Gravity Signature of the Waukesha Fault, Southeastern Wisconsin

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ABSTRACT

Gravity data were collected at approximately 1.6 km spacing over the Waukesha Fault in parts of Washington, Ozaukee, Waukesha, and Milwaukee Counties. The gravity signature of the fault trends northeast with gravity values to the northwest, on the upthrown side, approximately 10 mgal higher than on the downthrown side. Gravity models that closely approximate the observed gravity were constructed. The smallest residuals are obtained from models of the fault that have a gentle dip of about 10° to 20° to the southeast with a maximum offset across the fault of about 600 m.

INTRODUCTION

Although the presence of the Waukesha Fault in southeastern Wisconsin has been recognized for some time (Foley and others, 1953; Thwaites, 1957) the location, linear extent, and subsurface geometry of the fault have, until recently, been poorly constrained. The ambiguity related to the fault geometry is the result of previous reliance on predominantly shallow well data and only one significant surface exposure at the Waukesha Stone and Lime Quarry in the city of Waukesha. The fault strikes N 40° E at the quarry and appears to be a high angle normal fault downthrown to the southeast. The near-surface displacement on the fault has been estimated at between 10 (Mikulic and Mikulic, 1977) and 30 m (Foley and others, 1953). The displacement at depth is thought to be as great as 450 m (Thwaites, 1957). The first detailed geophysical work over the fault was a gravity survey covering Waukesha County conducted by Brukardt (1983). Preliminary interpretation of the data yielded a model of the fault that was consistent with the above mentioned characteristics. The survey also suggested that the gravity signature from the fault remained strong at the northeastern corner of the county, indicating that the fault continues toward Lake Michigan. Additional gravity data were collected by Sharon Herb in 1985 in parts of Washington, Ozaukee, and Milwaukee Counties to map the continuation of the fault northeast of Waukesha County. This paper presents the results of an interpretation of the combined gravity data sets of Brukardt and Herb.

DESCRIPTION OF THE SURVEY

The data were collected at approximately 1.6 km spacing at road intersections and benchmarks where elevations were given on US Geological Survey topographic maps. The survey area is outlined in figure 1.

A contour map of the data is shown in figure 2 and a 3-dimensional representation in figures 3a and b. The gravity signature of the fault is characterized by a northeast-trending zone roughly five km wide of tightly spaced contours that separate a region to the northwest with gravity values approximately 10 mgal greater than the region on the southeastern side of the

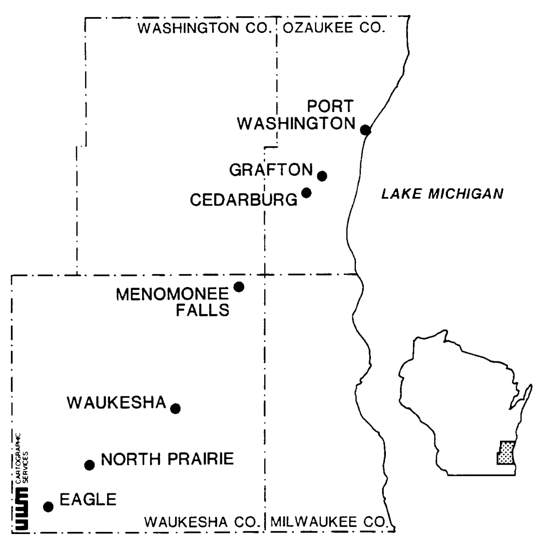

Figure 1. *Four county area of the gravity survey*

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fault. This is particularly evident in figures 3a and b where the perspective of the views are N 50° W, which is perpendicular to the gravity trend, and S 40° W, which is along the trend. When examined in greater detail, this zone of tightly spaced contours can be seen to change strike and is apparently offset in one location. At the southwestern end, the gravity signature trends roughly N 19° E for 10 km from a point 3 km south of Eagle, Wisconsin on the Waukesha-Walworth County line to the town of North Prairie. At North Prairie it turns to N 47° E and continues for about 13 km to a point due west of Waukesha where it is offset in a right-lateral sense 3 km to the western edge of the city of Waukesha. The location of this offset is evident in figure 3a where there is a pronounced break in the linear gravity high that appears as a valley in the Bouguer gravity surface. From that point it extends 23 km at N 38° E through Menomonee Falls to the Washington-Waukesha

