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Gravity Model Studies of the Northern Fossa Magna: Central Honshu, Japan

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Abstract : Interpretations of basement structure in the northern Fossa Magna region are proposed based on inverse gravity models. Results of gravity modeling are evaluated using nearby seismic refraction profiles and a geologic cross section compiled from well data.

The gravity models suggest the presence of two Neogene-age basins on either side of the Central Upheaval Zone. The basins are interpreted to be approximately 30 to 50 kilometers in width, and their extent based on the extent of lows in the Bouguer gravity anomalies. These basins have northeast-southwest trends and prior to the Pliocene probably extended unbroken along the length of the northeast Japan arc. Uplift of the Taishaku and Ashio Mountains (along the northeastern margin of the Fossa Magna) during the early Pliocene interrupted the basin southwest of the Central Upheaval Zone. The northeast-southwest trending gravity lows associated with these basins do not continue through the Itoigawa-Shizuoka tectonic line into southwest Japan.

Apparent offsets in the pattern gravity anomalies occur across a northwest trending zone between the Nishikubiki-Omine Block and the Kashiwazaki-Choshi tectonic line along the northeastern margin of the Fossa Magna. These are interpreted to represent right-lateral offsets in the underlying basins. These basins extend southwest and terminate against the Itoigawa-Shizuoka tectonic line (ISTL). The ISTL is interpreted to be a part of a deeper basin that extends along most of its length and separates northeast from southwest Japan.

1. Introduction

1.1 Approach

This study evaluates the structural significance of gravity anomalies in central Japan, particularly within the northern Fossa Magna region and along the Itoigawa-Shizuoka tectonic line. Gravity models and interpretations of the deeper basement structures along three profiles in the northern Fossa Magna of central Honshu in Japan (Fig. 1) are presented. The models are derived from two gravity data bases. One data set was compiled by Kono and Furuse (eds., 1990) and assumed a constant density of 2.67 g/cm^3 for the Bouguer plate and terrain corrections. The other data set (Fig. 1)

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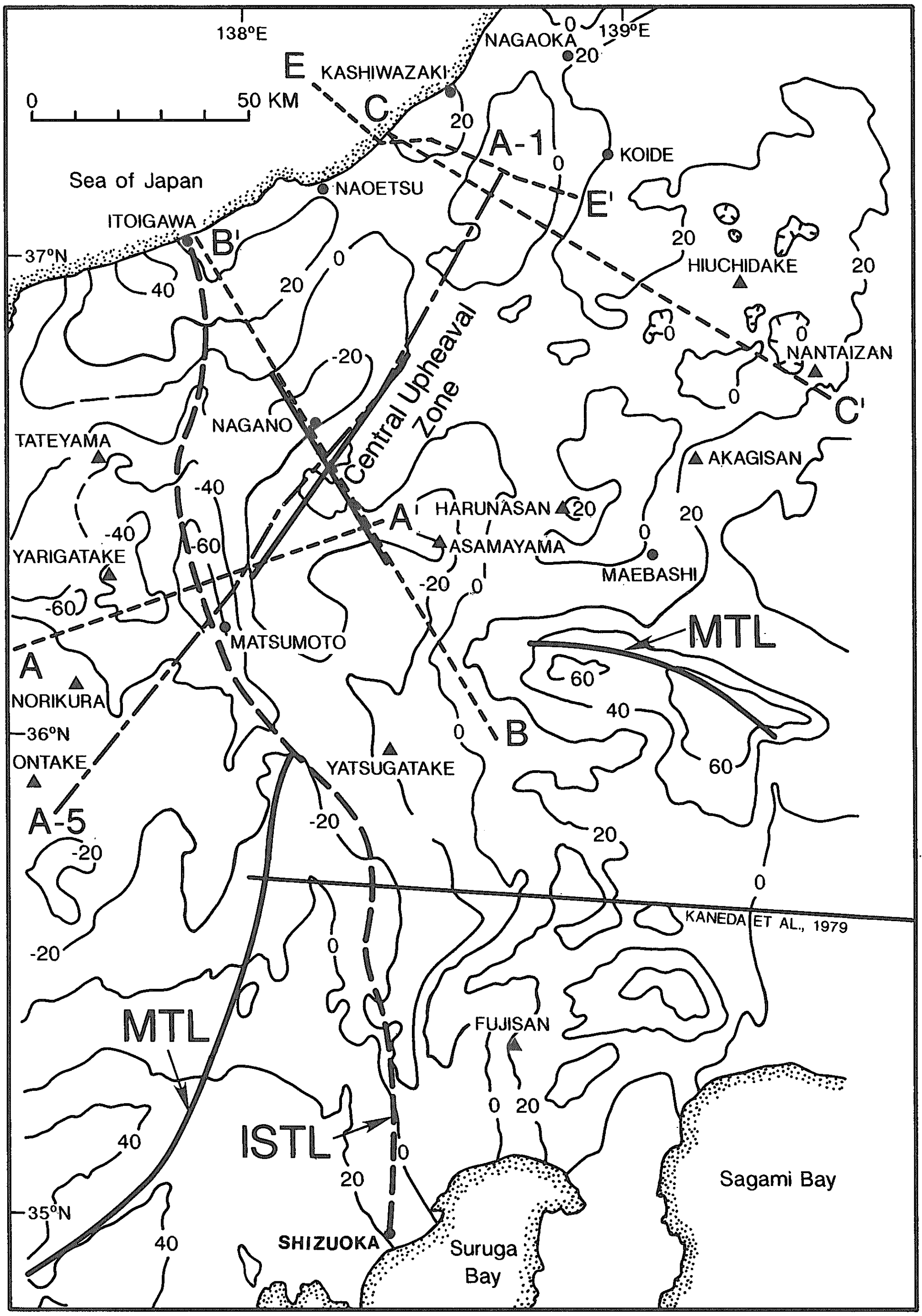


