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GRAVITY MODELLING AND ISOSTASY IN WESTERN CANADA

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ABSTRACT

A method of calculating relative isostatic anomalies by means of two-dimensional Fourier transforms is presented. The Airy anomalies in the western Canadian shield and plains are computed, sorted on the basis of wavelength, and interpreted in terms of regional geology.

INTRODUCTION

Current knowledge of the structure of the lithosphere in western Canada is quite sparse. Most of the available information is the result of various seismological studies that have utilized refraction, reflection and earthquake data. The gravitational field in western Canada, on the other hand, is well-established in a regional sense and provides an alternative source of deep structural information. In the present study, the gravity data will be modelled in terms of the theory of isostasy.

A base map showing the location of the study area is given in Figure 1. The map-area is bounded on the south by the 49th parallel which is the international boundary, and on the north by the 60th parallel which passes just south of Yellowknife, N.W.T. The western limit is the 118°W meridian which passes nearly through Kelowna, B.C., and the eastern limit is the 95°W meridian which passes east of the city of Winnipeg, Manitoba. The smoothed Bouguer anomaly for the interior of western Canada is shown in Figure 2. (The map-area is the same as on the base map in Figure 1.) The data for this map were obtained from some 26,000 gravity observations recorded by the Earth Physics Branch, Department of Energy, Mines and Resources, Canada. To enable further computations, it was decided to re-format these data onto a square 256-by-256-point grid with about eight kilometres between grid points. Since gravity stations are generally about ten kilometres apart, aliasing problems that might have occurred with a larger sampling interval were avoided. Frequency filtering was then used to produce smoother maps with grid sizes 128 by 128 and 64 by 64.

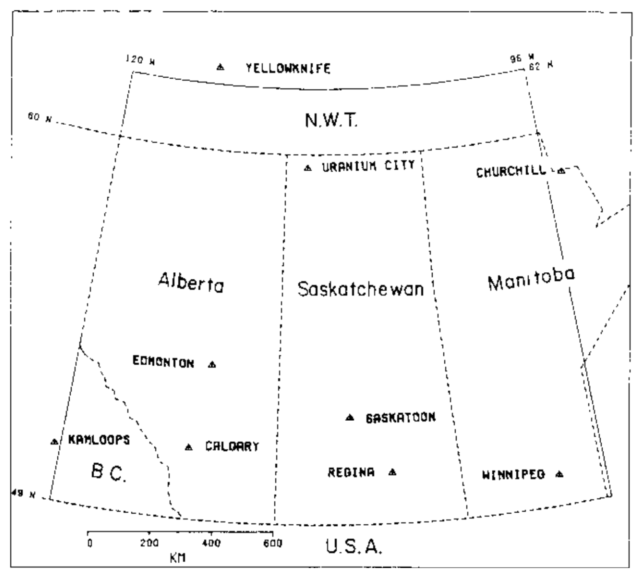

Fig. 1. The map-area for which gravity data were available for this study.

It is apparent that much of the Bouguer anomaly across the interior of western Canada is associated with the effect of deep-seated masses compensating the apparent excess surface mass due to physiographic changes. In order to study other effects on the field, it is necessary to remove the effect of compensation by performing an isostatic correction. A true isostatic correction is very laborious in that it involves estimating topographic height in zones extending right to the antipode of the station. In this study, only data from within the map-area are considered. Hence, the "isostatic correction" determined here should not be considered as valid from a geodetic point of view. However, although distant topography is significant, its effect is quite

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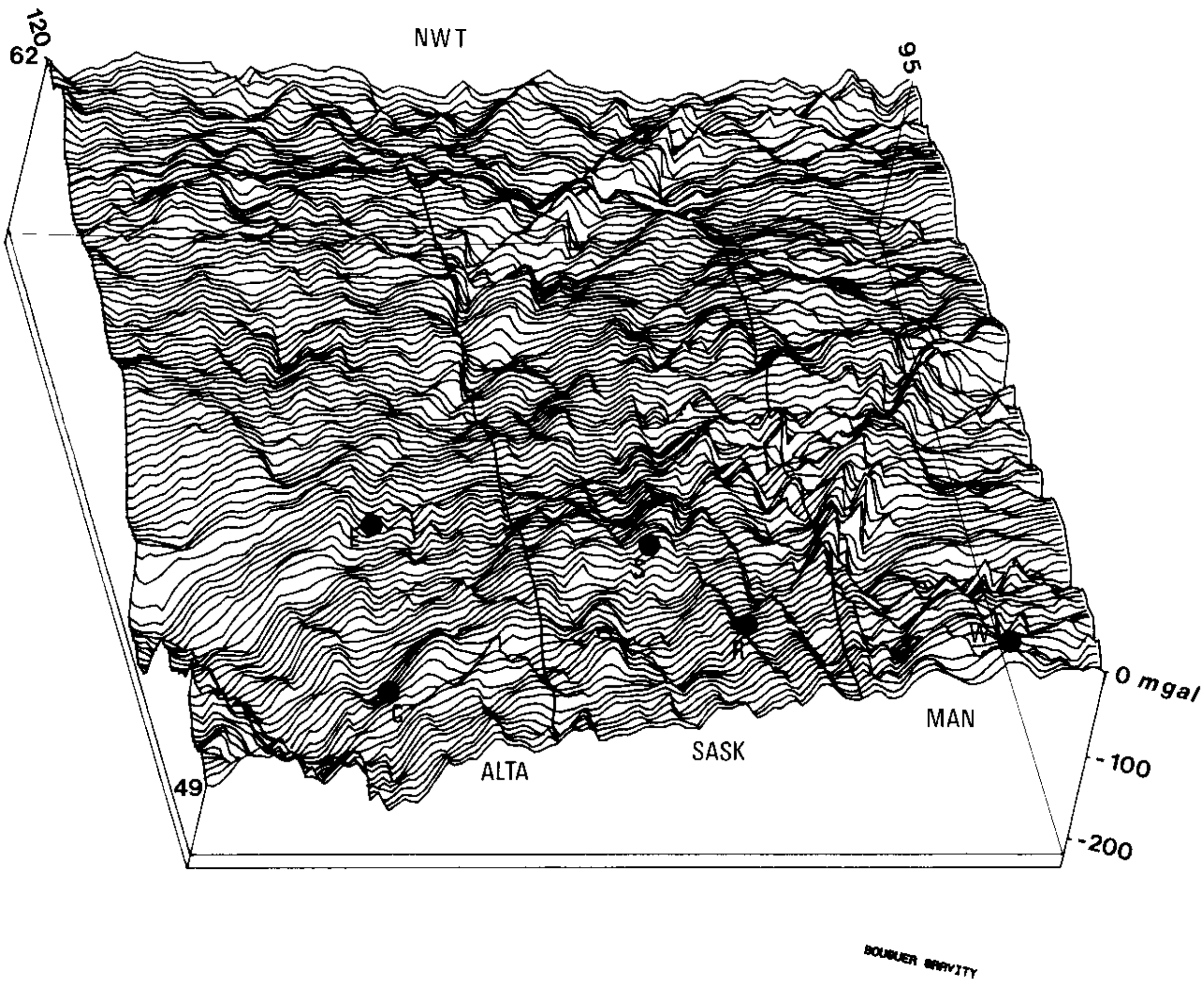