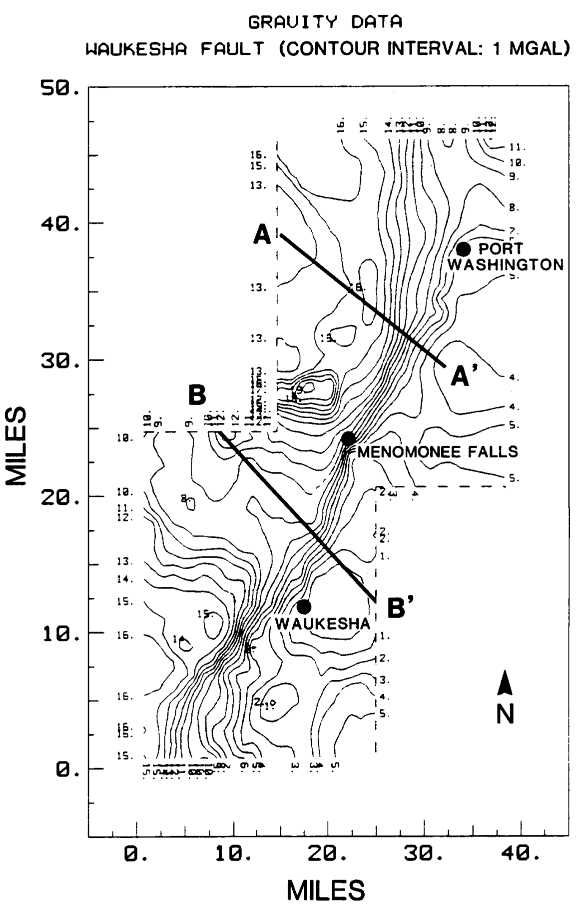

Figure 2. *Contour plot of the gravity data. Contour interval is one mgal. Locations of the two modelled profiles are indicated.*