Fig. 1 Locations of gravity profiles AA', BB', and CC' are shown on the (2.3) Bouguer anomaly map from Komazawa *et al.*, 1992. Locations of the supplementary data sets used in this study are also shown and include section EE' (Niigata Prefectural Government, 1988), refraction seismic profiles A and B from Asano *et al.* (1969) and the refraction seismic profile A5–A1 from Ikami *et al.* (1986). ISTL=Itoigawa-Shizuoka Tectonic Line. MTL=Median Tectonic Line.

was compiled by Komazawa *et al.* (1987) and assumed a constant density of 2.3 g/cm^3 for the Bouguer plate and terrain corrections. In the following discussions, these data sets are referred to simply as the 2.67 and 2.3 data sets, respectively. (After this study was finished, a part of the latter data set, that is gravity map of Joshin-Etsu District was published by Hiroshima *et al.*, 1994)

It is well known that gravity models are non-unique, and in addition to this non-uniqueness, we are faced with distortions of the data themselves, resulting from the assumption of a constant correction density in both cases. The surface geology in the Fossa Magna, and Japan in general, is quite complex and consists of a variety of sedimentary, igneous and metamorphic rocks. So the question of whether gravity anomalies corrected with a constant density can be related to subsurface structure in a meaningful way is an important question to ask. The accuracy of the derived gravity models is evaluated by comparison to existing seismic refraction data (Ikami *et al.*, 1986; Asano *et al.*, 1969), and subsurface data (Section EE', Niigata Prefectural Government, 1989) (Fig. 1).

Long wavelength regional influences of deeper density contrasts such as those associated with crustal thickening or descending oceanic plates are removed by filtering out anomalies with wavelengths greater than 150 km. Our interest is mainly to delineate upper crustal density contrasts associated with the basement structures observed in the seismic refraction profiles across this area. Our models assume that density contrasts portrayed in cross section do not extend to infinity normal to the profile, but only to some limited distance along strike (finite-model). A strike length of 100 km, comparable to the areal extent of the modeled gravity anomalies, was used for all models presented in this study. Inverse models were derived using an iterative procedure (Inman, 1985) to minimize the difference between the calculated and observed gravity.

The models presented here are simplified two or three layer models. This simplification is justified based on subsurface velocity models derived from seismic refraction observations over the area (Ikami *et al.*, 1986; Asano *et al.*, 1969). Densities estimated from seismic velocity using Nafe-Drake relationships (see Ludwig *et al.*, 1970, for example) suggest an average density of 2.36 g/cm^3 for the shallow sedimentary section, and a density of 2.71 g/cm^3 for the Pre-tertiary basement.

1.2 Geological Background Northern Fossa Magna

The Fossa Magna Region, proposed by Naumann (1885), is a huge half-graben like structure, which crosses the central part of Honshu, the main island of Japan. However, it is a vaguely defined transition zone between the southeast Japan (Seinan Nihon) and the northeast Japan (Tohoku Nihon) micro continents. There is general agreement that the western margin of the Fossa Magna coincides with the Itoigawa-Shizuoka Tectonic Line (ISTL). Although the ISTL is the boundary between the westward pre-Tertiary rocks and the eastward Tertiary rocks in general, in some places Miocene rocks within the Fossa Magna are distributed to the west of the ISTL. Hence, strictly speaking, the ISTL is not the westernmost boundary of the Fossa Magna basin during the Miocene time, although, it was a major growth fault in the basement and had a significant influence on Miocene sedimentation in and around the Fossa Magna region. As a boundary to the Fossa Magna, deformation is most significant during the Pliocene. The exact location of the eastern margin of the Fossa Magna is less well defined since the area is covered by Neogene formations and, in general, there is no clear evidence of Neogene age deformation.

The northern and southern parts of the Fossa Magna are separated geologically by the Median Tectonic Line (MTL, Fig. 1). The MTL divides the basement of southwest Japan into two parts, the Outer Zone along the trench or Pacific side of Japan, and the Inner Zone along the Japan Sea side. Along the ISTL, this division occurs near the Suwa region of Nagano prefecture. The northern Fossa Magna lies in the Inner Zone and is divided into several blocks, which underwent differential vertical movements during the Neogene. For example, the Central Upheaval Zone (Fig. 1), a major NE-SW trending horst block, has actively developed since the Middle Miocene. The tectonic activity of the southern Fossa Magna is controlled by the relatively dynamic processes of micro block (Izu Peninsula) collision and northward subduction of the Philippine Sea Plate.

1.3 Upper Crustal Structures in the northern Fossa Magna

Ikami *et al.* (1986) present refraction seismic data across the Matsumoto Basin that reveal the presence of a restricted low velocity (3.8 km/s) region beneath the Matsumoto Basin that extends to depths of 4 km or more (Fig. 2). The geological interpretation of the velocity model shown in Fig. 2 (from Kato, 1992) suggests that the deeper high velocity layer (5.9-6.0 km/s) is associated with pre-Tertiary granites to the southwest and with Tertiary granites and other pre-Tertiary basement rocks to the northeast.

An interpretation of the geometrical configuration of the restricted low-velocity region is presented by Hagiwara *et al.* (1986) and Okubo *et al.* (1990). They suggest that offset along the northeast flank of the basin is reverse and has been thrust several kilometers upwards with respect to the southwest. A similar interpretation is suggested by Ikami *et al.* (1986) (Fig. 2).