Fig. 2. A perspective view of the Bouguer gravity anomaly for the interior of western Canada.

smooth over the map-area (Karki *et al.*, 1961), and the character of the resulting isostatic anomaly would be little affected. In order to obtain the isostatic correction, it is assumed that the excess surface mass is compensated by roots of crustal material as suggested by Airy in 1855.

The Airy anomaly can be calculated in the following manner:

$$g_a(x,y) = g_b(x,y) - g_c(x,y) \qquad [1]$$

where $g_a(x,y)$ is the Airy anomaly, $g_b(x,y)$ is the Bouguer anomaly, and $g_c(x,y)$ is the isostatic correction. The function $g_c(x,y)$ can be rapidly calculated for a set of grid values by using two-dimensional Fourier transforms in the following manner:

$$F\{g_c(x,y)\} = -2\pi G d e^{-|\vec{k}|Z_o} \sum_{n=1}^{\infty} \frac{|\vec{k}|^{n-1}}{n!} F\{h^n(x,y)\} \qquad [2]$$

where F signifies that a two-dimensional Fourier transform is to be taken of the quantity in brackets, d is the density contrast between the crust and mantle, G is the universal gravity constant, $\vec{K}$ is the wavenumber vector in the spatial frequency domain, and h(x,y) is the subsurface topography on the Mohorovicic surface measured relative to a level at the depth Z_o beneath the surface. An outline of the derivation of the above algorithm can be found in Parker (1973). In practice, equation [2] becomes a quickly convergent series expansion of fast Fourier transforms and is thus a very inexpensive method of computing gravitational attraction. By using Z_o = 33 km as the depth of the standard crust, a crust-mantle density difference of 500 kg/m^3, and regional elevation data, the Airy crustal model (Fig. 3) was calculated. The theoretical gravity anomaly predicted by this model is the Airy correction. This correction was calculated by means of equation [2] and applied to the Bouguer anomaly map according to equation [1]. The Cordillera was not included in this analysis for lack of sufficient gravity and elevation control.

The resulting Airy anomaly for western Canada was separated on the basis of wavelength into components for further analysis. It will be apparent from the results discussed below that large sections of the western Canadian shield and plains are anomalous. Although