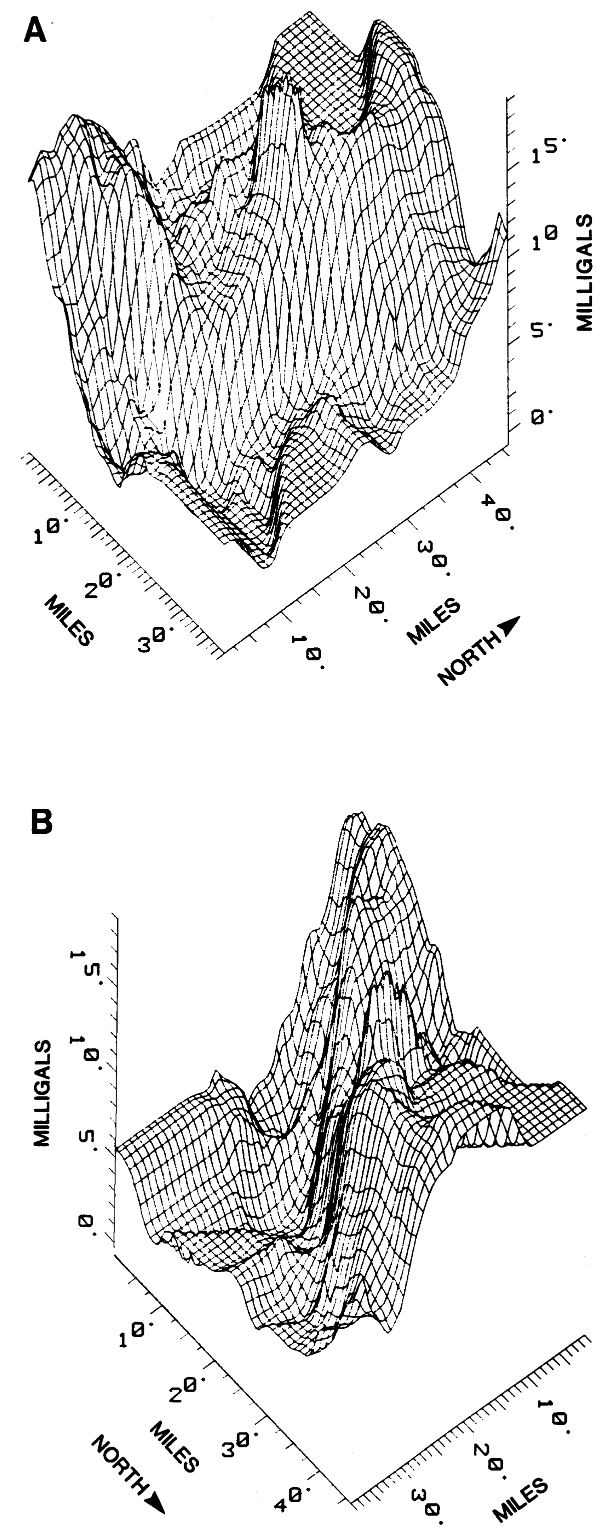

Figure 3. *3-dimensional plot of the gravity signature of the Waukesha Fault viewed from the southeast in a direction N 50° W (3a) and from the northeast in a direction S 40° W (3b).*

county line roughly 2.5 km west of the Ozaukee County line. It then continues for 6 km with a strike of N 27º E until, about 5 km southwest of Cedarburg, it changes strike to N 36º E and extends through Cedarburg and Grafton 22 km to Port Washington. The offset in the fault west of Waukesha was interpreted by Brukardt (1983) to be due to a second fault striking N 60º W.

MODEL GEOLOGY

Bedrock in southeastern Wisconsin dips gently to the east from the Wisconsin Dome into the Michigan Basin. The area was differentially eroded before Pleistocene deposition so that the contact between bedrock and glacial deposits is irregular (Distelhorst, 1967; Brukardt, 1983).

The basement Precambrian consists of granite, slate, and quartzite which dip to the east. The Precambrian is overlain by Cambrian and Ordovician sandstone. These are in turn overlain by Ordovician and Silurian shale and dolomite (Thwaites, 1940; Dutton and Bradley, 1970). The surficial materials are glacial deposits that vary in thickness from essentially zero to several hundred meters.

The general stratigraphy down to the Precambrian is from Moretti (1970) and the Wisconsin Utility Project report on the Haven nuclear power plant site (Wisconsin Electric Power Company, and others, 1979a). The depth of Lake Michigan and the depth to bedrock beneath the lake are from Wold and others (1981). The gross characteristics of the thickness of the unconsolidated material were obtained from Distelhorst (1967), Skinner and Borman (1973), Gruetzmacher (1974), Brukardt (1983), and well logs obtained from the Wisconsin Geological and Natural History Survey.

The general distribution of the Precambrian quartzite and granite is based on work by Thwaites (1940) and Dutton and Bradley (1970). Well data to the northwest of the fault is sufficient to fix the depth to the Precambrian in a regional manner. However, no known wells extend to the Precambrian on the southeastern side of the fault. In addition, Thwaites (1940) states that the Precambrian surface is more than 800 meters below sea level on the southeast side.

Gabbro was included in the models because of the presence of mapped gravity and magnetic highs in the Lake Michigan Basin that come onshore in Ozaukee County and are attributed to mafic rock at depth (Wisconsin Electric Power Company, and others, 1979b). In addition, models without the gabbro present required 2000 meters or more of displacement on the fault to produce the observed amplitude of the gravity signature, which is far in excess of any previous estimates.