Earlier, we (Wilson and Kato, 1992) presented gravity models (Figs. 3 and 4) for the 2.67 and 2.3 data sets along profile AA' across this area (Fig. 1), which suggest that both flanks of the basin dip to the southwest rather than to the northeast. Profile AA' does not coincide with the refraction profile of Ikami *et al.* (1986), but lies close to it where it crosses the Matsumoto Basin area. The orientation of the gravity profile was chosen to trend normal to the trend of the gravity anomaly associated with the basin. The derived gravity models are consistent with the hypothesis that subduction of northeast Japan beneath southwest Japan may be occurring along the ISTL (see for example, Nakamura, 1983; Kobayashi, 1983) along the western margin of the Fossa Magna.

Asano *et al.* (1969) present seismic refraction data along two lines, one across the strike of the Central Upheaval Zone and the other along its axis, near Nagano (Fig. 1). Gravity profile BB' (Fig. 1) was located along the refraction profile

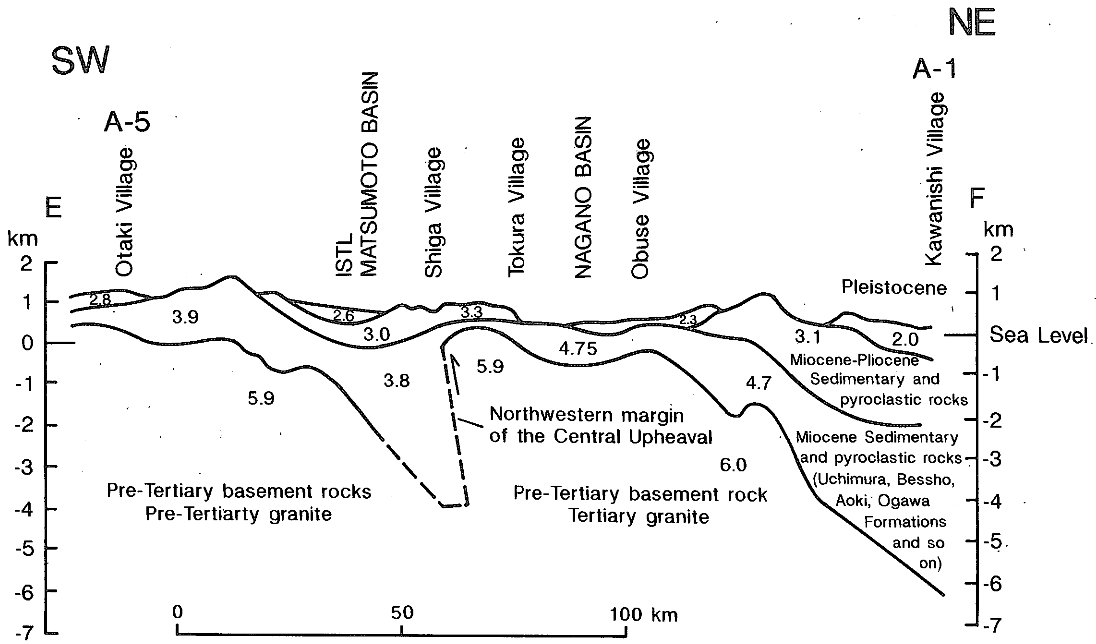


Fig. 2 The velocity structure derived from the refraction seismic survey presented by Ikami *et al.* (1986) is shown along with a geological interpretation of the section from Kato (1992).

