A gravity profile across southern Saganash Lake fault: implications for the origin of the Kapuskasing Structural Zone

B. Nitescu and H.C. Halls

Abstract: A high-resolution gravity profile, with station elevations and locations determined by a differential Global Positioning System, shows that the Saganash Lake fault that defines the northwestern boundary of the southern Kapuskasing Structural Zone (KSZ) is southeast dipping and of reverse type. Previous interpretations of a normal fault, caused by crustal collapse following east-verging thrusting along the Ivanhoe Lake fault that forms the southeastern boundary of the KSZ are no longer tenable. Instead, the reverse nature of the Saganash Lake fault is more in harmony with a model of the Kapuskasing zone, whereby its fault-bounded, uplifted blocks are positive flower structures formed by dextral shear along a zone of left-stepping en echelon faults.

Résumé : Un profil gravimétrique à haute résolution, dont l'emplacement et l'élévation des stations ont été déterminés par des méthodes de GPS différentiel, montre que la faille du lac Saganash, qui définit la limite nord-ouest de la zone de Kapuskasing sud, est de type inversé et qu'elle a un pendage vers le sud-est. Des interprétations antérieures d'une faille normale, causée par un effondrement de la croûte après un chevauchement à vergence est le long de la faille du lac Ivanhoe, qui forme la limite sud-est de la zone de Kapuskasing, ne tiennent plus. La nature inversée de la faille du lac Saganash correspond mieux à un modèle de la zone de Kapuskasing selon lequel ses blocs soulevés et limités par des failles sont des structures positives de « fleurs » formées par un cisaillement dextre le long d'une zone de faille en échelons senestres.

[Traduit par la Rédaction]

Introduction

The Kapuskasing Structural Zone (KSZ) is a northeast-trending, fault-bounded, discontinuous belt of Archean high-grade (granulite to upper amphibolite) metamorphic rocks, which cuts diagonally across the generally east–west subprovince structure of the south-central Superior Province and extends 500 km southwestward from James Bay (Fig. 1). The high-grade rocks within this discordant structure are characterized by high values of density, magnetic susceptibility, and seismic velocity. The strong contrast in physical properties between the rocks of the KSZ and the adjacent lower metamorphic-grade rocks of the Wawa and Abitibi subprovinces produces prominent gravity, magnetic, and seismic anomalies, which attenuate and disappear about 20 km southwest of Chapleau, Ontario.

Various interpretations have been proposed for the KSZ. Early models included thinning of the granitic upper crust (Garland 1950), mafic intrusions along a rift system (Innes et al. 1967), a horst (Bennett et al. 1967), an intercontinental suture (Wilson 1968), a failed arm of a triple junction associated with the Keweenawan rift (Burke and Dewey 1973), and a sinistral transcurrent fault zone (Watson 1980). Based on evidence obtained from geological mapping, geobarometric measurements, and gravity modelling, Percival and Card (1983, 1985) and Percival and McGrath (1986) have interpreted the KSZ as an east-verging Proterozoic thrust fault system. In this model, a slab of deep crust was uplifted along the northwest-dipping Ivanhoe Lake fault, which represents the southeastern boundary fault of the KSZ (Fig. 1). The thrust model was confirmed by the results of seismic surveys conducted under the auspices of Lithoprobe (Boland and Ellis 1989; Percival et al. 1989; Geis et al. 1990; Clowes et al. 1992; Lithoprobe Seismic Atlas (on-line)). On the basis of the configuration of the Matachewan dyke swarm, West and Ernst (1991) proposed a modification of the simple thrust model by inferring substantial Proterozoic dextral displacement of up to about 70 km.

The northwestern boundary fault of the central and southern KSZ is represented by the Saganash Lake fault. In the Groundhog River block and northern Chapleau block, the Saganash Lake fault separates the Kapuskasing granulites from the amphibolite-facies rocks of the Wawa subprovince to the west, whereas in the southern Chapleau block, there is lithological and metamorphic continuity across the fault (Fig. 1).

The geophysical data have led to contradictory interpretations regarding the nature and characteristics of the Saganash Lake fault. On the basis of gravity and magnetic investigations in central and southern KSZ, Percival and Card (1983), Percival and McGrath (1986), and Atekwana et al. (1994) have proposed that it is a northwest-dipping normal fault formed by collapse in response to crustal uplift that occurred

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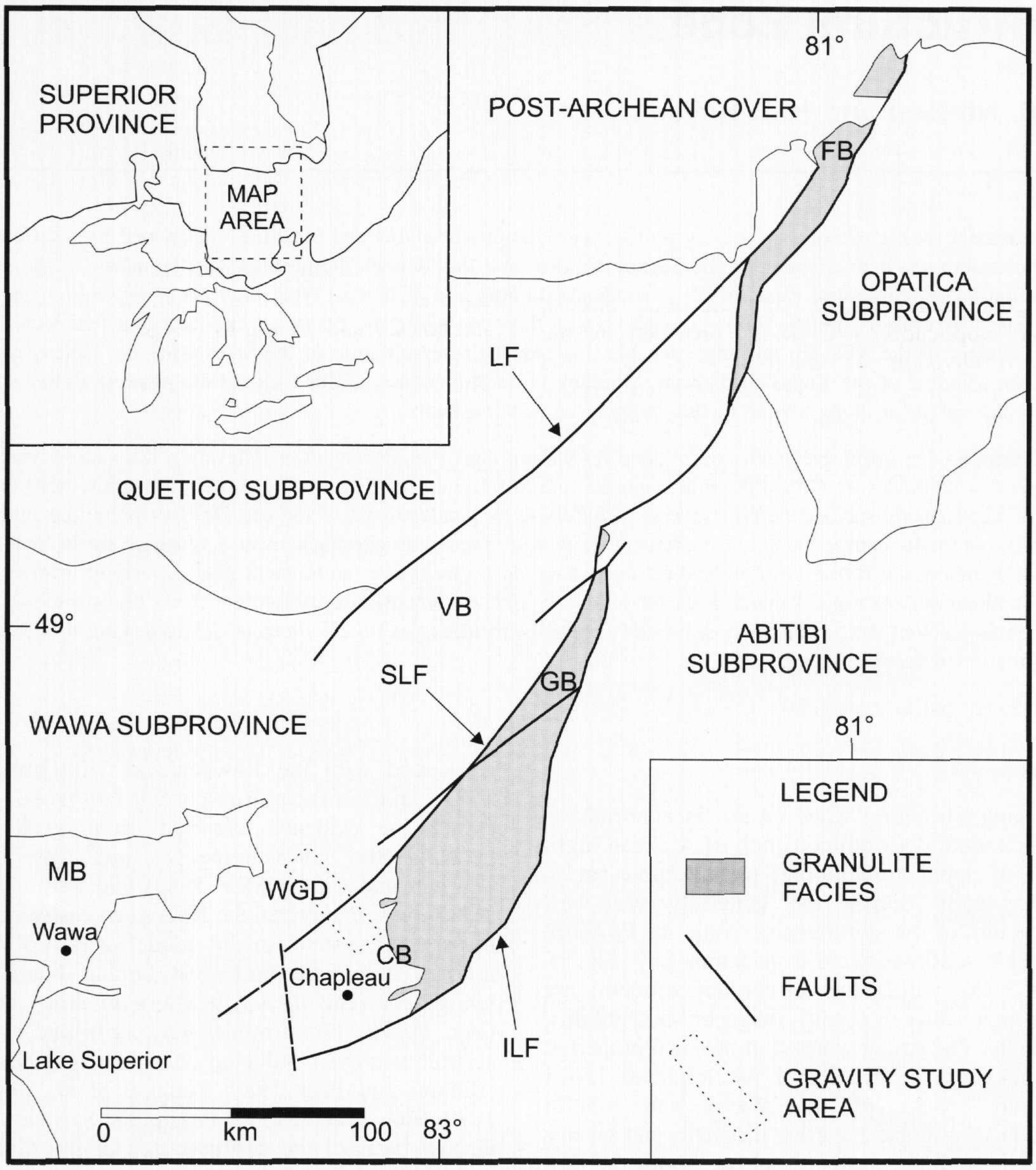
Fig. 1. Geological sketch map of the central Superior Province showing the fault-bounded blocks of the Kapuskasing Structural Zone (modified from Bursnall et al. 1994). The shaded areas indicate the surface extent of granulite-facies rocks within the zone. CB, Chapleau block; FB, Fraserdale–Moosonee block; GB, Groundhog River block; VB, Val Rita block; ILF, Ivanhoe Lake fault; LF, Lepage fault; SLF, Saganash Lake fault; MB, Michipicoten Belt; WGD, Wawa Gneiss Domain.