Table 1. *Densities used for model calculations.*

Density (g/cm3)	Rock
1.00	Lake Michigan
1.80	Unconsolidated Sediment
2.60	Sandstone (Ordovician - Cambrian)
2.63	Quartzite (Precambrian)
2.67	Dolomite and Shale (Silurian - Ordovician)
2.69	Granite (Precambrian)
2.74	Crustal Rock at Depth
3.00	Gabbro

DISCUSSION

Two profiles across the fault were chosen for modelling. The locations of the profiles, labelled A-A' and B-B', are shown in figure 2. The observed gravity along the profiles is given in figure 4.

The rock types and associated densities used in the modelling are given in table 1. In the modelling process we found it necessary to slightly alter some of the densities depending on the nature of the model in order to obtain reasonable residuals. A Talwani computer program was used in the calculations (Talwani and Ewing, 1959). The models used in the program were extended on either side of the ends of the profiles for a distance roughly equal to the lengths of the profiles to eliminate edge effects.

Our initial models were of steeply dipping faults because the Waukesha Fault has been generally accepted as being nearly vertical. Model 1 along profile B-B' is an example of these and is illustrated in figure 5. This model incorporates a fault having a dip of 80 degrees to the southeast. The vertical offset of the Silurian and Ordovician dolomite and shale is 30 m. The underlying Ordovician and Cambrian sandstone are offset by 30 m at the top and 400 m at the bottom. This results in a significant thickening of the sandstone east of the fault. The gabbro in this model appears as two distinct intrusive bodies rather than a single mass offset by the fault. The residual gravity values for this model are plotted in figure 9. The magnitudes of the station residuals are generally less than 0.2 mgal with the exception of stations 19 and 22 on either side of the fault and station 34 at the eastern end of the profile. The RMS error for this model is a relatively large 0.128 mgal.

Although the data are adequately modelled at stations several km away from the fault, the residual gravity curve has a characteristic shape in the immediate vicinity of the fault that suggests the dip is too steep. The expected residual gravity curve produced by a model with a fault dipping at an angle greater than the actual fault being studied is shown in figure 6. The characteristic signature of a growing negative residual approaching the fault that reverses and passes through zero across the fault and then grows to a maximum positive residual on the other side is quite clear. As a result, we elected to try models that included shallow dipping faults despite the long-standing belief that the Waukesha Fault is a high angle fault.

