of the gravimeter. In all other respects the survey was conducted normally.

The elevation of each station was determined with an accuracy of ±0.03 metres.

Data Treatment

It was evident that every aspect of the treatment of the observed data required more than usual care in these special circumstances. The most notable change in approach which we adopted was that we did not carry the data reduction to the Bouguer Anomaly, we applied only the Free Air and Latitude corrections, thereby terminating the reduction at the Free Air Anomaly. The effects of topography and structure were treated in the three dimensional numerical modelling of the Free Air Anomaly.

Free Air Corrections

With the extreme elevation range which the survey area contained we felt that we should examine the possibility that the use of a single mean Free Air Gradient would be inappropriate. It was found that over the total elevation range of 532.8 metres on the traverse, the use of a single gradient caused a maximum error of 0.2 $\mu m/sec^2$ (ie 0.02 mgals). This error was small enough to permit the use of a single mean gradient over the whole elevation range. We adopted the figure -3.0818 $\mu m/sec^2/m$ (ie -0.09393 mgl/ft) using a mean elevation of 1596 m and a latitude of 51°7'N.

Latitude Correction

This presented no special difficulties other than in the lateral locations of stations in which we experienced the same difficulty as in the other aspects of surveying mountainous topography.

Numerical Modelling

The four topographic maps were digitized by means of a gradicon digitizer with point density on each contour being made approximately proportional to the severity of the curvature of the contour. Judgement as to the density of points needed for accurate definition of each contour was entirely at the discretion of the observer.

The Talwani and Ewing algorithm was then applied to this data to compute the effect of the mass situated above the geoid using a mean density of 2.72 x 10^3 kg/m^3 (2.72 gm/cc). This computation, which also took into account the curvature of the earth, provided the theoretical Free Air Anomaly minus structural effects. The mean density was derived by taking a weighted average of individual rock unit densities according to the known volumes of occurence in the area.

The observed and theoretical Free Air Anomalies were then compared as shown in Figure 2(b). The close fit of the two Free Air profiles confirmed that the mean density of 2.72 x 10^3 kg/m^3 was a good estimate and we found no need to adjust it. This may be seen to constitute Nettletons density determination technique.

The single process of computing the effect of the three dimensional mass above the geoid is directly equivalent to the two stage process of first correcting for the Bouguer slab and then correcting for the terrain which the slab does not treat. The single stage process does not provide figures for the terrain effect directly but we felt that some figures for this effect would be of interest and therefore derived terrain effect figures for the station at the base of the cliff and for the station which was most remote from the cliff. These were -377 $\mu m/sec^2$ (-37.7 mgl) and -217 $\mu m/sec^2$ (-21.7 mgl) respectively.

Returning to Figure 2(b) it is clear that the difference between the observed and theoretical Free Air Anomalies was caused by structural effects plus the effects of the inherent deficiencies of the topographic maps used in the numerical modelling. This difference is shown in Figure 2(c) and it is in fact the Bouguer Anomaly. It must be emphasized that in this case the Bouguer Anomaly represent the effects of all structures within the topography and that it can not be viewed as the effect of structures below any arbitrary datum plane. Thus any computation of the effects of subsurface structure had to be related to the topographic surface.

Using the known structure a set of 32 contour maps of the structural units was constructed and digitized in the same way that the topographic maps were treated. These maps also included the