along the Ivanhoe Lake fault. Based on Lithoprobe seismic reflection data from the southern KSZ, Manson and Halls (1997) suggested that the Saganash Lake fault dips to the southeast, so that the KSZ in the vicinity of Chapleau has the geometry of a pop-up or positive flower structure bounded by inward-dipping reverse faults.

The different interpretations of the Saganash Lake fault indicate the necessity of new geophysical investigations. This gravity study was initiated to investigate the attitude and the depth extent of the Saganash Lake fault at its southern end. The gravity data were obtained along a profile crossing the fault in the region of metamorphic and lithologic continuity between the amphibolite-grade rocks of the Wawa subprovince and those of the southern KSZ.

Gravity data acquisition and processing

The gravity survey was conducted along a logging road that crosses the Saganash Lake fault about 30 km north of Chapleau (line A–B in Fig. 2). In total, 57 gravity stations (numbered 1 to 57 from northwest to southeast) were established, spaced at distances of 0.3–1 km when projected on a straight line orthogonal to the strike of the fault. The gravity observations were made during a five-day period, with repeat measurements at the beginning and end of each day at Control Station 9002–84 of the Canadian Gravity Standardization Net located at Chapleau Airport and having a gravity value of 980751.06 mGal. The instrument was a Lacoste-Romberg Model G gravity meter with an accuracy of 0.01 mGal and a drift rate of 0.5 mGal/month. To determine the elevation and geographical position of each of the field stations a differential Global Positioning System (GPS) was used. The GPS survey involved two Ashtech GPS receivers, one remaining permanently fixed at the base station and the other being used to occupy each of the field stations. The resulting elevations and geographical positions, are estimated to be accurate at the decimetre level.

The raw gravity observations were corrected for tidal variations, irregular drift, latitude and elevation effects, using a software application (PCGRAV) provided by the Geodetic Survey Division of Geomatics Canada. The Bouguer correction was applied using the standard crustal density of 2.67 g/cm^3. Given the small topographic irregularities in the study area (regional relief of less than 80 m over 20 km), terrain corrections were omitted, as they were negligible. The final uncertainty in the Bouguer gravity values due to the various sources of error in data acquisition and reduction is estimated to be less than 0.2 mGal.

The gravity profile was produced by projecting the positions of the gravity stations on a straight line perpendicular to the strike of the fault, its orientation having been inferred from aeromagnetic data (Fig. 2B). Due to the lack of access, the profile could not be continued to the southeast beyond station 57 and, as a result, the crest of the anomaly was not well defined. To remove this uncertainty, six previously established gravity stations situated southeast of station 57 on the direction of the profile were used to extend the gravity profile. The Bouguer gravity values corresponding to these stations were obtained from the national gravity database. The extended gravity profile has a total length of 57 km and defines the entire gravity anomaly associated with the northwestern boundary fault of the Chapleau block (Fig. 3). The Bouguer gravity values show an increase of over 35 mGal from the northwest to the southeast of the profile, which reflects the presence of uplifted dense crust southeast of the Saganash Lake fault.

Another characteristic of the Bouguer anomaly curve is represented by the positive local anomalies of short lateral extent and small amplitude (less than 3 mGal) superimposed on the regional anomaly associated with the Saganash Lake fault. To remove these short-wavelength anomalies, the Bouguer anomaly curve was smoothed graphically (Fig. 3). The smoothing procedure was unequivocal since most of the local anomalies are clearly distinguishable from the background gravity.

The aeromagnetic data indicate that in most cases these local gravity anomalies are observed at stations situated near north-trending 2.45 Ga Matachewan and east-northeast-trending ~2 Ga Kapuskasing dykes (Fig. 4). Based on this observation, it is inferred that the local anomalies are produced by dykes. In some cases, the anomalies might include the effects of more than one dyke. For example, the residual anomaly observed at station 45 is likely the sum of the gravity effects of both a Matachewan and a Kapuskasing dyke, which intersect near this station. The local anomalies have larger amplitudes northwest of the Saganash Lake fault than to the southeast (Fig. 3). This difference can be explained by both a lower dyke–host density contrast and a smaller thickness of dykes within the Kapuskasing zone (Ernst and Halls 1983; Halls and Nitescu, field observations). To confirm the correlation observed between the local anomalies and the dykes crossed by the gravity profile, the gravity effects of several dyke models having parameters (density contrast 0.25–0.4 g/cm^3, width 10–30 m) similar to those of the dykes from the study area were calculated using a 2.5-dimensional (2.5-d) forward modelling program. The maximum amplitudes obtained for the computed dyke anomalies (0.5–1.6 mGal) are similar to the amplitudes of most of the local anomalies. However, the anomalies observed in stations 20 and 29 are too large (2.5–3.5 mGal) to be produced only by the dykes visible on the aeromagnetic image. These anomalies represent either the cumulate effect of a larger number of dykes, unresolved by the aeromagnetic data or include the effects of unknown shallow density contrasts.