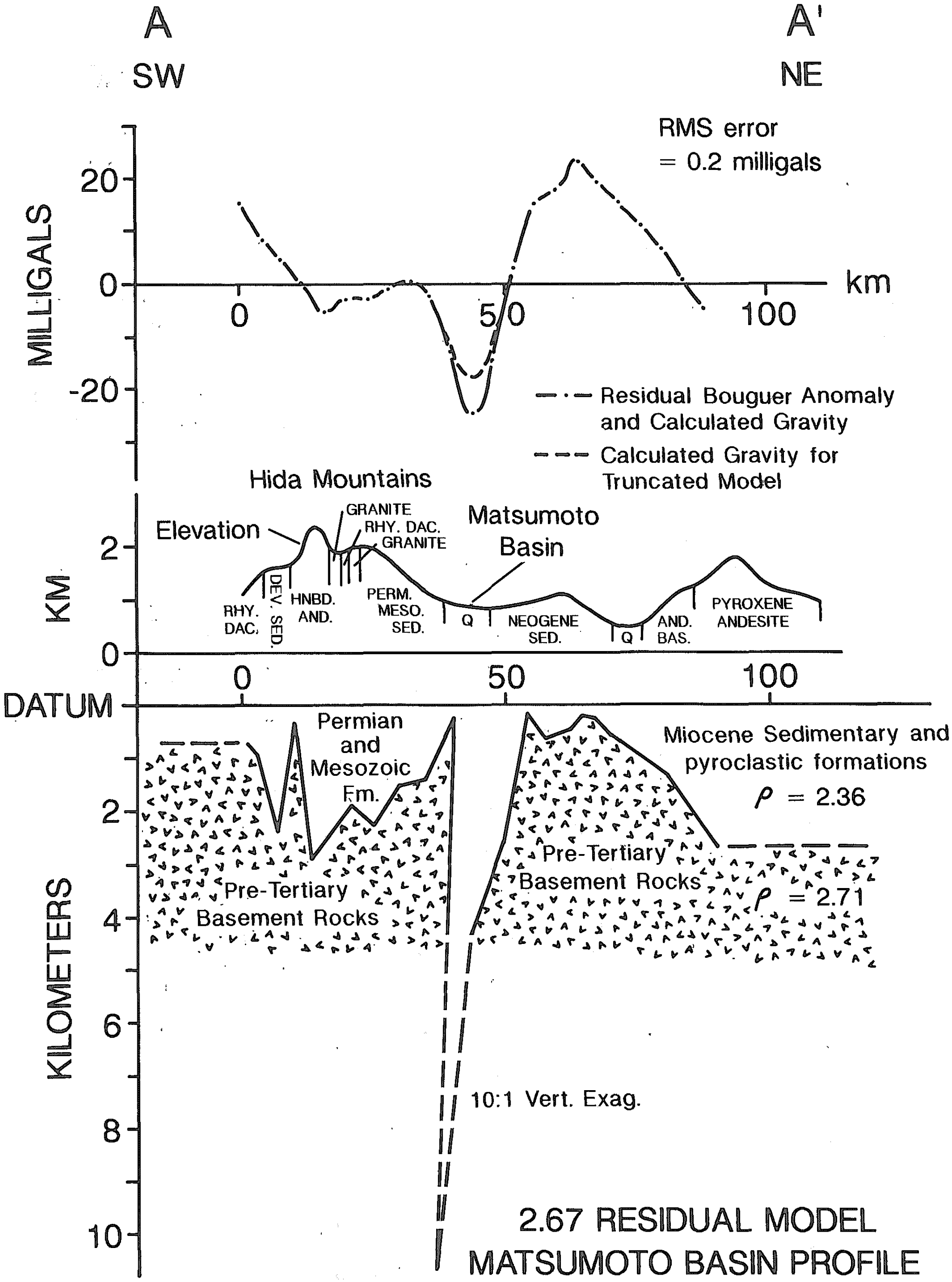


Fig. 3 The density model (bottom) was derived from the (2.67) residual Bouguer gravity data (top) along profile AA' across the Matsumoto Basin (Fig. 1). Elevation variations along the profile are shown in the middle of the figure along with the geologic units exposed along the profile (Geological Survey of Japan, 1987). The residual Bouguer gravity was derived from the (2.67) Bouguer gravity data presented by Kono *et al.* (1990).

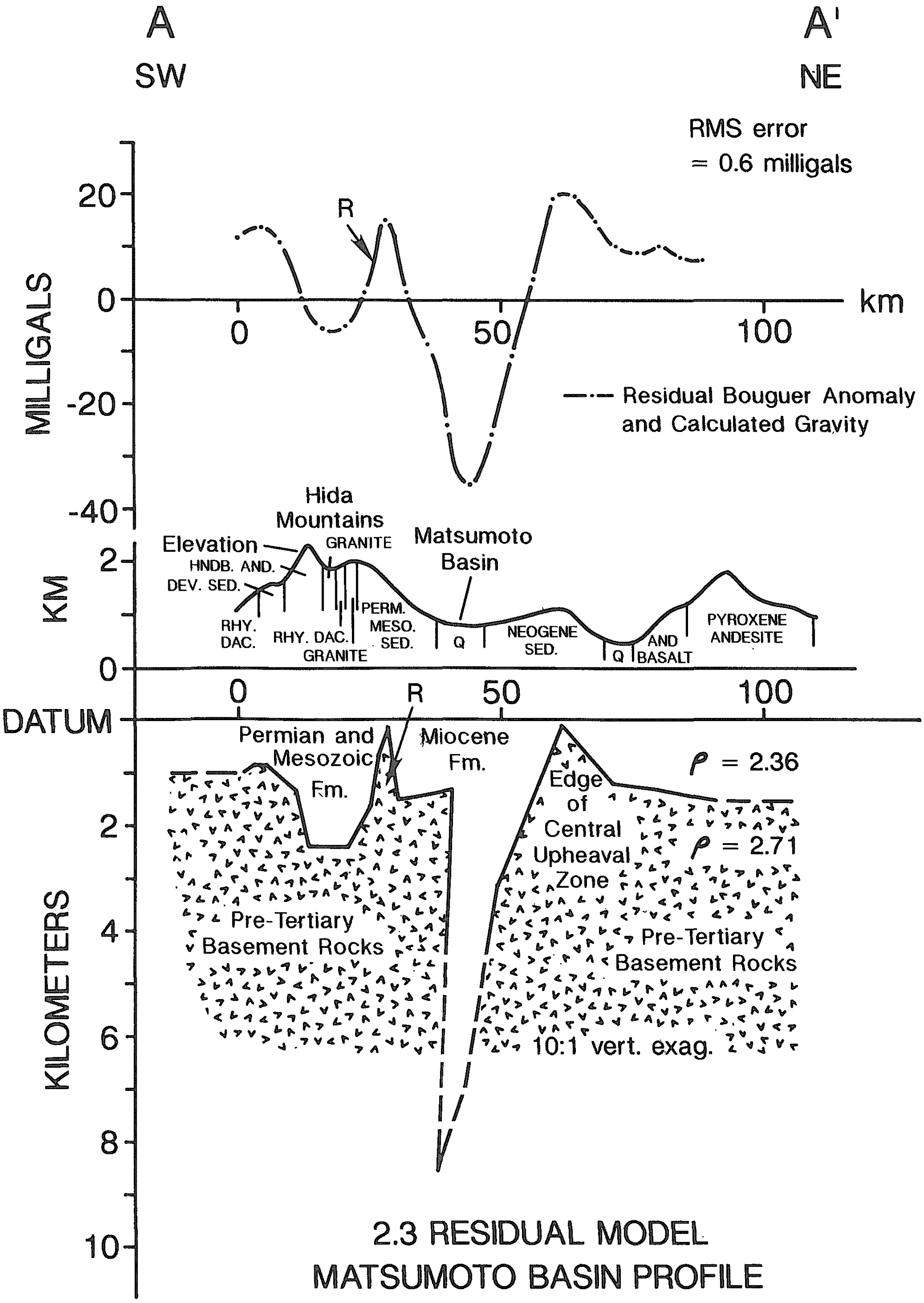


Fig. 4 The density model (bottom) was derived from the (2.3) residual Bouguer gravity (top) along profile AA' across the Matsumoto Basin (Fig. 1). Elevation variations along the profile are shown in the middle of the figure along with surface geologic units exposed along the profile (Geological Survey of Japan, 1987). In this case, the residual was derived from the (2.3) Bouguer gravity data presented by Komazawa *et al.* (1987). R denotes local anomaly discussed in text.

that crosses the Central Upheaval Zone (Profile B, Fig. 5) and is continued northwest to Itoigawa and southeast across an adjacent gravity low (Fig. 1).