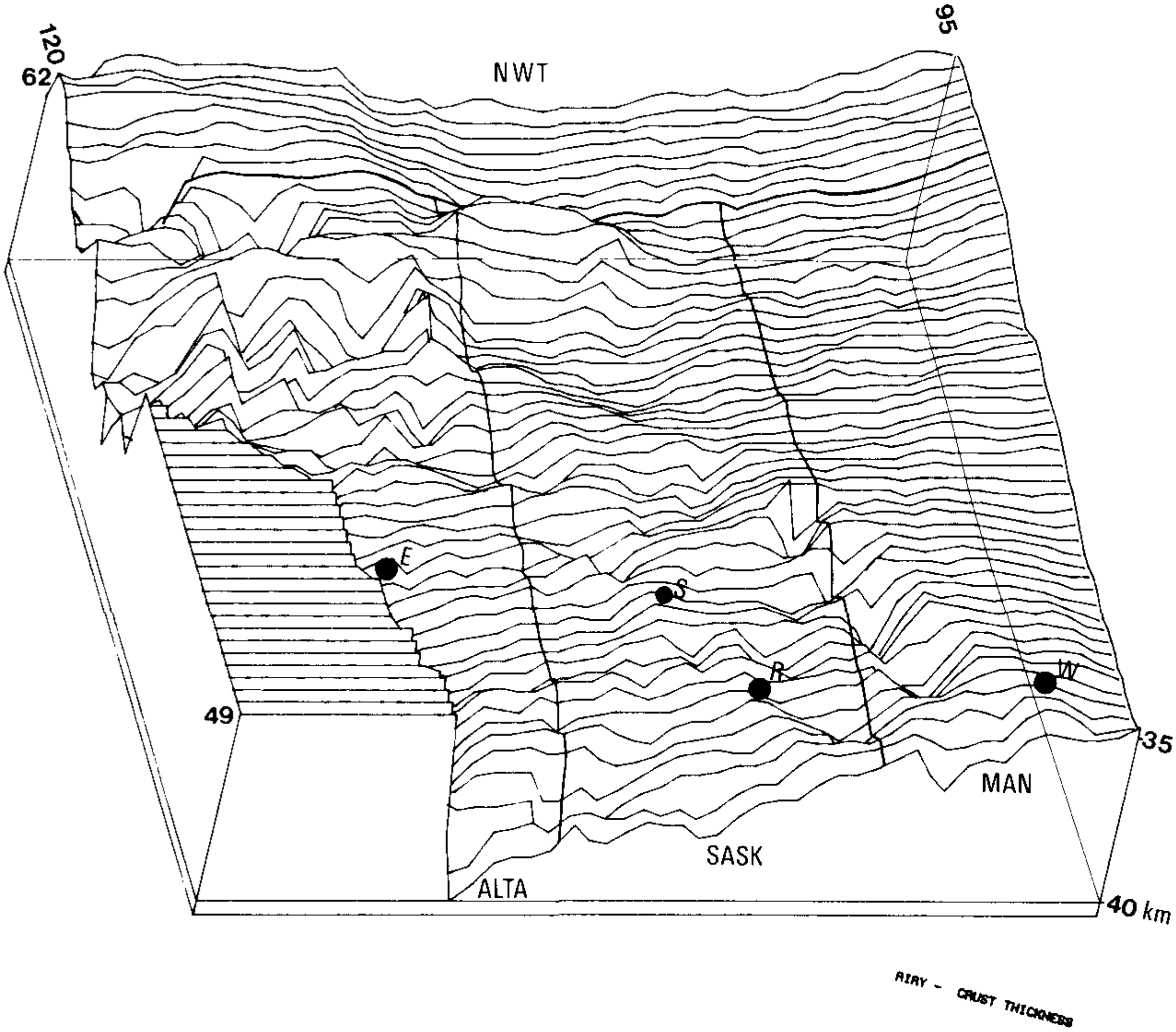

Fig. 3. The crustal thickness in western Canada according to the Airy hypothesis, in which the mass per unit area above sea level is balanced by an equivalent mass deficiency per unit area at the level of the Mohorovicic discontinuity. A density contrast of 500 kg/m^3 was assumed at the base of the crust.

the nature of the compensation is undoubtedly more complicated than the form suggested by Airy, it is difficult to escape the conclusion that much of the map-area is out of isostatic equilibrium.

Long-Wavelength Airy Anomaly

The long-wavelength portion of the Airy anomaly over the map-area is shown in Figures 4 and 5. All wavelengths shorter than about 1000 km have been filtered out. As the filtering process used to obtain this very low wavenumber map produced rather severe edge effects, one should consider only the shape of the surface toward the centre of the map as significant. Nonetheless, it is evident that the amplitude of this long-wavelength component is quite high in that it ranges from -30 to $+9$ milligals with a pronounced low in the northeast corner of the map-area and a distinct high in the Canadian portion of the Williston Basin.

The trend toward a low isostatic anomaly in the northeast corner of the map-area suggests increasing overcompensation in that direction. A very probable explanation is incomplete recovery of the lithosphere from the Pleistocene ice loads (Andrews, 1968; Walcott, 1969).

If the long-wavelength component of the Airy anomaly is indeed due to the former ice load, then it is possible to use the isostatic anomaly to estimate the amount of uplift still to come. If the lithosphere attained equilibrium under the ice load, then sufficient mantle material had to be displaced to compensate for the glacial load. If the present long-wave Airy anomaly is assumed to be a direct measure of the relict glacial roots, then, on the basis of the Airy theory, a mass deficiency per unit area of $h(x,y)d(x,y)$ can be expected where $h(x,y)$ is a depression near the level of the Moho and $d(x,y)$ is the density of the mantle material displaced (Garland, 1965, p. 122). Then, by using the well-known formula for the gravitational attraction of an infinite