Interpretation of the gravity data

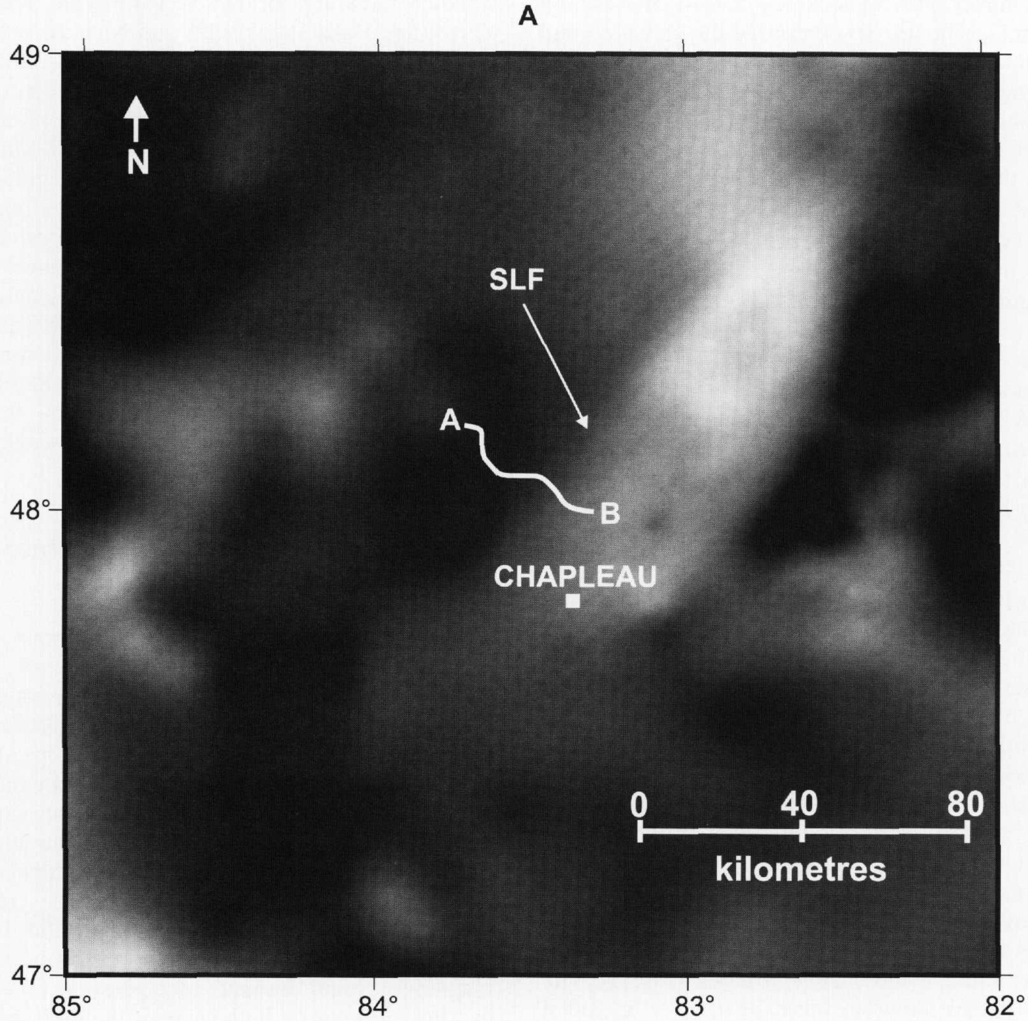
Density determinations

In the area of the gravity survey outcrops are scarce, most of the surface being covered by dense vegetation and surficial deposits of glacial origin. To investigate if a surface density contrast exists across Saganash Lake fault, the densities of 48 rock samples collected from outcrops along the gravity line were determined. The samples from the Wawa Gneiss Domain were mostly tonalite–granodiorite gneiss with a few massive granitoids. Inside the Chapleau block, they were mafic tonalite and tonalite–granodiorite gneiss. Macroscopic analysis and a study of 27 thin sections revealed that all samples contain quartz, plagioclase, and biotite and (or) amphibole. Common accessory minerals are sphene and magnetite. Small amounts of potassium feldspar are present in some samples on both sides of the fault, but pyroxene and garnet are absent. Samples from the Wawa Gneiss Domain contain 5%–10% amphibole and biotite, whereas those from the Chapleau block contain a larger proportion of mafic minerals (15%–20% amphibole and biotite) and are characterized by a coarser grain size (cf. Halls and Mound 1998). In the area of study, the metamorphic grade (middle amphibolite facies) remains uniform across the fault. Hydrous alteration products like sericite, epidote, and chlorite are more evident in the rocks from the Wawa Gneiss Domain, but they are also present in some samples from KSZ. The lower degree of hydrous alteration observed in the samples from southern KSZ indicates a deeper crustal level for the rocks situated southeast of the Saganash Lake fault.

The sample density variations show that a surface density contrast is associated with the southern segment of Saganash Lake fault (Fig. 5). This contrast probably arises from an increased proportion of mafic minerals (5%–15% more biotite and amphibole) and less hydrous alteration in the rocks southeast of the fault (cf. Halls and Mound 1998).

The density determinations cannot give a precise estimate of the density contrast across the fault, because the proportions

Fig. 2. Potential-field data of the southern Kapuskasing Structural Zone showing the location of the gravity profile (line A–B). (A) Bouguer gravity map. The field values increase from black (–80 mGal) to white (–10 mGal). (B) Shaded relief aeromagnetic image (total field intensity). The aeromagnetic expression of the Saganash Lake fault (SLF) is clearly visible. Illumination: azimuth 295°, inclination 22°.