A geological interpretation of the velocity structures shown in profile B is presented in Fig. 6 for the central portion of the profile (from Kato, 1992). Both Profiles A and B (Fig. 5) reveal that beneath the upper one kilometer or so, the subsurface is dominated by a dual velocity structure. The velocity structure outlines the region of uplift on the southeastern half of the profile associated with the Central Upheaval Zone. The 4.0 km/s layer (Fig. 5) is inferred to represent Miocene formations (Kato, 1992). The 6.0 km/s intervals on the southeast end of the line are believed to be associated primarily with Miocene age quartz-diorite, based on drilling data (see Kato and Akahane, 1986). The 6.0 km/s intervals associated with the Central Upheaval Zone and the area northwest, are believed to be associated with pre-Tertiary rocks.

A third profile (CC', Fig. 1) is also presented across the northern Fossa Magna. Seismic refraction data are not available in this area, however, a nearby cross section (Fig. 1, section EE') based on well data (Niigata Prefectural Government (NPG), 1989) provides control for the derived gravity model. Additional cross sections to the north of profile CC' (NPG, 1989) also show that a deep sedimentary basin coincides with the gravity low, and continues offshore to the north.

2. Gravity Models

2.1 Section AA'

The inverse gravity models (Figs. 3 and 4) were derived from the residual Bouguer anomaly under the assumption that the major features observed in the residual are the result primarily of a single density contrast. This assumption is supported by the velocity structure observed in the seismic refraction profile (Fig. 1, A1-A5) across this area (Ikami *et al.* 1986). Also it is implicit in this assumption that the Bouguer plate and terrain corrections have compensated for above-sea-level contributions to the Bouguer anomaly. We know that this is not the case. The differences between the two models (Figs. 3 and 4) illustrate this, since the differences between the two data sets are due solely to differences in the terrain correction

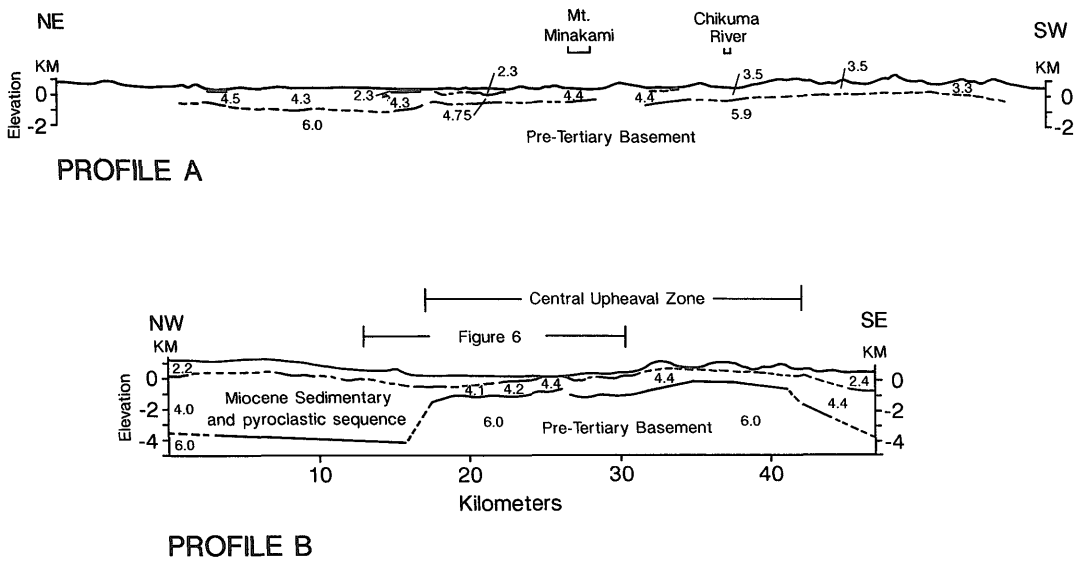


Fig. 5 Velocity structure presented for seismic refraction profiles A and B of Asano *et al.* (1969). The portion of profile B interpreted by Kato 1992, (Fig. 6) is noted. Profile B coincides with gravity profile BB' across the Central Upheaval Zone (Fig. 1).

and Bouguer plate terms, and therefore to differences between the densities of rock volumes above sea level and the replacement density.

Nonetheless, one can superimpose these two models and see that although there is considerable short-wavelength variability between the models, there is considerable similarity between the major structural characteristics of the basement (high-to-low density) interface in both models. Gravity lows over the Hida Mountains and the Matsumoto Basin are both attributable to density contrasts within the upper 6 km or so of the subsurface.

Correlation coefficients between the residual gravity anomaly and topographic variations along the line are -0.005 and -0.27 for the 2.3 and 2.67 data sets respectively. The slight negative correlation between topographic variations and the residual anomaly for the 2.67 data set suggests that the correction density is too high. The lack of correlation for the 2.3 data set suggests that, on the average, the 2.3 g/cm^3 correction density is a better approximation of the near-surface density in this area.