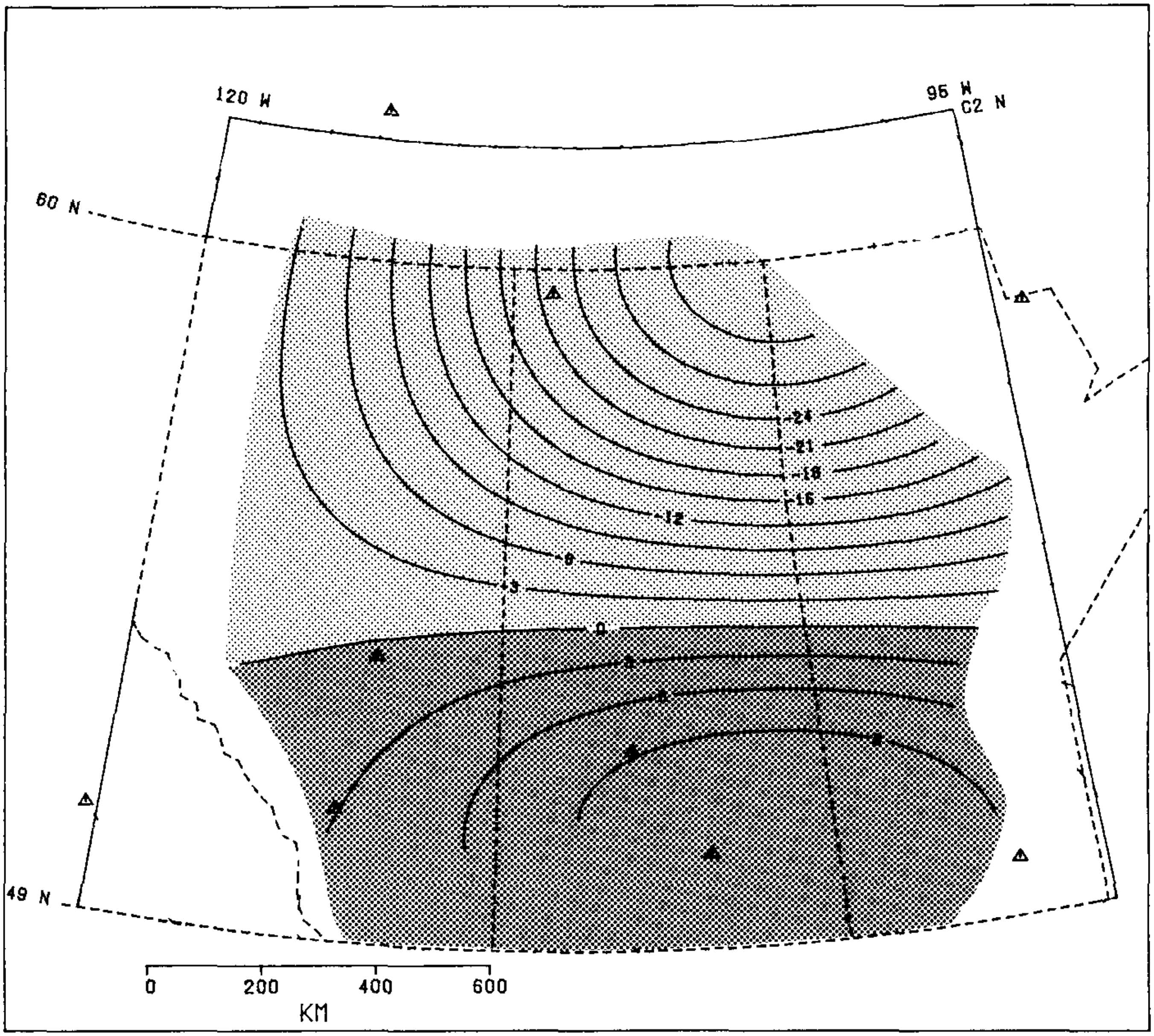

Fig. 4. Long-wavelength Airy anomaly in western Canada. Only wavelengths greater than about 1000 km are shown. The contour interval is 3 milligal. The triangles represent major cities within the map-area.

slab, the amount of depression on the base of the crust in the northeast portion of the map-area is found to be somewhat in excess of 200 m, a value in fair agreement with that calculated by Innes (1960), whose data were based on concentric averages of the isostatic anomaly around Hudson Bay.

The long-wavelength positive Airy anomaly associated with the Williston Basin area cannot, of course, be interpreted in terms of glacial loading. Nor can it be explained in terms of undercompensation for the sedimentary load in the basin, a situation in which a very thin crust would be expected, since Kanasewich (1966) has pointed out that the thickest crust in North America occurs under geological depressions such as the Williston Basin. It is apparent that either the Williston Basin is still subsiding or tectonic forces are maintaining the imbalance. These forces could be horizontal, associated with plate interaction, or vertical, associated with upper-mantle density variations. The Airy anomaly over this area is of a wavelength greater than 1000 km; hence, it does not seem likely that the negative load of the basin is supported by the crust. The long wavelength also excludes the possibility that the Airy anomaly is due to the dense basement rock of the area (Burwash and Culbert, 1976) being entirely compensated by a deeper root since, in this case, unlike the case for shorter wavelengths to be discussed later, the gravity effect of the dense basement would not be significantly greater than the effect of the deeper root because both have such great lateral extent.

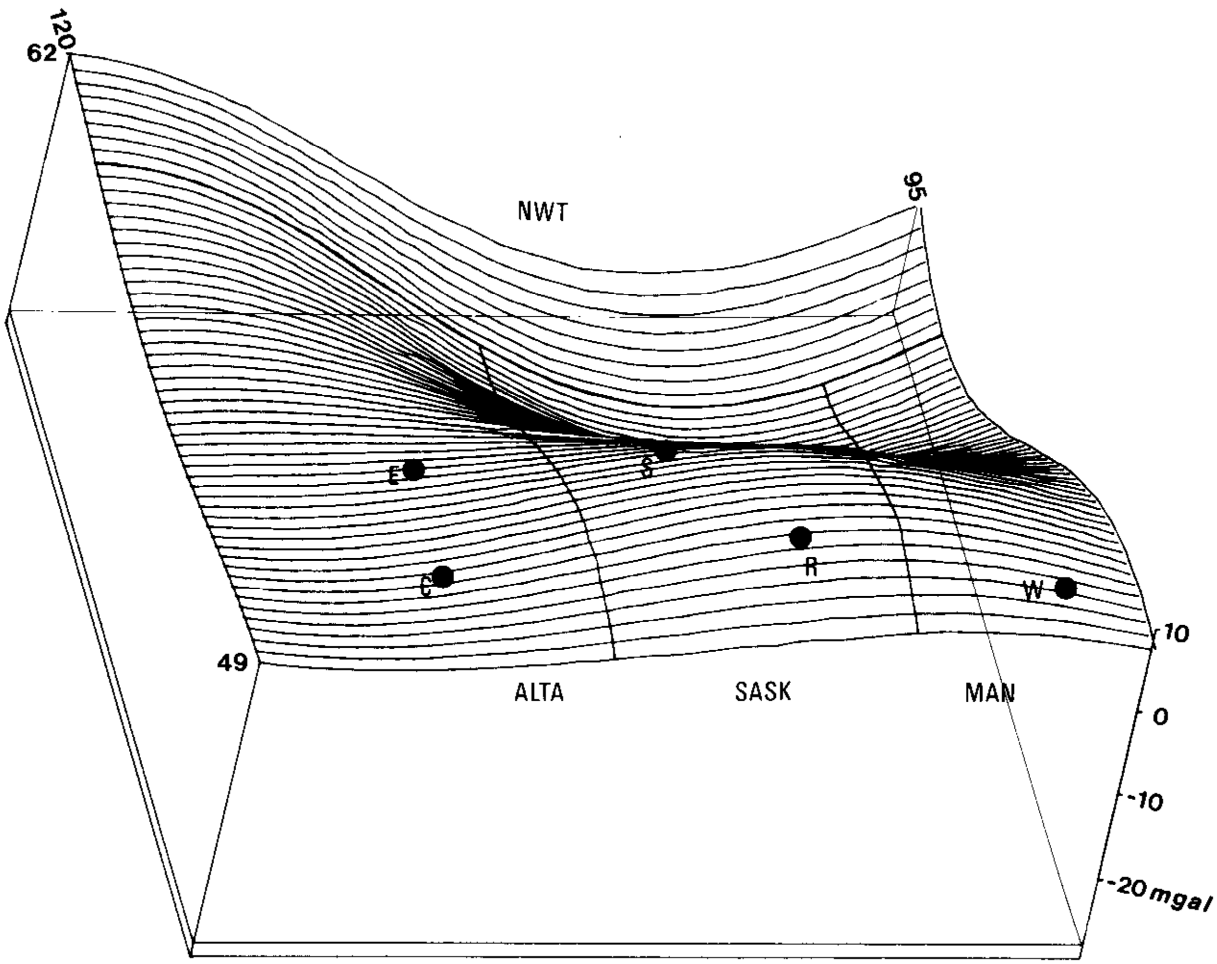

Fig. 5. A perspective view of the long-wavelength Airy anomaly in western Canada.