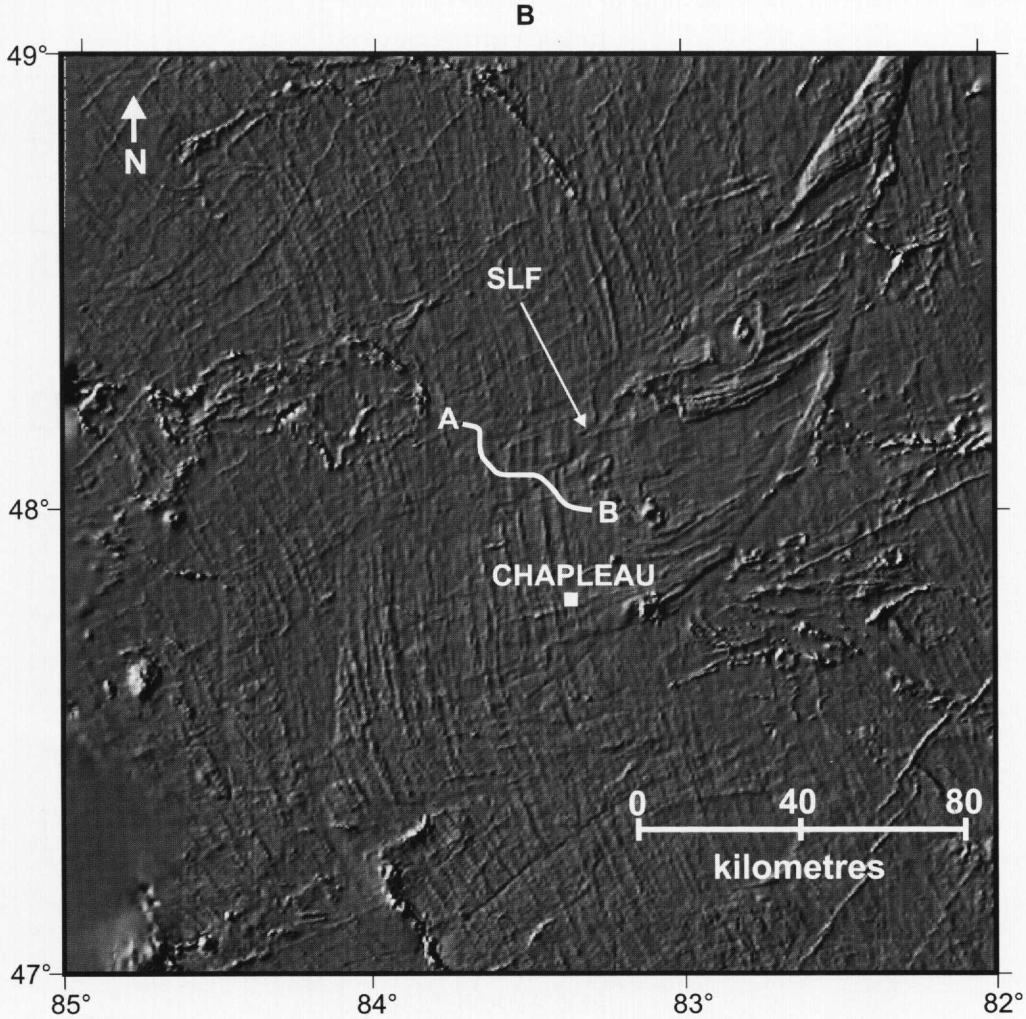
of the different rock types and their variation in hydrous alteration are unknown. However, since the samples were collected from as many locations along the gravity profile as possible, a simple density average could give an approximate estimate of the average surface density. The average density of the rock samples from the Wawa Gneiss Domain is 2.69 g/cm^3 and for those from the KSZ is 2.75 g/cm^3, suggesting a surface density contrast of 0.06 g/cm^3. This value may underestimate the real surface density contrast, as it takes no account of the southeastward increase in abundance of mafic gneiss enclaves within the tonalite gneiss. If a contact similar to that observed at surface across northern Saganash Lake fault between granulites of the northern Chapleau block and amphibolite-facies gneisses of the Wawa Gneiss Domain is buried in southern KSZ, then the density contrast at depth is higher than that observed at surface across southern Saganash Lake fault. Therefore, the value of the density contrast obtained from samples can be regarded as a lower limit for the average density contrast between the Wawa Gneiss Domain and southern KSZ.

The source geometry and the position of the fault

The model of a fault-bounded slab of uplifted deep crust for the KSZ, based on Lithoprobe seismic surveys and previous gravity interpretations (Percival and Card 1985; Percival and McGrath 1986; Atekwana et al. 1994; Percival and West 1994), suggests a step geometry for the source of the gravity anomaly associated with the northwestern boundary of this structure in southern Chapleau block. Although a geological simplification, the assumption of a truncated horizontal slab is sufficient to determine the Saganash Lake fault parameters.

The unequivocal determination of the fault attitude requires an accurate location of the fault at the surface with respect to the gravity profile. Forward modelling (see the following text section) shows that an unconstrained position of the fault leads to equally acceptable step models incorporating a normal, vertical or reverse fault. The estimation of the attitude of the fault is one of the main objectives of this study, so the position of the fault trace represents the most critical constraint on the model. Although the fault has no topographic expression, its position with respect to the gravity profile is successfully

Fig. 2 (*concluded*).



determined from the analysis of the aeromagnetic data (Fig. 4). In the region of the gravity profile the aeromagnetic expression of the fault is a northeast–southwest linear negative anomaly (width ~0.6 km, amplitude ~100 nT) defined by the truncation and dextral offset of the Matachewan dykes. If the positions of the gravity stations are plotted on the aeromagnetic map, the point of intersection between the gravity profile and the trace of the fault occurs near station 36. The uncertainty in the position of the fault is ±0.3 km about station 36.

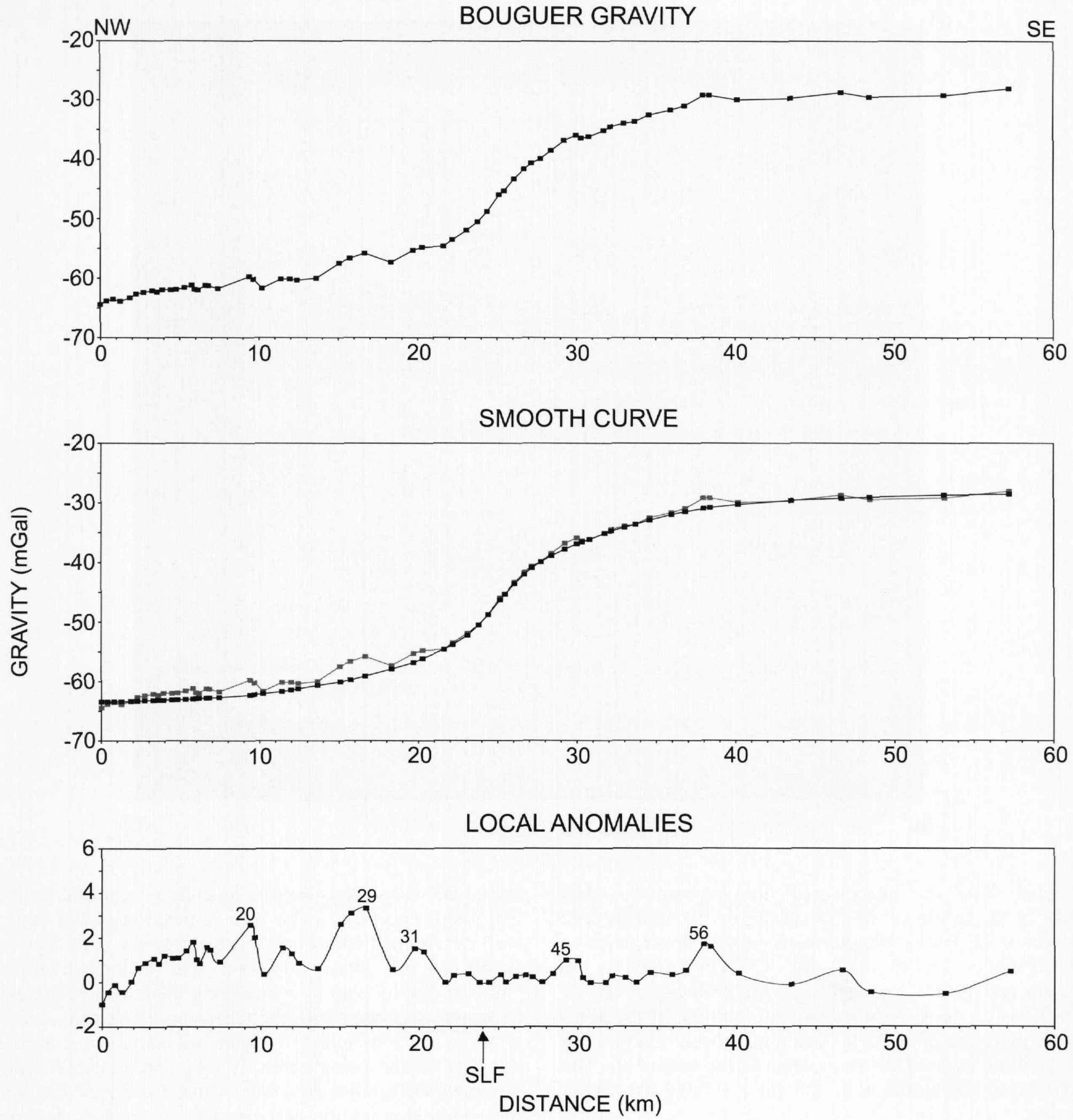
Forward modelling

The gravity anomaly observed across southern Saganash Lake fault was interpreted using a 2.5-d non-iterative modelling software, which calculates the gravity effect of a horizontal body having arbitrary polygonal cross-section and finite strike.