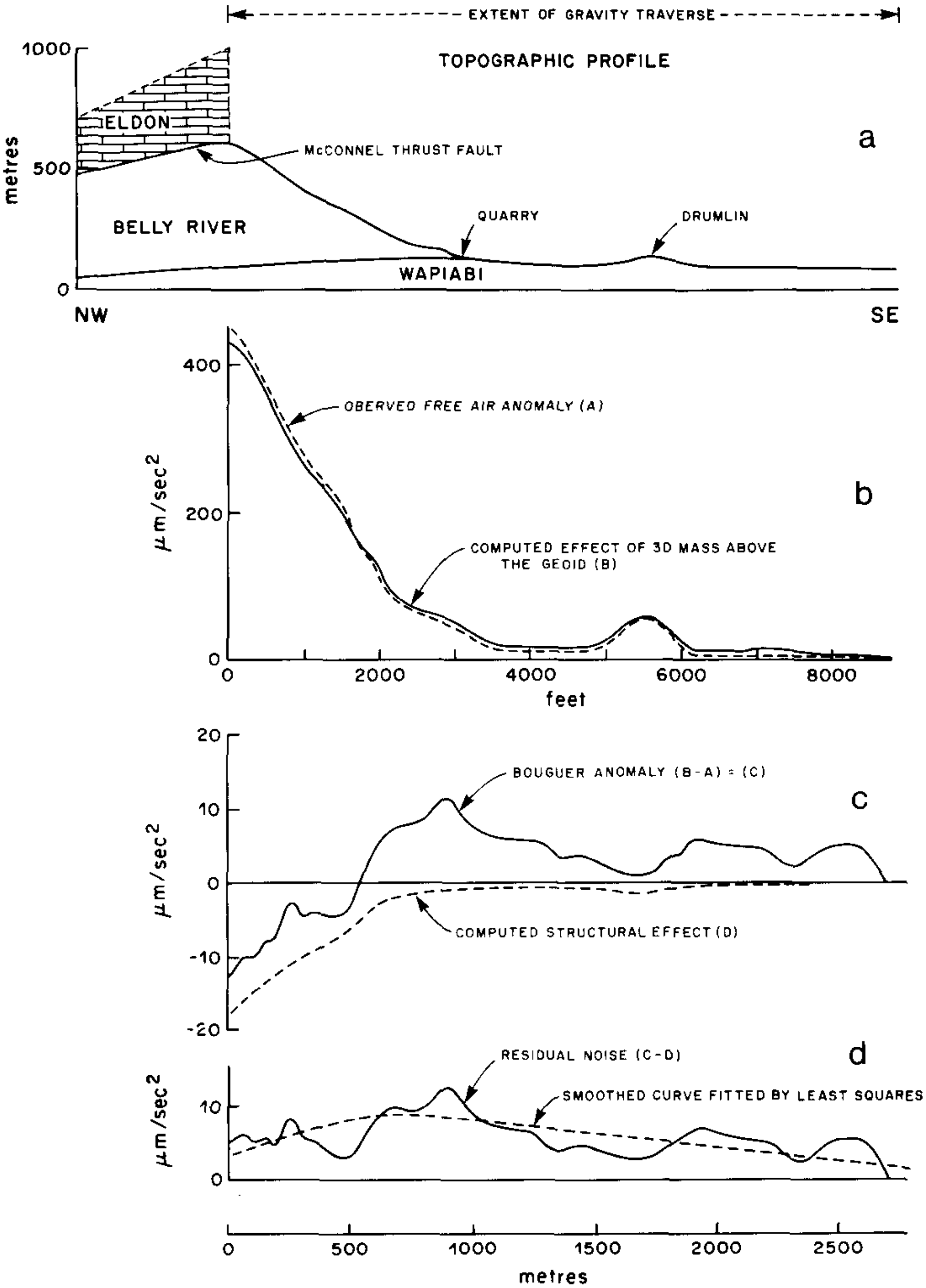

Fig. 2. The topographic profile compound with the various observed and modelled gravity profiles.

drumlin which is shown in Figure 2(a). The density contrasts for each rock unit with respect to the mean density of 2.72 x 10^3 gm/m^3 were then used with the structural maps, in the Talwani and Ewing algorithm to generate the gravity effect, at the topographic surface, of all known subsurface structures. This is shown in Figure 2(c) for comparison with the observed Bouguer Anomaly. It is evident that a better fit between them could have been achieved by iterative modification of the structural model. However, the cost of redigitizing 32 maps and computation of their effect was prohibitive. We were therefore forced into a further compromise and decided to adopt a pragmatic approach. This consisted of taking the difference between the observed Bouguer Anomaly and the computed structural effect and then attempting to separate this residual difference into its two components ie. inherent noise and unknown structural effects. The separation was achieved by means of a curve smoothing process. The smoothing process which we adopted was a simple polynomial curve fitting. The residual, after subtraction of the structural effect from the Bouguer Anomaly, is shown in Figure 2(d). The smooth curve through this residual consists of a first order polynomial up to the base of the talus slope and a second order curve in the region of the talus slope. It appears reasonable to regard the smooth curve as representing the effects of unknown structures while the high frequency component represents inherent topogaphic noise plus a possible contribution from a variable drift thickness and minor near surface structures.

Discussion

The structure and lithology underlying the traverse are shown in Figure 2(a). This diagram was extended 600 metres beyond the north west end of the traverse in order to illustrate the McConnell thrust fault which outcrops at the base of the cliff. The thrust fault separates the cliff forming Middle Cambrian Eldon limestone from the Upper Cretaceous Belly River sandstones and shales. The Belly River outcrop corresponds roughly to the talus slope, with the plain in front of the talus slope being underlain by Upper Cretaceous Wapiabi. The Wapiabi is covered by glacial drift over the extent of the traverse.