Middle-Wavelength Regional Airy Anomalies

A map showing Airy anomalies of wavelengths from 500 to 1000 km is given in Figure 6. Although edge effects due to the filtering process for this band of wavenumbers are not as severe as in the low-wavenumber map, such effects still occur. Most of the anomalies on the map, however, seem to be significant. Theoretical stress studies suggest that these anomalies are far too great in lateral extent to be explained by masses supported by the lithosphere (Woolard, 1959; Walcott, 1969). It is therefore postulated that they are possible relics of the earth's attempt to restore isostatic equilibrium. If so, they represent fundamental divisions of the lithosphere and may indicate the nature of ancient tectonic regimes. As a test of this hypothesis, it is interesting to compare these isostatic anomalies with known geological zones in western Canada.

The Precambrian basement and shield in western Canada have been essentially divided into five divisions as shown in Figure 7 by Burwash and Culbert (1976) on the bases of petrology, isotope dating and geophysical information. More recently, Camfield and Gough (1977) have suggested the existence of a possible Proterozoic plate boundary in the map-area as shown by a dotted line on the same figure. The four division boundaries of Burwash and Culbert (1976) and the suggested boundary of Camfield and Gough (1977) are replotted on the isostatic gravity map in Figures 8 and 6. These fundamental lineaments seem to bear some relation to the middle-frequency Airy anomalies.

Negative isostasy is indicated for the Liard block, the covered southwest portion of the Cree Lake - Calgary belt, the extreme northeast corner of the map-area, and the Superior province. Positive isostatic anomalies occur over the Athabaska mobile belt, the Kisseynew-Sweetgrass belt, and the northeast portion of the Cree Lake - Calgary belt.

Burwash and Culbert (1976) have performed extensive statistical analyses of much of the geological data available for the basement rocks of the western Canada basin. By considering together this geological information and the Airy anomalies, some interesting observations can be made about isostasy and its relation to geologic and, in particular, metamorphic history.

The Athabaska mobile belt, for example, is a zone of intense K-metasomatism (Burwash and Culbert, 1976), a reaction that proceeds only at the expense of density. Hence the crustal rocks of this zone have decreased in density during their metamorphic history. The Athabaska

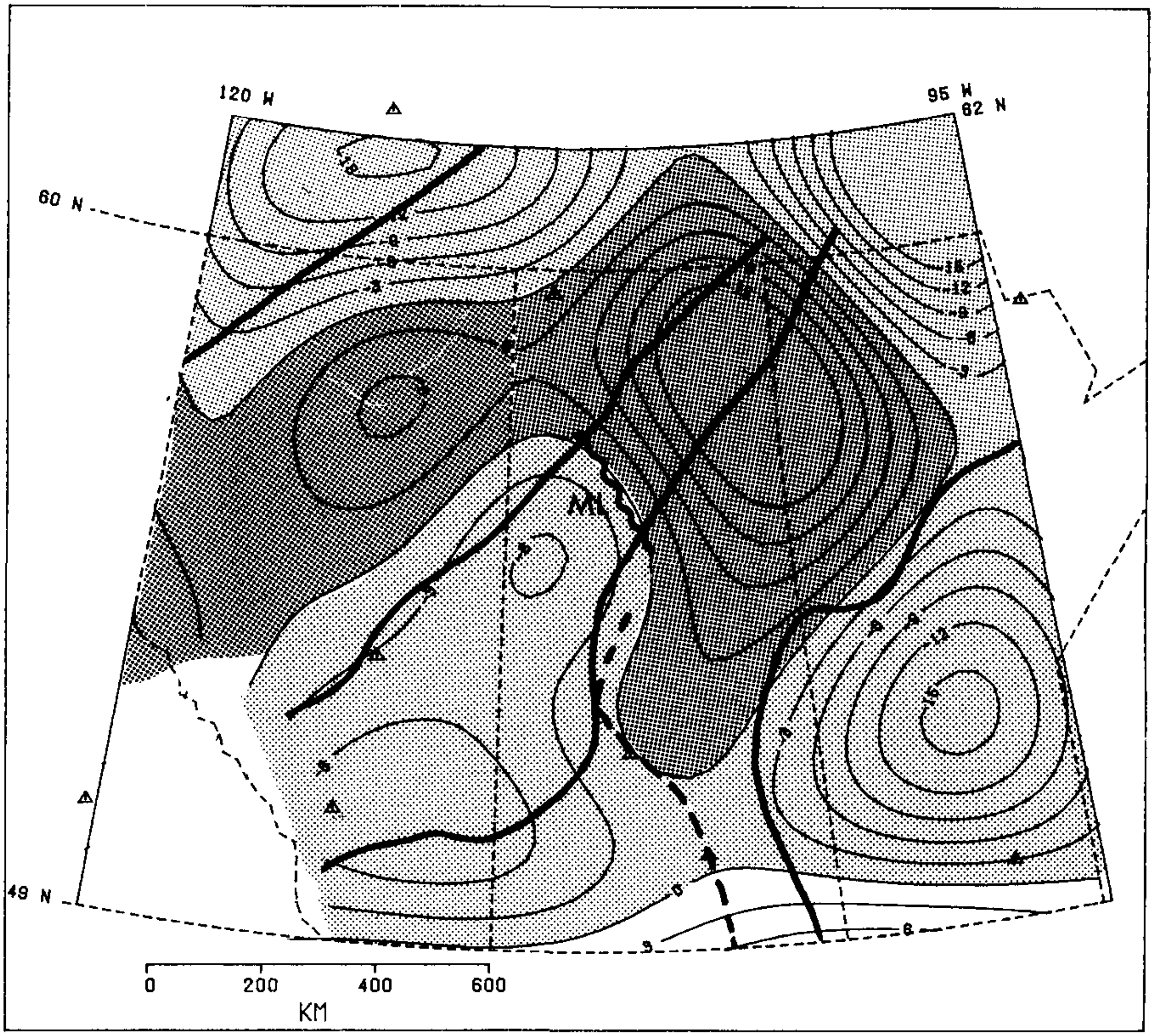

Fig. 6. Geologic zone boundaries in western Canada plotted on the middle-wavelength isostatic map. The contour interval is 3 milligal. The triangles represent major cities within the map-area. The Maurice Lake structure is indicated by ML.