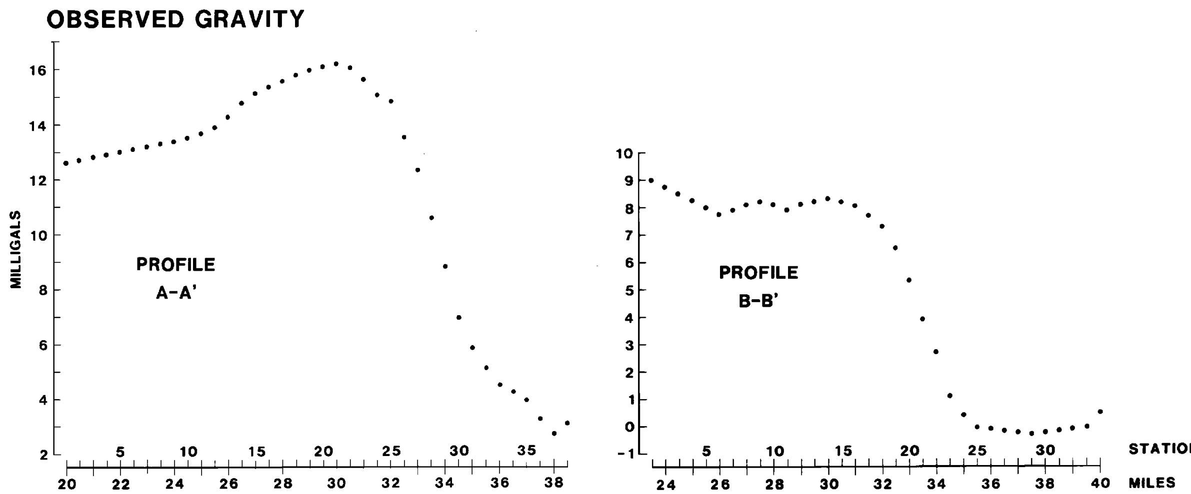

Figure 4. *Observed gravity along profiles A-A' and B-B' (fig. 2).*

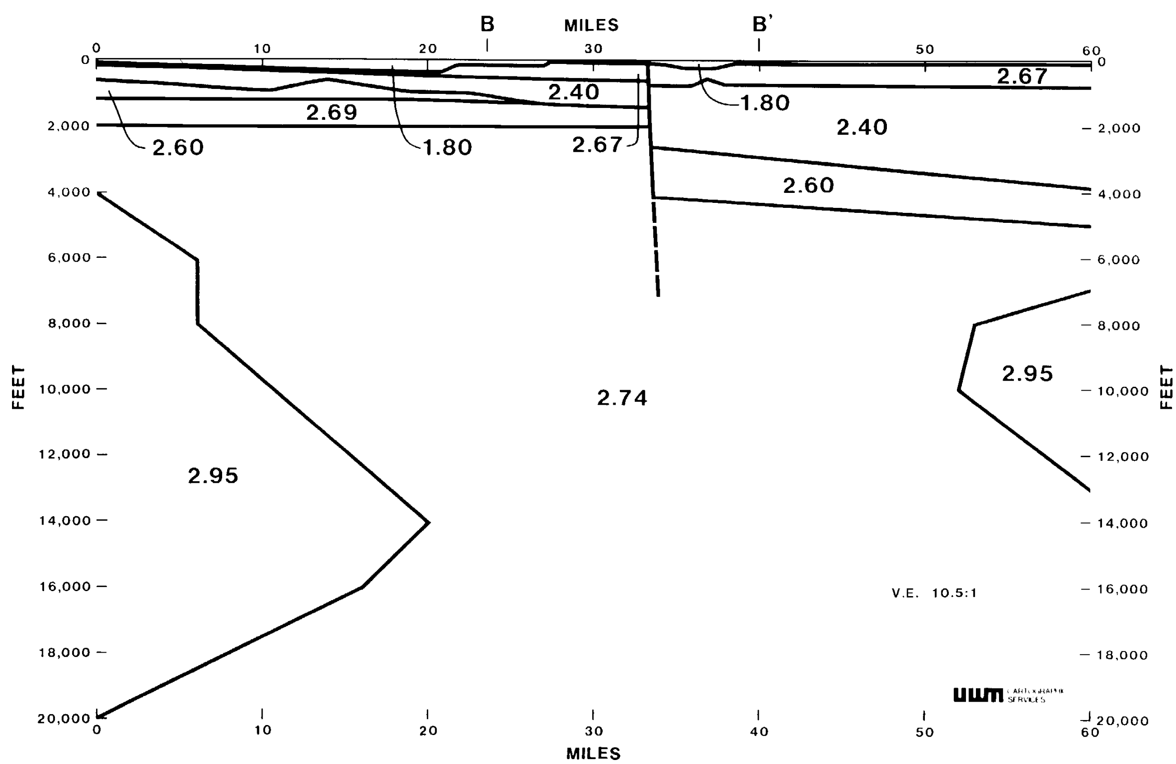

Figure 5. *Geological model 1 along profile B-B'. Dip of the fault is approximately 80º.*

Two models with shallow dipping faults were constructed. Model 2 is also along profile B-B' and model 3 is along profile A-A' (fig. 2). Models 2 and 3 are illustrated in figures 7 and 8 respectively. In both models the residual gravity values at all stations are within our expected measurement accuracy and the RMS error for each profile is 0.03 mgal, which is well below our measurement accuracy (fig. 9). The dip of the fault in models 2 and 3 is roughly 9 and 20 degrees respectively. While this is substantially lower than expected, it is not contradicted by any available well data. The observation that the fault is nearly vertical at its exposure in the Waukesha Stone and Lime Quarry suggests that it may be a listric fault steeply dipping near the surface for a relatively short distance and then rapidly decreasing in dip with increasing depth. If this is the case, the overall geometry of the fault remains constrained by the gravity data to have a relatively shallow dip to first order.