Density information for this study was derived from a wide variety of sources including our own sampling. The mean densities of the three rock units shown in Figure 2(a), which we derived from these investigations were; Eldon 2.73 x 10^3 kg/m^3, Belly River 2.60 x 10^3 kg/m^3 and Wapiabi 2.65 x 10^3 kg/m^3. These figures show that the major density contrast lies at the McConnell thrust fault. The numerical modelling of the effect of the drumlin indicated that an effective density of 2.20 x 10^3 kg/m^3 was appropriate for the drift material.

The observed Bouguer Anomaly and the computed structural effect which are illustrated in Figure 2(c) both show a decline towards the north west end of the traverse. This was caused by the low density of the Belly River formation. It appears that, in fact, a slightly lower density could have been used in modelling the Belly River because a slight residual negative remained in the smoothed difference curve of Figure 2(d). The smoothed curve also shows a regional gradient which possibly represents a deficiency in the structural model for deep seated structures.

If we can regard the deviations of the residual difference curve from the smooth curve as representing the effect of inherent topographic noise plus the effect of unknown changes of drift thickness we can see that these effects account for anomalous magnitudes ranging from + 5 to − 5 μm/sec^2 (± 5 mgls). The density of 2.20 x 10^3 kg/m^3 which was determined for the drift indicates that the maximum total anomaly due to changes in drift thickness is unlikely to exceed 2 μm/sec^2. Thus it seems that topographic noise can cause total anomalies of the order of 10 μm/sec^2 (1 mgl) even in the face of the most determined efforts to control these effects in such an environment.

The figure of 10 μm/sec^2 (1 mgl) is a deliberately conservative estimate and it is possibly too high. An evaluation of the detail of the residual noise anomaly suggests that the contribution to this anomaly by inherent topographic noise may not be as severe as the 10 μm/sec^2 figure indicates.

Consider the talus slope which is underlain by the interbedded sandstones and shales of the Belly River formation. We used a single density 2.60 x 10^3 kg/m^3 for this unit, yet it is possible that a significant density difference exists between the sandstone and the shales. We have sample determinations of density showing sandstones 2.62 x 10^3 kg/m^3 and shales 2.58 x 10^3 kg/m^3. The prominent positive anomaly located at approximately 900 metres SE coincides with a sandstone outcrop which forms a well defined cliff while the negative at 500 metres SE corresponds to a recessive shale. The respective thicknesses of the sandstones and shales, which are both of the order of fifty feet, and the possible density contrast of 0.04 x 10^3 kgm/m^3 suggests that this deficiency in our model could explain these two anomalies.

On the plain the residual noise may contain a significant contribution due to unknown changes in drift thickness. This is indicated by the negative residual anomaly corresponding to the drumlin. This suggests that we were not entirely successful in our attempts to model this feature. In addition the traverse data on the plain may contain some interpolation errors because we could not follow the desired straight line in making our measurements on the plain. In this area we distributed stations, where possible, around the desired line and interpolated onto the desired line from those observations.

With these considerations in mind it appears possible to say that the contribution to the residual noise anomaly from inherent topographic control problems did not exceed $\pm 2\ \mu m/sec^2$ (± 0.2 mgls).

ACKNOWLEDGEMENTS

This study was supported by NRC operating grant A7037.

We are indebted for their aid in the very arduous field work to Mrs. R. M. White and Mr. A. S. Saydam.

The Fortram IV programme for the Talwani and Ewing algorithm was very kindly provided by the authors, and it was adapted to input from the gradicon digitizer with the aid of Mr. R. D. Borowski.

REFERENCES

Bally, A. W., Gordy, P. L., and Stewart, G. A. 1966. *Structure, seismic data and orogenic evolution* of the Southern Canadian Rocky Mountains. Bull. Can. Petrol. Geol., 14, pp. 337-381.

Beach, H. H., 1943. Moose Mountain and Morley Map Areas, Alberta. G.S.C. Memoir 236.

Fitzgerald, E. L., 1962. Structure of the McConnell Thrust Sheet in the Ghost River Area, Alberta. Jour. Alberta Soc. Petrol. Geol., 10, pp. 553-574.

Haman, P. J. and Ozsezginer, 1967. Stereogrammetry applied to Rocky Mountain structures in the Mount Yamnuska area, Alberta. West Canadian Research Publications of Geology and Related Sciences, Series 1, No. 2.

Price, R. A. and Mountjoy, E. W., 1970. Geology along the Bow River from west of Calgary to Lake Louise. Alberta Soc. Petrol. Geol.

Talwani, M. and Ewing, M., 1960. Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape. Geophysics 25, pp. 203-225.

White, R. M., 1976. Noise level in a mountain gravity survey. M.Sc. Thesis, University of Calgary.