The geometry considered for the source of the gravity anomaly is that of a horizontal truncated plate. The parameters of the model are the depths to the top and bottom of the plate, the density contrast, the fault dip, the surface position of the fault with respect to the gravity profile, and the strike extent and width of the source body. The values for some of these parameters were determined from independent geological and geophysical data. The surface position of the fault was well constrained based on the aeromagnetic data. The strike length of the model (85 km) was estimated from the Bouguer gravity map by considering the length of the gravity anomaly associated with the Chapleau block (Fig. 2A). The width of the source body (45 km) was obtained from that of the KSZ in the survey area. It was also assumed from the observed surface density contrast that the top of the anomalous body reaches the surface. The parameters determined from the modelling of the anomaly were the fault dip, the depth extent of the anomalous body, and the density contrast, which was not well constrained from the density determinations.

The modelling procedure was to fix the surface position of the fault from its aeromagnetic expression and to determine the values of fault dip and density contrast that produce the best agreement between theoretical and observed gravity for various model depths. The density contrast was varied until the calculated curve had an amplitude similar to the observed anomaly, and the dip of the fault was changed until the points of steepest gradient on the calculated and observed curves coincided. Initially, this procedure was performed for

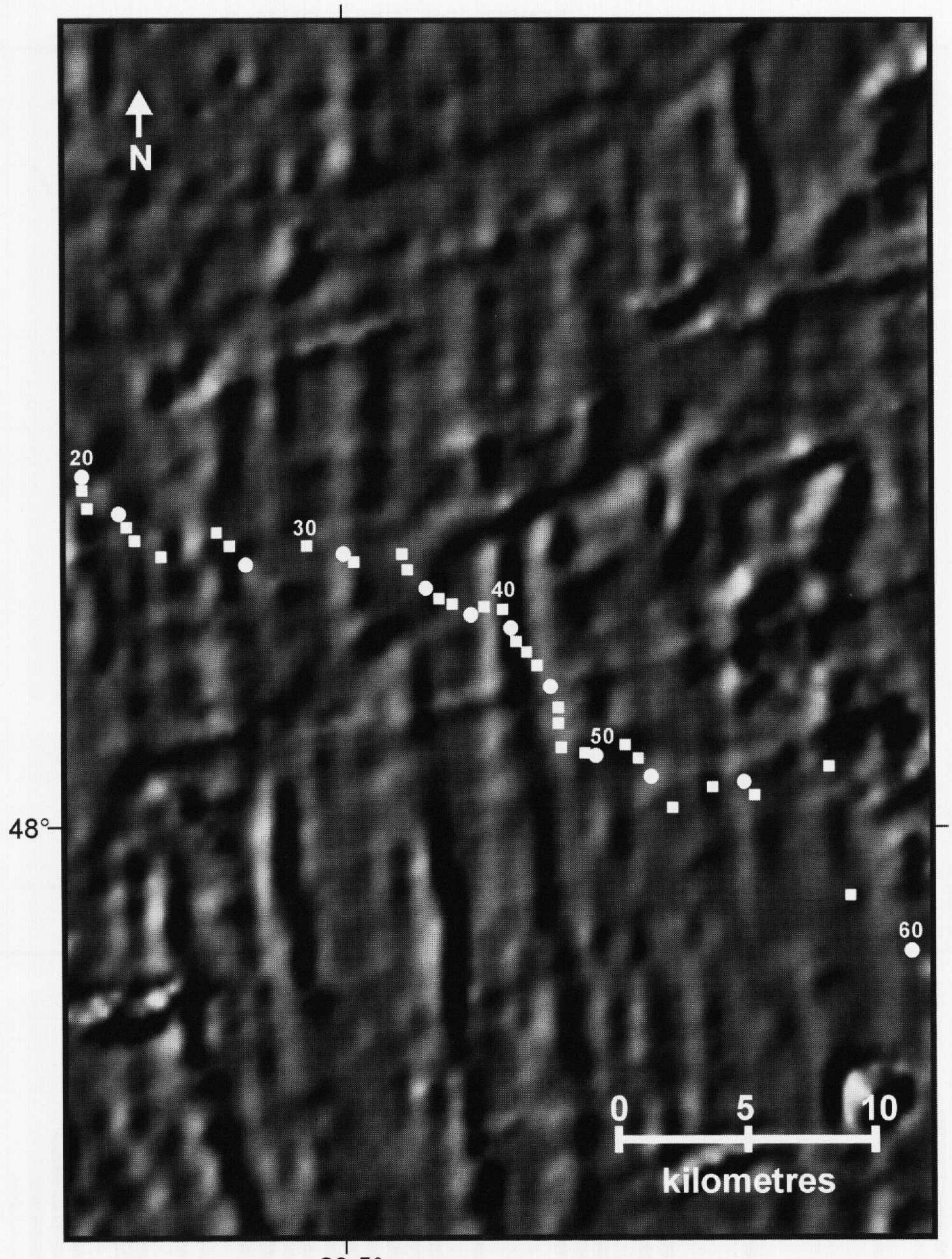
Fig. 3. The Bouguer gravity profile, the smooth gravity curve, and the local anomalies removed through smoothing. Data were projected on a northwest–southeast line perpendicular to the strike of the Saganash Lake fault.



models having depth extents of 5, 10, 15, and 20 km. The depths of 5 km and 20 km yielded poor fits between calculated and observed curves. The best agreement was obtained for models with depths of 10 and 15 km (Fig. 6). These two models indicated density contrasts of 0.1 and 0.07 g/cm^3, respectively, and a fault dip of 60°–70° to the southeast. The range of dip values corresponds to the range of possible positions of the fault trace in the uncertainty interval (±0.3 km about station 36). The analysis of various models with depth extents between 10 and 15 km showed an optimal fit for a model characterized by a depth of 12 km, a density contrast of 0.085 g/cm^3, and a dip of 60°–70° to the southeast (Fig. 7A).

All models indicate that the Saganash Lake fault is reverse. A significant difference between calculated and observed gravity is produced (Fig. 7B) for a vertical or normal fault with a surface trace lying within the prescribed limits, regardless of its depth extent. To model the observed anomaly with a vertical or normal fault, the fault trace must intersect the gravity profile 2 km southeast of the position indicated by

Fig. 4. Shaded relief aeromagnetic image (total field intensity) showing the positions of most of the gravity stations. The round dots correspond to those stations where local gravity anomalies have maximum amplitudes. Illumination: azimuth 295°, inclination 22°.