Examination of surface geological exposure along the profile (Figs. 3 and 4) reveals no clear relationship between the structural characteristics of the model and surface geology or topography, with the exception of Quaternary alluvial deposits along the gravity low over the Matsumoto Basin. These Quaternary deposits may reach a thickness of approximately 500 meters based on the results of a shallow seismic reflection survey across the basin (Yokokura *et al.* 1987). Yokokura *et al.* (1987), note that the average velocity of the Quaternary is approximately 2.5 km/s. Velocity-density relationships suggest that this interval will have a density of approximately 2.1 g/cm^3. The thick low-density alluvium will accentuate the magnitude of the negative anomaly over the Matsumoto Basin, and may lead to derivation of a basin that is deeper than actual. In the 2.3 model, for example, elimination of the deep extension of the basin reduces the calculated anomaly by approximately 7 milligals (Fig. 4) — an amount that may be related to density contrasts in the shallow Quaternary section.

A gravity high in the 2.3 anomaly (labeled R in Fig. 4 near 30 kilometers along the profile) is not observed in the 2.67 anomaly (Fig. 3). The anomaly may result from a high density igneous intrusion or ridge in the basement that extends into the near-surface. It does not correlate with an outcrop of any particular unit in this area. Its short wavelength (approximately 8 km) implies that it cannot have its origins beneath depths of 2 km or so. The gravity model (Fig. 4) suggests that the feature (also labeled R) may be a narrow (4 km width) high-density region that extends almost to the surface from a depth of

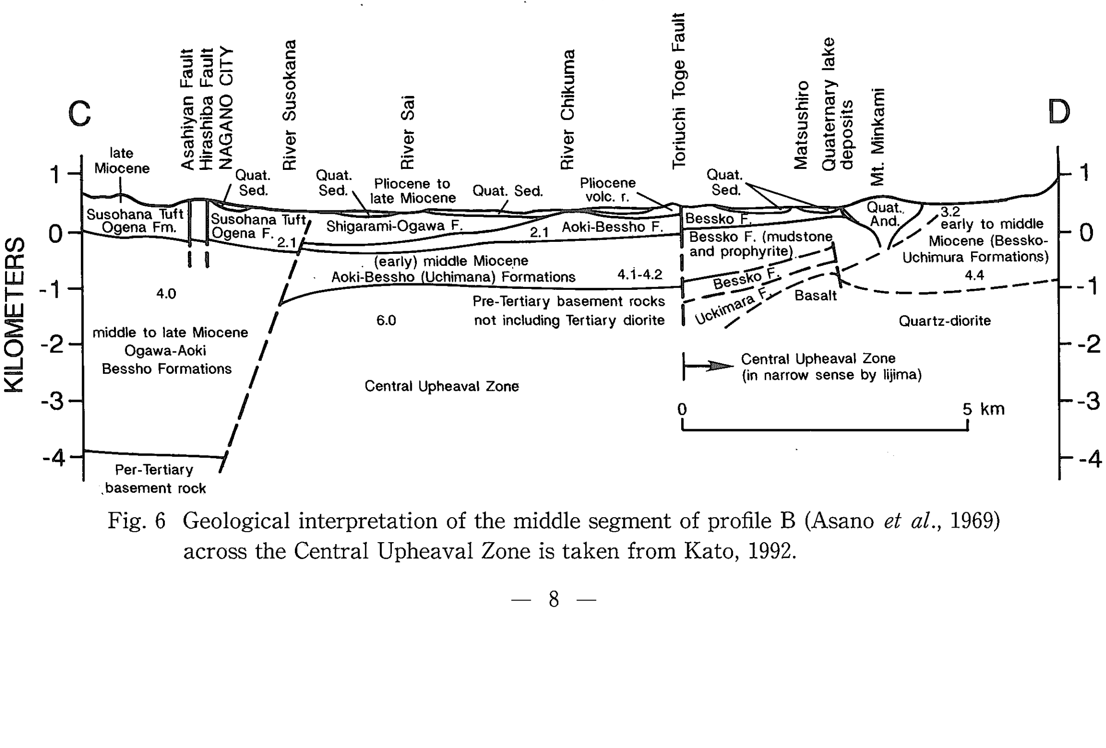


Fig. 6 Geological interpretation of the middle segment of profile B (Asano *et al.*, 1969) across the Central Upheaval Zone is taken from Kato, 1992.