The offset of the fault in the Silurian rock in these two models is 30 m. The offset of the sandstone unit increases from 30 m to about 500 m from top to bottom similar to model 1. The other large difference in these two models is that the gabbro has been modelled as a single intrusive mass that is offset by the fault. The maximum offset is seen at the base of the gabbro where it reaches roughly 600 m.

The results of this study show that the Waukesha Fault extends through Waukesha and Ozaukee Counties to Lake Michigan. Models of two profiles across the fault indicate that it may be a high angle normal fault as previously expected but can also be modelled accurately as

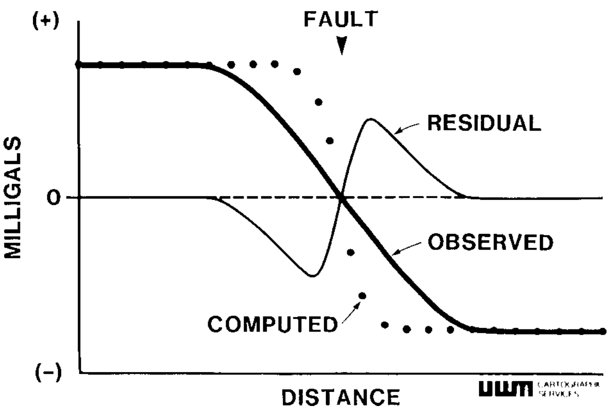

Figure 6. *Plot of the observed, model and residual gravity where the model fault is steeper than the actual fault.*