belt, however, shows a relatively positive isostatic anomaly. Perhaps a regional high on the Moho or anomalously high mantle densities still exist today beneath the Athabaska mobile belt as a relic of the Hudsonian orogeny. Either would explain the positive isostatic anomaly over the belt. Such an uncompensated feature would have to be supported either by the inherent strength of the lithosphere or by tectonic forces. In the Athabaska mobile belt, there is some evidence that recurring positive tectonic forces have in fact continued to be active since the Hudsonian orogeny. Burwash and Krupicka (1970) have concluded from paleographic data that the Peace River Arch, which lies within the mobile belt, has been a long-term positive feature during Phanerozoic time. They further postulated that the metasomatic decrease in density of the rocks during Hudsonian time has resulted in this persistent uplift as a result of the isostatic process. However, the time scale involved for such a process would be many orders of magnitude different. Crittenden (1963), for example, has shown from studies of the unloading of Pleistocene Lake Bonneville that changes in elevation with time due to isostatic imbalance follow exponential curves that decay in a matter of only several thousand years. An alternative explanation of the persistent positive nature of the Peace River area is that recurring vertical tectonic forces have been affecting the Athabaska mobile zone. It is significant in this regard that recent seismicity including at least three events of magnitude greater than 4 have been recorded in this zone (Milne *et al.*, 1978).

The Liard block and the southwest portion of the Cree Lake - Calgary belt have also decreased in density during their metamorphic history. As the isostatic

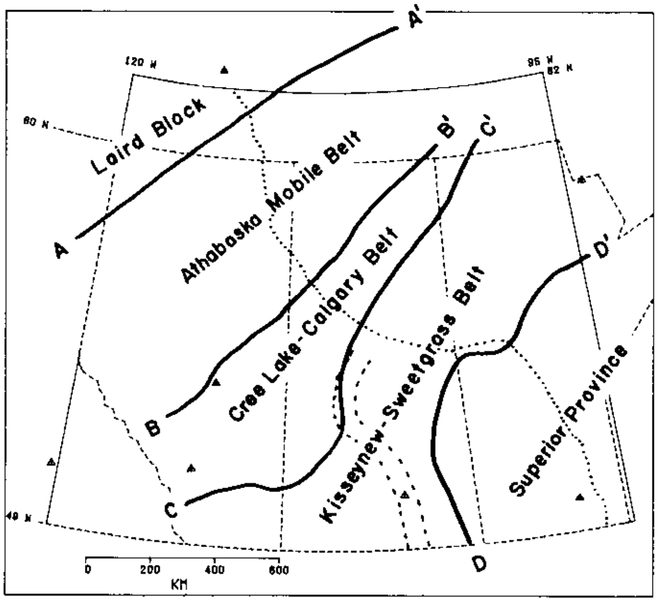

Fig. 7. Geologic zones and boundaries in western Canada. The triangles represent major cities within the map-area. A-A' is the Hay River fault zone, B-B' is the Athabasca Axis, C-C' includes the southern Alberta rift, and D-D' is the Nelson Front.

anomaly over these zones is negative, the negative load of the density decrease appears to be supported by the lithosphere.

The exposed northeast portion of the Cree Lake - Calgary belt has, however, a strongly positive isostatic anomaly. This anomaly suggests the existence of a possible new fundamental boundary in the lithosphere, separating the Cree Lake - Calgary belt into two zones. A long northwest-trending fault, known as the Maurice Lake structure, has been observed in this belt in north-central Saskatchewan (Byers, 1962). Perhaps this fault as shown in Figure 6 marks the location of the subdivision boundary. Alternatively, the boundary might lie parallel to this fault but southwest of it, so that it is covered by sedimentary rock. Another possibility is that the northeast portion of lineament C-C' in Figure 7 should simply not be considered as a fundamental tectonic boundary for the map-area because it seems to bear little correlation with the isostatic data.

Over all, the Kisseynew-Sweetgrass belt coincides with a net positive Airy anomaly, possibly a result of an anomalously high density mantle in the area that may be partly associated with Williston Basin tectonics.