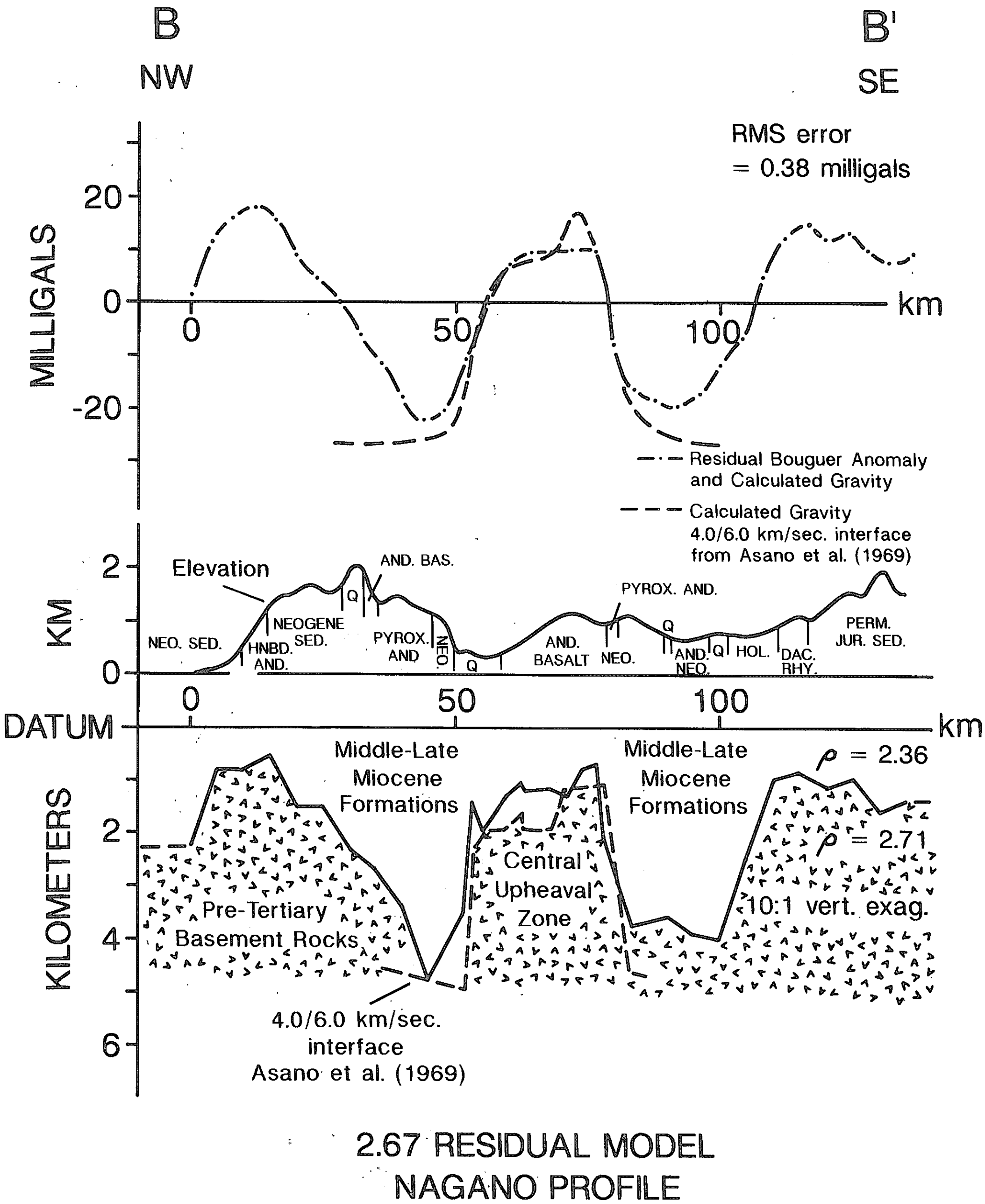
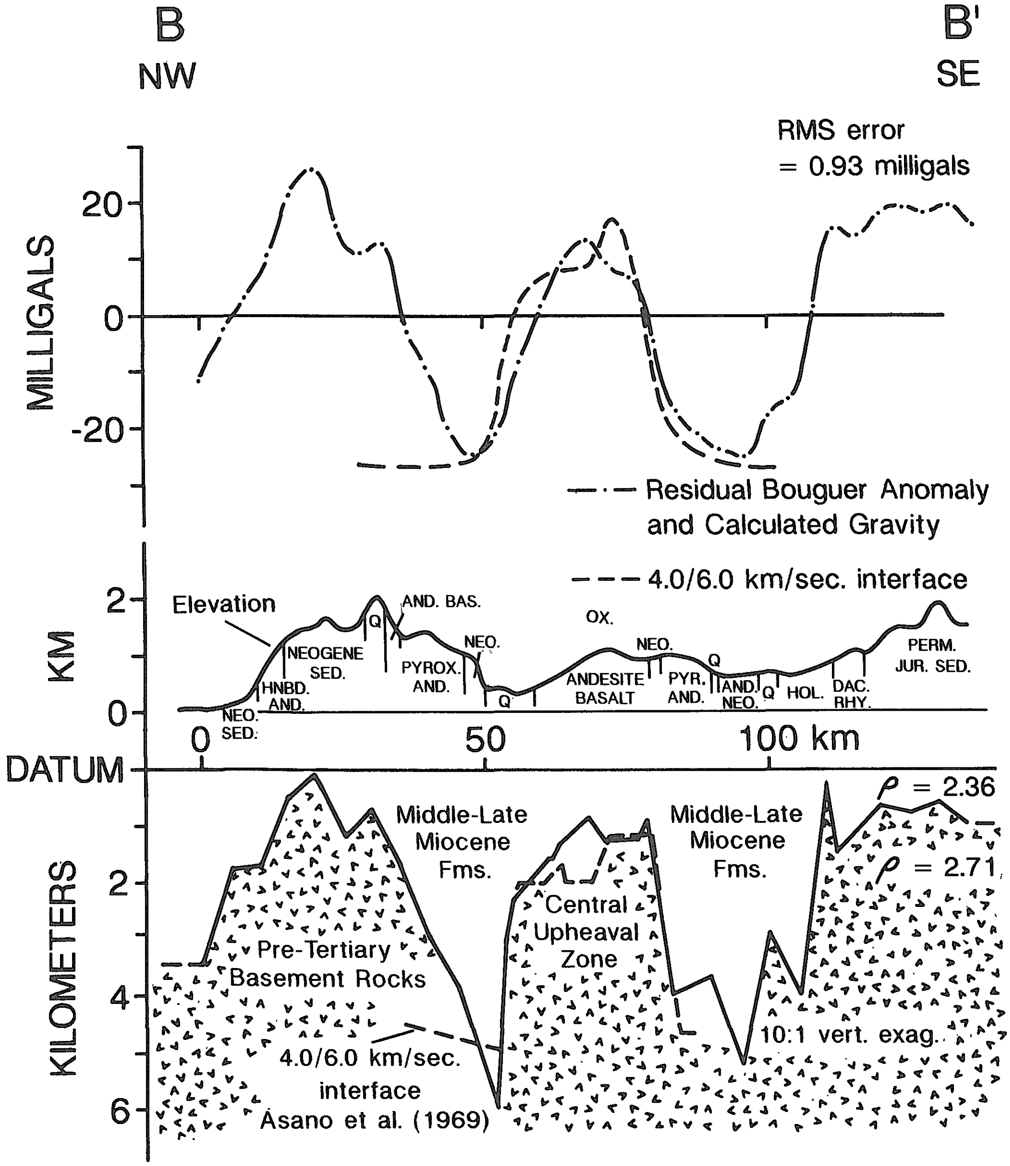