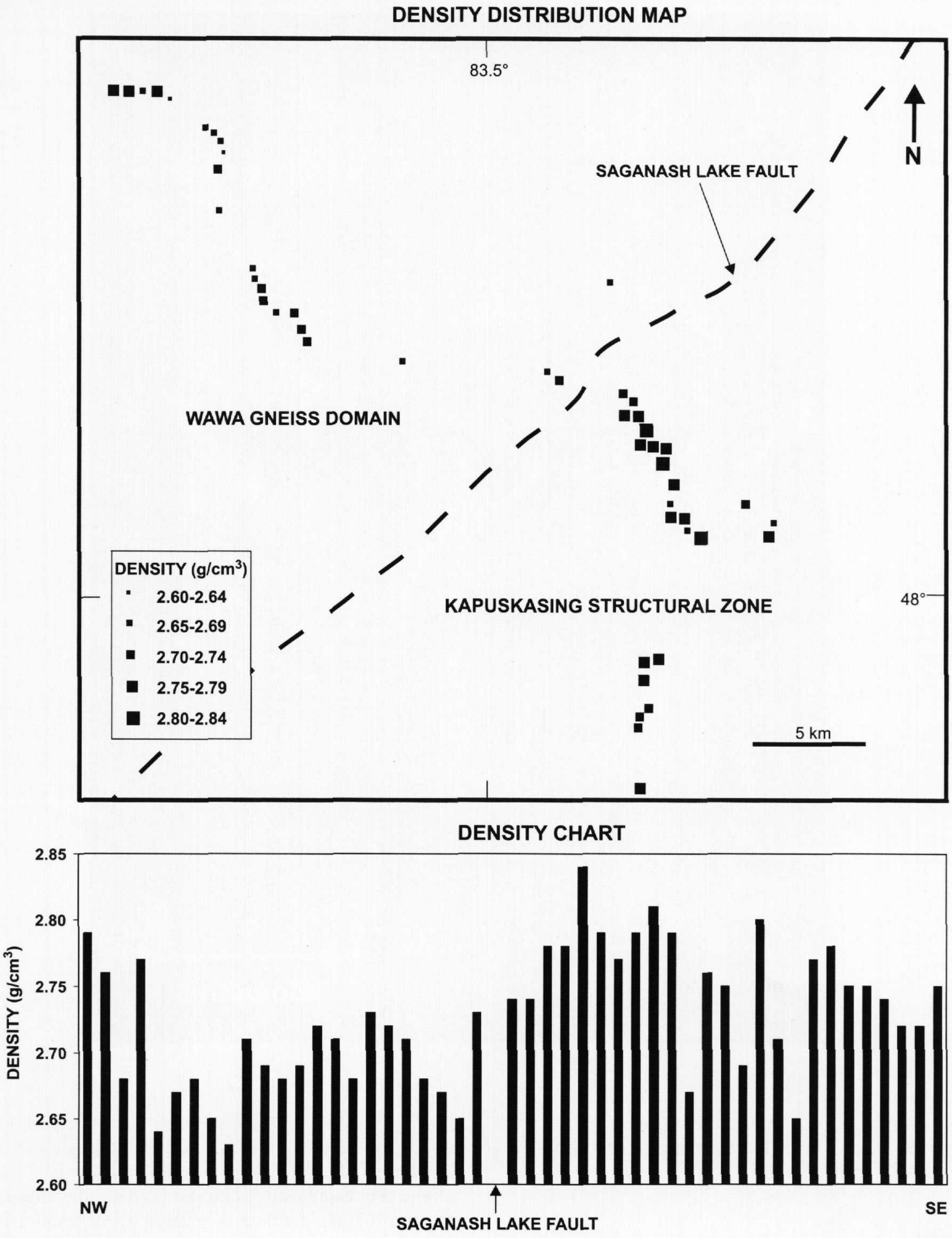
the aeromagnetic data. Thus, the gravity anomaly associated with southern Saganash Lake fault cannot be produced by a normal or vertical fault model.

Discussion

The gravity model shows that the northwestern boundary of the Chapleau block could not have formed as a collapse fault in response to uplift along the Ivanhoe Lake fault, as suggested previously. It is likely that the Saganash Lake fault was initiated or reactivated at a late stage during the compressive regime responsible for the main Kapuskasing uplift, which occurred at 1.9–1.85 Ga. The crustal shortening in the Chapleau block may have been accommodated in the upper brittle crust through thrust duplication mainly along the Ivanhoe Lake fault zone and, to a much lesser extent, along the Saganash Lake fault. The development of the Saganash Lake fault as a reverse fault parallel to the main thrust may have helped accommodate uplift of the upper crust caused by thickening of lower crust as a result of shortening and by isostatic adjustment following erosion (Percival and West 1994).

The differential uplift across southern Saganash Lake fault, estimated at 4–5 km from geobarometric (Percival et al. 1994) and seismic reflection data (Percival and West 1994; Nitescu 2000), has juxtaposed rocks from different

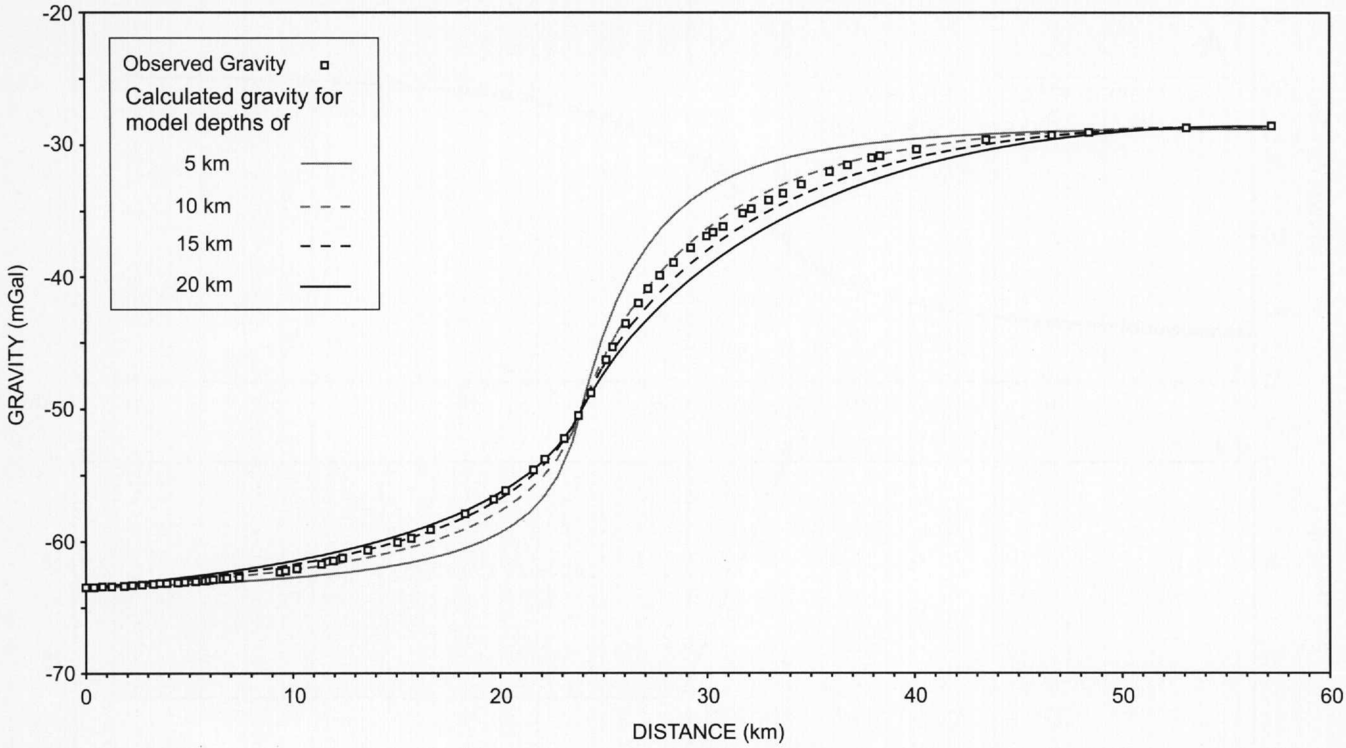
Fig. 5. Map (upper diagram) showing the locations and density values of rock samples. Density chart (lower diagram) showing the approximate order of the samples from northwest to southeast, although the distance scale is not drawn to scale.