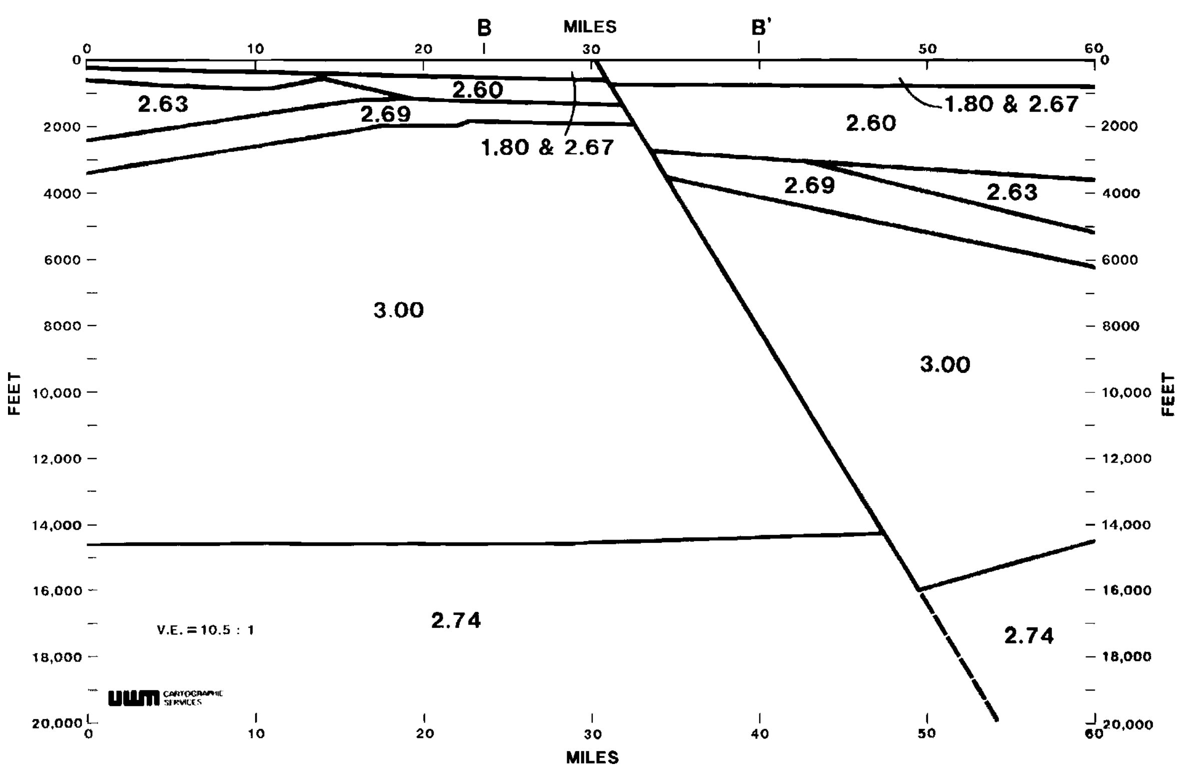

Figure 7. *Geological model 2 along profile B-B'. Dip of the fault is approximately 9º.*

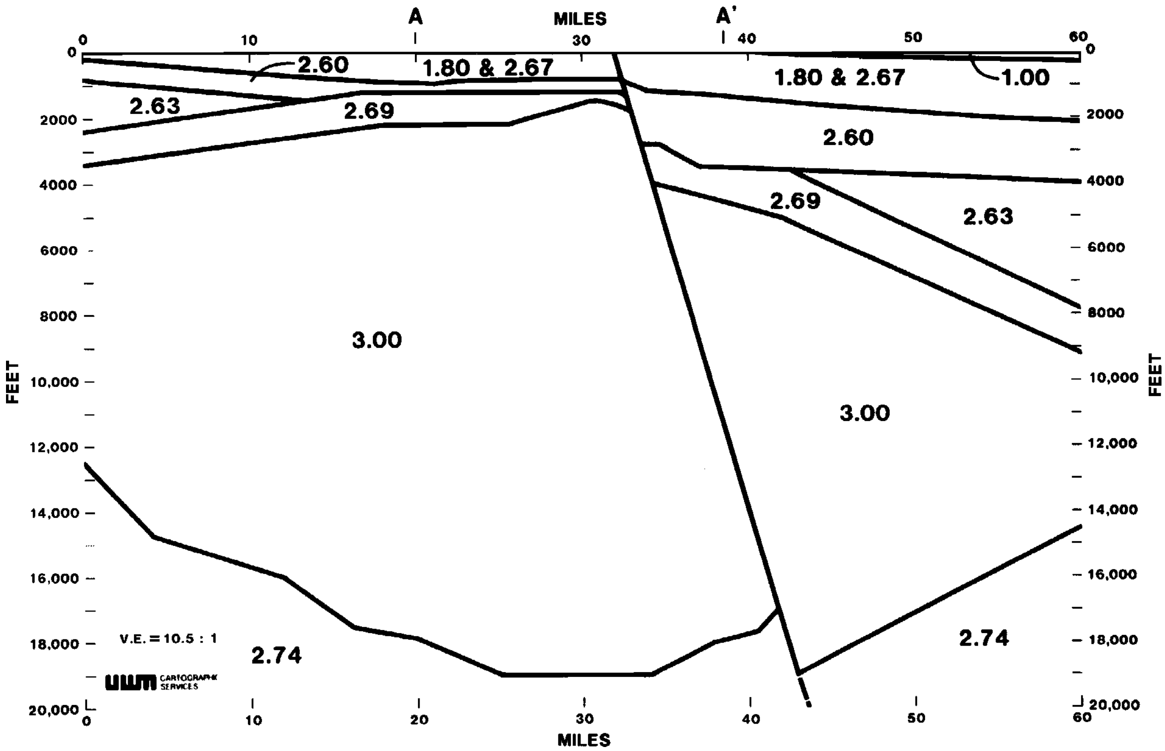

Figure 8. *Geological model 3 along profile A-A'. Dip of the fault is approximately 20°.*

a listric fault with a shallow dip at depth ranging between roughly 10 and 20 degrees to the southeast. We believe that further work on the fault is needed before this ambiguity can be eliminated.