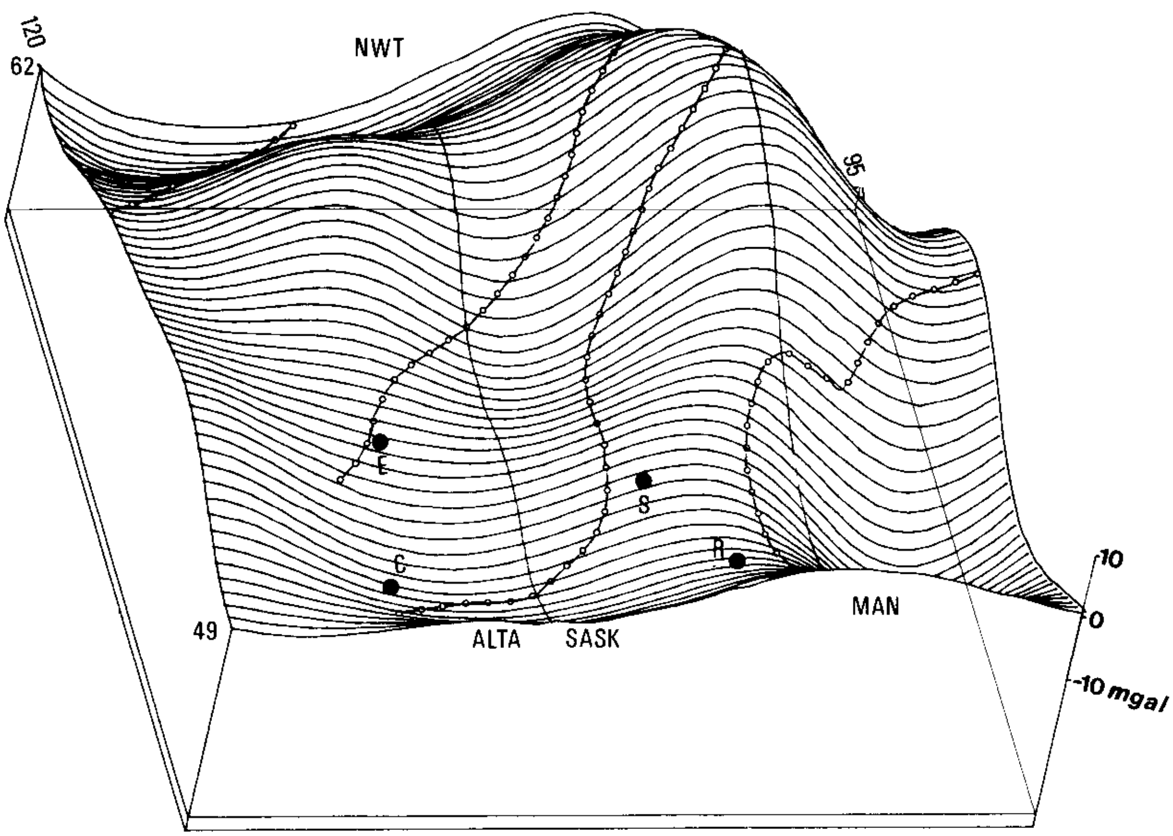

Fig. 8. Perspective view of the middle-wavelength Airy anomalies in western Canada. Major geological boundaries are also shown.

In fact, the persistent positive gravity of this belt can be traced considerably southward on the Free Air Gravity Map of the United States (McGinnis *et al.*, 1979).

The Superior province, which is located to the southeast of D-D′ on Figure 7, is well delineated on the Airy anomaly map. In relation to the zones of the Churchill province discussed above, it shows a negative isostatic anomaly, suggesting possible overcompensation at this time. Seismic results in the province, however, show evidence of a thin crust in the Superior province as compared with the Churchill. Hence, the isostatic imbalance between the two provinces is due probably to the pronounced difference in the type of metamorphism that has occurred in each, rather than to gross crustal structure.

If the intense negative anomaly in the extreme northeastern corner of the map-area is not a result of the filtering process, it may be due to an Aphebian volcanic mass occurring between Rankin Inlet and Churchill. Perhaps the low isostatic anomaly records the existence of an ancient volcanic regime. Alternatively, this isostatic low might represent a local intense depression in the crust due to glacial loading, as this area is located at the point of maximum Pleistocene glacial thickness.

Short-Wavelength Regional Airy Anomalies

The Canadian Shield, including the portion that underlies the western Canada sedimentary basin, has been stable, with the possible exception of isostatic adjustment and some faulting, since the late Proterozoic. The basement geology has therefore remained largely unchanged since the last major orogeny 1800 million years ago. Yet Airy anomalies of the order of 40 milligals and of wavelength greater than 150 km are present (Figure 9). Walcott (1968) suggested that these anomalies cannot represent departure from isostatic equilibrium, because the time constants involved in restoring equilibrium as determined from ice and lake load studies are many orders of magnitude less than the apparent age of the anomalous material. Regardless of the nature of compensation, these anomalous areas do seem to show at least some correlation with the known geologic boundaries in the map-area. The Nelson Front, the boundary between the Superior province and the Kisseynew-Sweetgrass belt of the Churchill province (Bell, 1971) is typified by an isostatic low to the west and a parallel high to the east. The southern Alberta rift (Kanasewich *et al.*, 1969) is associated with an isostatic low in Alberta and possibly western Saskatchewan. The Athabaska Axis (Darnley, 1981) tends to