crustal levels, thus creating a density contrast, which according to the gravity interpretation extends to a depth of ~12 km. If the fault extends beyond 12 km, the lack of a significant density contrast below this depth could be caused either by a smaller component of vertical displacement or by a small density gradient in the middle to lower crust.

The pop-up geometry inferred respectively for the Fraserdale–Moosonee and Chapleau blocks (FB and CB in Fig. 1) by Percival and McGrath (1986) and by Manson and Halls (1997) raises the problem of the structure of the intervening segment of the KSZ that includes the Groundhog River block (GB in Fig. 1). The reverse character of the southern Saganash Lake fault and the unbroken continuity of its aeromagnetic expression along the southern and central

Fig. 6. Comparison of the observed Bouguer gravity with the gravity effect of 2.5-d step models having depths of 5, 10, 15, and 20 km.



KSZ (Fig. 2B), as well as recent aeromagnetic modelling (Farrokhi 1999), suggest that the fault also has a reverse nature where it defines the Groundhog River block. Also, the compressive regime that led to the development of the Saganash Lake fault could have produced the uplift of the northwestern Val Rita block along a reverse Lepage fault (Fig. 1). This would explain the large gravity anomaly observed in Val Rita block and the granulite occurrences along the Lepage fault. To test this model for the central KSZ, a reinterpretation of the gravity data, based on detailed sampling and accurate positioning of the fault traces, is necessary.

The central and southern blocks of the KSZ (GB and CB in Fig. 1) were most recently interpreted by Percival and co-workers as the product of a major east-verging thrust zone, in which the western margin was the result of gravitational collapse of the elevated thrust wedge. However our result indicating that the western margin is a west-verging reverse fault does not accord with this interpretation, but instead suggests an alternative origin for the Kapuskasing zone.

In this model, the Kapuskasing zone originated as a series of left-stepping faults (Fig. 8A) which, when subjected to transpression with dextral shear, produced a discontinuous series of uplifts in the regions of en echelon overlap (Fig. 8B), similar to that shown by Sylvester (1988) in his review of strike-slip faults (see his fig. 17C). Uplifts in the form of positive flower or palm structures described and llustrated in Sylvester's paper (his fig. 22) would be consistent with the inward-dipping reverse faults of the Chapleau and Fraserdale–Moosonee blocks. These areas of uplift would also be bounded by transverse thrust faults similar to the situation shown in Fig. 8C, which is modified after fig. 23.37 of Ramsay and Huber (1987). The model is consistent with (1) the known dextral displacement along the zone (West and Ernst 1991), (2) the attitude and displacement sense of the bounding faults (SLF and ILF in Fig. 1), (3) the occurrence of transverse thrust faults like the McEwan Lake fault at the southern end of the Chapleau block (Halls and Mound 1998), (4) the discontinuous nature of the uplifted blocks, and (5) a maximum horizontal compressive stress varying from northwest to west in orientation, as given by small-scale faulting in Matachewan dykes at the southern end of the Kapuskasing zone (see fig. A-7 in Zhang 1999).

Conclusions

A detailed gravity survey across the southern end of the Saganash Lake fault that forms the northwestern boundary of the Kapuskasing zone demonstrates, consistent with interpretations of seismic reflection and aeromagnetic data, that the fault dips to the southeast and is of a reverse nature. The Chapleau block at the southern end of the Kapuskasing zone and other fault-bounded uplifted blocks farther north along the zone may have formed as positive flower structures during dextral shear on a system of left-stepping faults.