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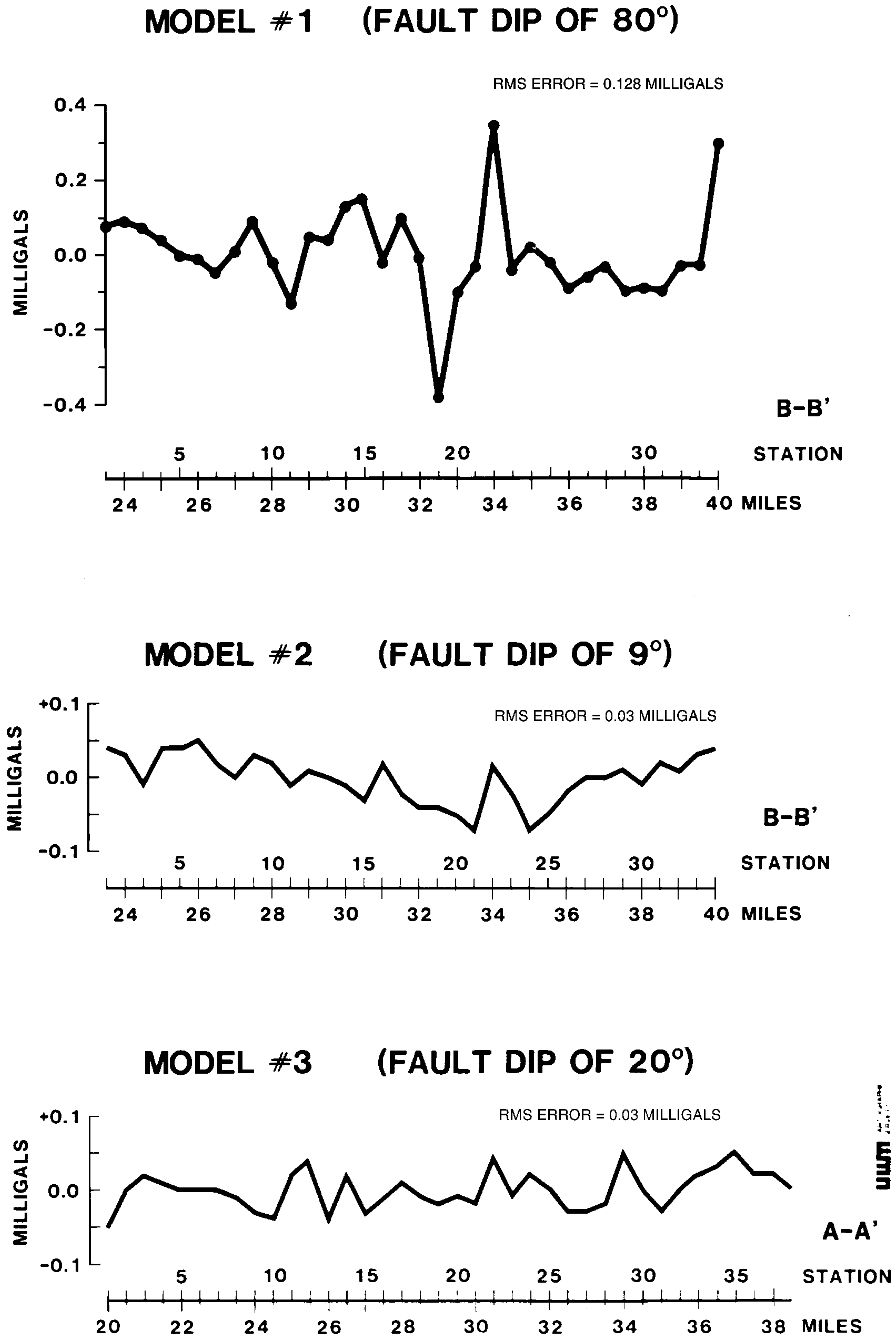

Figure 9. *Plots of the residual gravity produced by the models.*

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