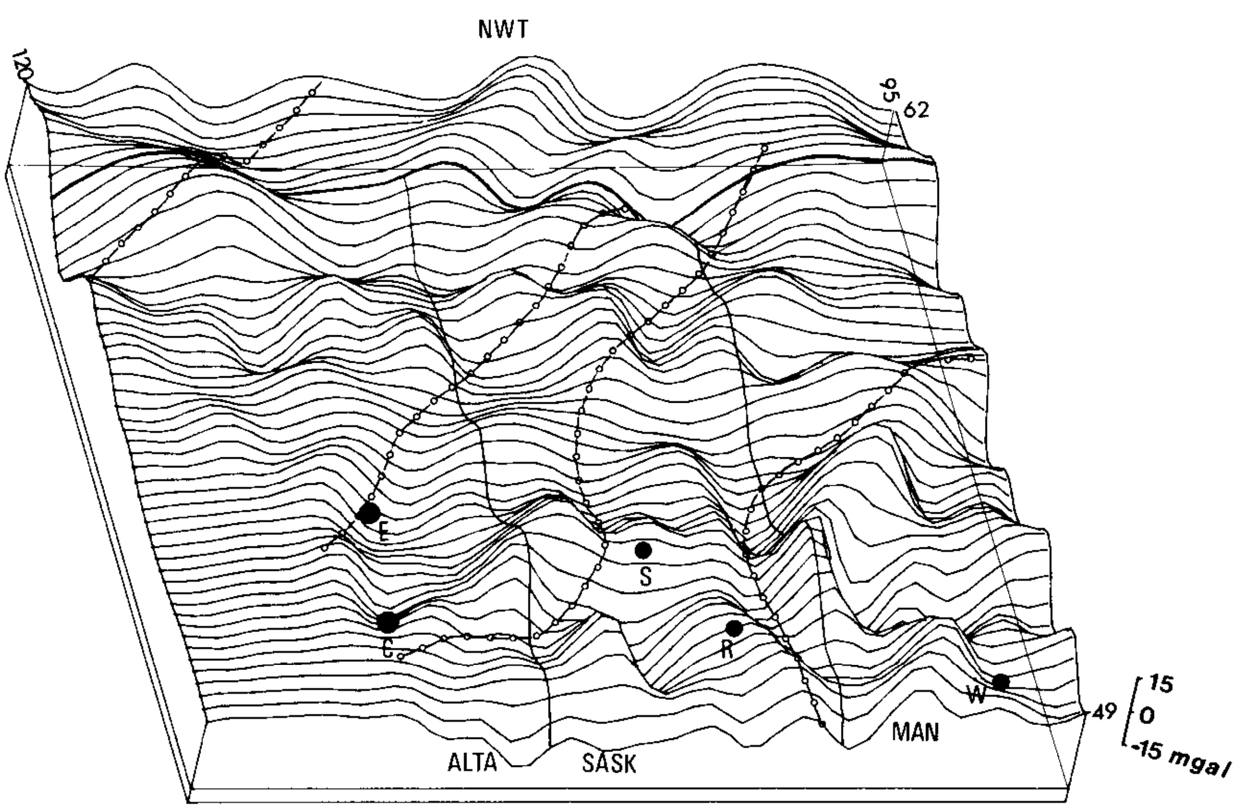

Fig. 9. A perspective view of the short-wavelength regional Airy anomalies in western Canada. The known geologic zones and boundaries are also shown.

follow a broad isostatic low from central Alberta to northeastern Saskatchewan.

Discussion

An algorithm based on Fourier transforms was found to be an efficient means of estimating the relative isostatic anomaly in western Canada. The long-wavelength portion of the isostatic anomaly shows a strong trend toward overcompensation to the northeast, due probably to incomplete recovery of the lithosphere from the Pleistocene ice load. The isostatic anomaly was used to estimate the remaining uplift and a value of over 200 m was calculated, a figure in agreement with other studies. A long-wavelength isostatic anomaly also was found to be associated with the Williston Basin area.

Middle-wavelength isostatic anomalies (500 to 1000 km) were found to be strongly related to known geologic divisions in western Canada. The Liard block and the Superior province were found to exhibit negative isostasy, while positive isostatic anomalies were found for the Athabaska mobile belt and the Kisseynew-Sweetgrass belt.

Short-wavelength (150 to 160 km) isostatic anomalies of amplitudes up to 40 milligals were found to occur extensively in the map-area. These anomalies show some correlation with the known geological boundaries.

References

Andrews, J. T., 1968, Pattern and cause of variability of post-glacial uplift and rate of uplift in Arctic Canada: J. Geol., v. 76, p. 404.

Bell, C. K., 1971, History of the Superior-Churchill boundary in Manitoba: Geol. Assoc. Canada, Special Paper, v. 9, p. 5-10.

Burwash, R.A. and Krupicka, J., 1970, Cratonic reactivation in the Precambrian basement of western Canada: Can. J. Earth Sci., v. 7, p. 1275.

_____, Krupicka, J. and Culbert, R. R., 1973, Cratonic reactivation in the Precambrian basement of western Canada. III. Crustal evolution: Can. J. Earth Sci., v. 10, p. 283-291.

_____ and Culbert, R. R., 1976, Multivariate geochemical and mineral patterns in the Precambrian basement of western Canada: Can. J. Earth Sci., v. 13, p. 1-18.

Byers, A. R., 1962, Major faults in western part of the Canadian Shield with special reference to Saskatchewan: Roy. Soc. Canada, Special Publication 4, p. 40-59.

Camfield, P. A. and Gough, D. I., 1977, A possible plate boundary in North America: Can. J. Earth Sci., v. 14, p. 1229-1238.

Crittenden, M. D., 1963, Effective viscosity of the earth derived from isostatic loading of Pleistocene Lake Bonneville: J. Geophys. Res., v. 68, p. 5517-5530.

Darnley, A. G., 1981, The relationship between uranium distribution and some major crustal features in Canada: Mineralogical Magazine, v. 44, p. 425-436.

Garland, G. D., 1965, The Earth's Shape and Gravity: New York, Pergamon Press Ltd., 183p.

Innes, M. J., 1960, Gravity and isostasy in northern Ontario and Manitoba: Dominion Observatory, v. 21, no. 6.

Kanasewich, E. R., 1966, Deep crustal structure under the plains and Rocky Mountains: Can. J. Earth Sci., v. 3, p. 937-945.

_____, Clowes, R. M. and McCloughan, C. H., 1969, A buried Precambrian rift in western Canada: Tectonophysics, v. 8, p. 513-527.

Karki, P., Kirioja, L. and Heiskanen, W. A., 1961, Topographic-isostatic reduction maps for the world: Publications of the Isostatic Institute of the International Association of Geodesy, No. 35.

Mcginnis, L. D., Wolf, M. G., Koshmann, J. J. and Ervin, C. P., 1979, Regional free air gravity anomalies and tectonic observations in the United States: J. Geophys. Res., v. 84, p. 591-601.

Milne, W. G., Rogers, G. C., Riddihough, R. P., McMechan, G. A. and Hyndman, R. D., 1978, Seismicity of western Canada: Can. J. Earth Sci., v. 15, p. 1170-1193.

Oldenburg, D. W., 1974, The inversion and interpretation of gravity anomalies: Geophys., v. 39, p. 526-536.

Parker, R. L., 1973, The rapid calculation of potential anomalies: Geophys., v. 39, p. 447-455.

Walcott, R. I., 1968, The gravity field of Saskatchewan and northeastern Alberta: Gravity Map Series of the Dominion Observatory, Maps 16-20.

_____, 1969, Isostatic response to loading of the crust in Canada: Can. J. Earth Sci., v. 7, p. 716-727.

Woolard, G. P., 1959, Crustal structure from gravity and seismic measurements: J. Geophys. Res., v. 64, p. 1521-1544.