Acknowledgments

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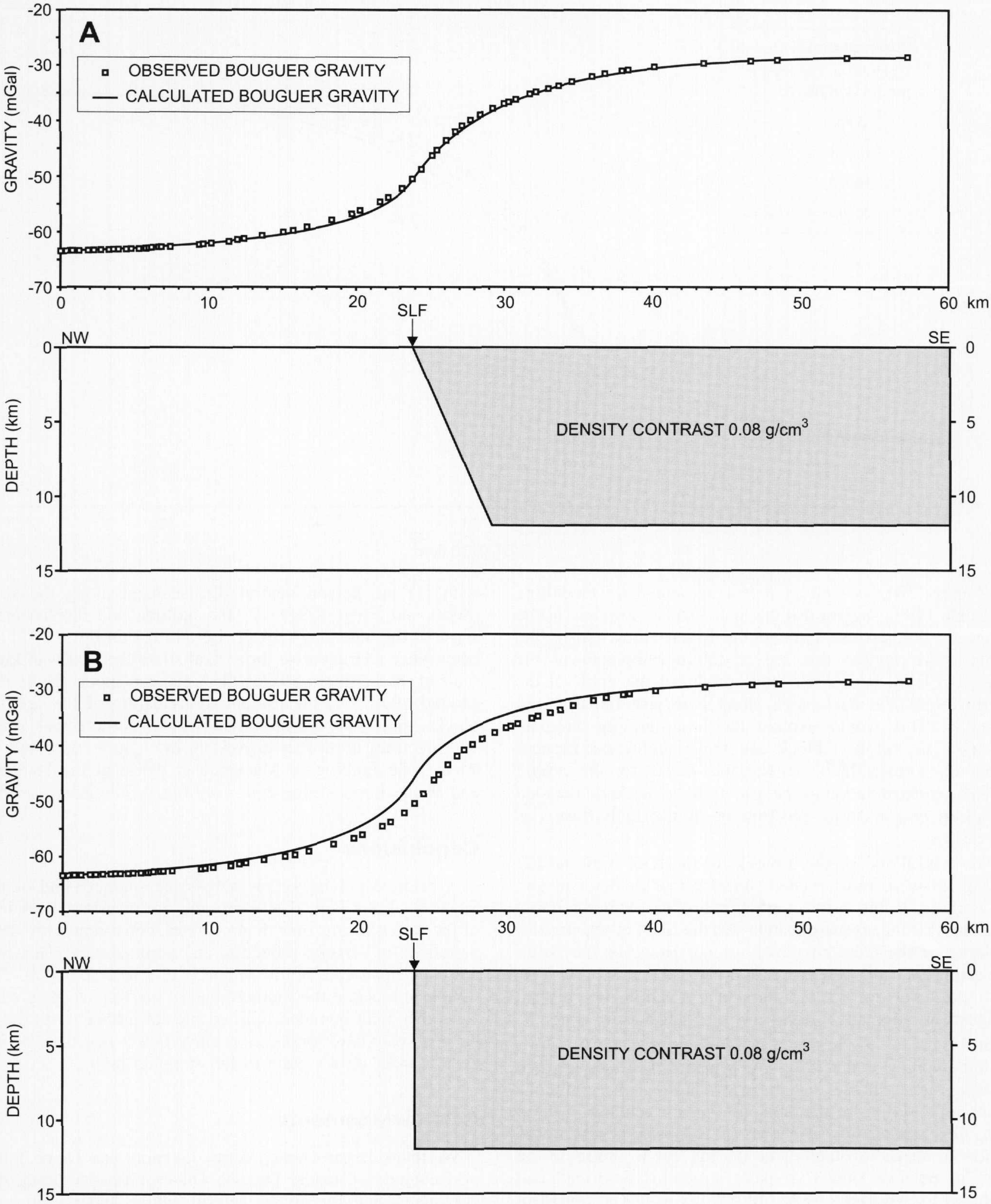
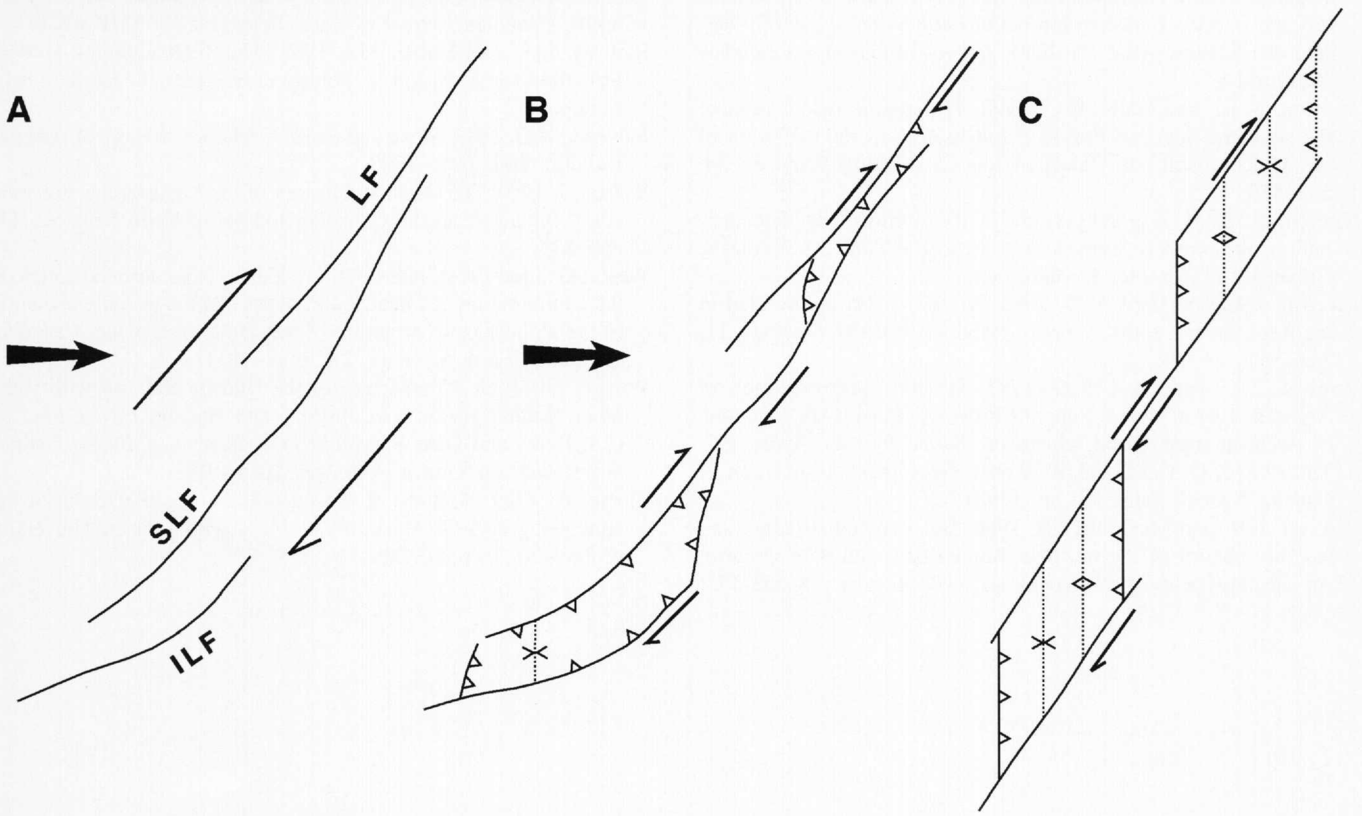
Fig. 7. (A) The best-fit 2.5-d step model. Depth extent: 12 km. Fault dip: 66°SE. (B) The relatively poor fit for a vertical fault.



sets of the Kapuskasing zone; and Sheryl Bunting for helping in the field. The 2.5-d gravity interpretation was performed using a non-iterative program written by Karl Bouchard, École Polytechnique, Montréal, Quebec. Huntly Cutten of the Department of Geology and Geophysics, University of Western Australia, Perth, Western Australia, originally suggested, after a talk given by HCH at UWA, that the discontinuous uplift along the Kapuskasing zone is the natural

Fig. 8. (A) Schematic view of three en echelon fault segments that ultimately become the Ivanhoe Lake (ILF), Saganash Lake (SLF), and Lepage (LF) faults. The faults may have originated as sinistral faults with local upthrusting along the ILF, although the early configuration of the KSZ is unknown. The fault system is shown to be under late dextral shear in response to west to northwest compression following the model of West and Ernst (1991). (B) The development of local uplifts in response to dextral shear. These structures correspond to the Chapleau–Groundhog River and Fraserdale–Moosonee blocks (Fig. 1). Note that the southern end of the Kapuskasing zone is extended to include the newly discovered Pineal Lake block, which is later offset sinistrally from the Chapleau block along a north–south fault, as shown by Halls and Zhang (1998), and that north–south-trending folds expected from the model are observed (see fig. 3 of Halls and Zhang 1998). (C) The idealized development of localized fault-bounded uplifts and associated folds as illustrated by Ramsay and Huber (1987). Note the similarity to diagram B.



consequence of dextral shear along a left-stepping en echelon fault system. This observation was based on field observations of the Alpine transcurrent fault in New Zealand. The paper benefited from reviews by G.F. West and M. Pilkington. The research was supported by Natural Science and Engineering Research Council grant A7824 awarded to HCH.

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