Fig. 7 The density model (bottom) was derived from the (2.67) residual Bouguer gravity shown at the top along profile BB' through Nagano. Elevation variations along the profile are shown in the middle of the figure, along with the surface geologic units exposed along the profile (Geological Survey of Japan, 1987). The residual was derived from the (2.67) Bouguer gravity data presented by Kono *et al.* (1990). Basement structure from profile B is also plotted for comparison to the derived basement model, and the calculated gravity for this structure is plotted relative to the other data sets across the top.



2.3 RESIDUAL MODEL NAGANO PROFILE

Fig. 8 The density model (bottom) was derived from the (2.3) residual Bouguer gravity shown at the top along profile BB' through Nagano. Elevation variations along the profile are shown in the middle of the figure along with surface geologic units exposed along the profile (Geological Survey of Japan, 1987). In this case, the residual was derived from the Bouguer gravity data presented by Komazawa *et al.* (1987). Basement structure from profile B is plotted for comparison to the derived basement model, and the calculated gravity for this structure is plotted at the top.

approximately 1.5 km.

2.2 Profile BB'

The 2.3 and 2.67 models for this profile are compared to the results of seismic refraction data along the central portion of the profile (Fig. 5, profile B) presented by Asano *et al.* (1969) across the Central Upheaval Zone. The calculated gravity associated with the interface between the 4 km/s and 6 km/s velocity intervals observed on the refraction profile is plotted for reference in Figs. 7 and 8. The calculated gravity for this model (dashed line, Figs. 7 and 8, top) agrees well with the magnitude of the 2.67 and 2.3 residual anomalies across the Central Upheaval Zone.

Inverse models (Figs. 7 and 8, bottom) were then calculated from both data sets to estimate the geometrical configuration of the basement interface on either side of the refraction profile. The inverse models yield a good fit between the residual Bouguer gravity and calculated gravity. During the calculations we also allowed for adjustment of the boundary between the two layers across the Central Upheaval Zone to improve the fit between the calculated and residual gravity in this area. We did this to get a measure of how the complexity of actual near-surface density contrasts and other features not included in the density model would lead to distortions of the basement structure. The distortions are minor compared to the regional scale characteristics of the basement across the Central Upheaval Zone. The basement in both the 2.3 and 2.67 models forms a horst-like structure that is approximately 25 km in width and has a structural relief of a little more than 3 km. The basement interface northwest of the Central Upheaval Zone has been distorted in both models. The basement in the gravity models does not flatten out as shown by the refraction data (Fig. 5), and additional features have been introduced into the interface across the Central Upheaval Zone.

In terms of the general regional structural characteristics of this horizon the distortions produced by near-surface density contrasts, not included in the model, are relatively minor. General agreement between the gravity models and the refraction seismic data along the profile, support the idea that regional highs and lows in the Bouguer gravity of the Fossa Magna are associated with regional scale structural highs and lows in the basement rocks of this region. Small correlation coefficient between the 2.3 and 2.67 residual Bouguer anomalies and elevation variations are nearly zero (0.01 and 0.02 respectively) so that the differences between the refraction data and the gravity models are not simply topographic in origin but related to lateral density contrasts not re-

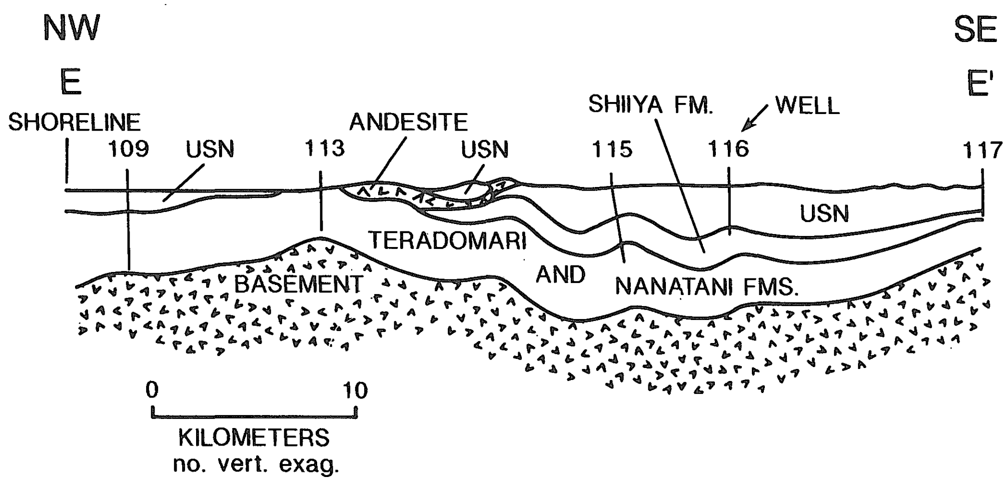


Fig. 9 The cross section shown above is taken from section EE' presented by the Niigata Prefectural Government (NPG) (1988). The portion of section EE' extending from the shoreline to the southeast is shown. USN denotes the Pleistocene Uonuma Group, and the Pliocene Shiroiwa and Nishiyama formations.

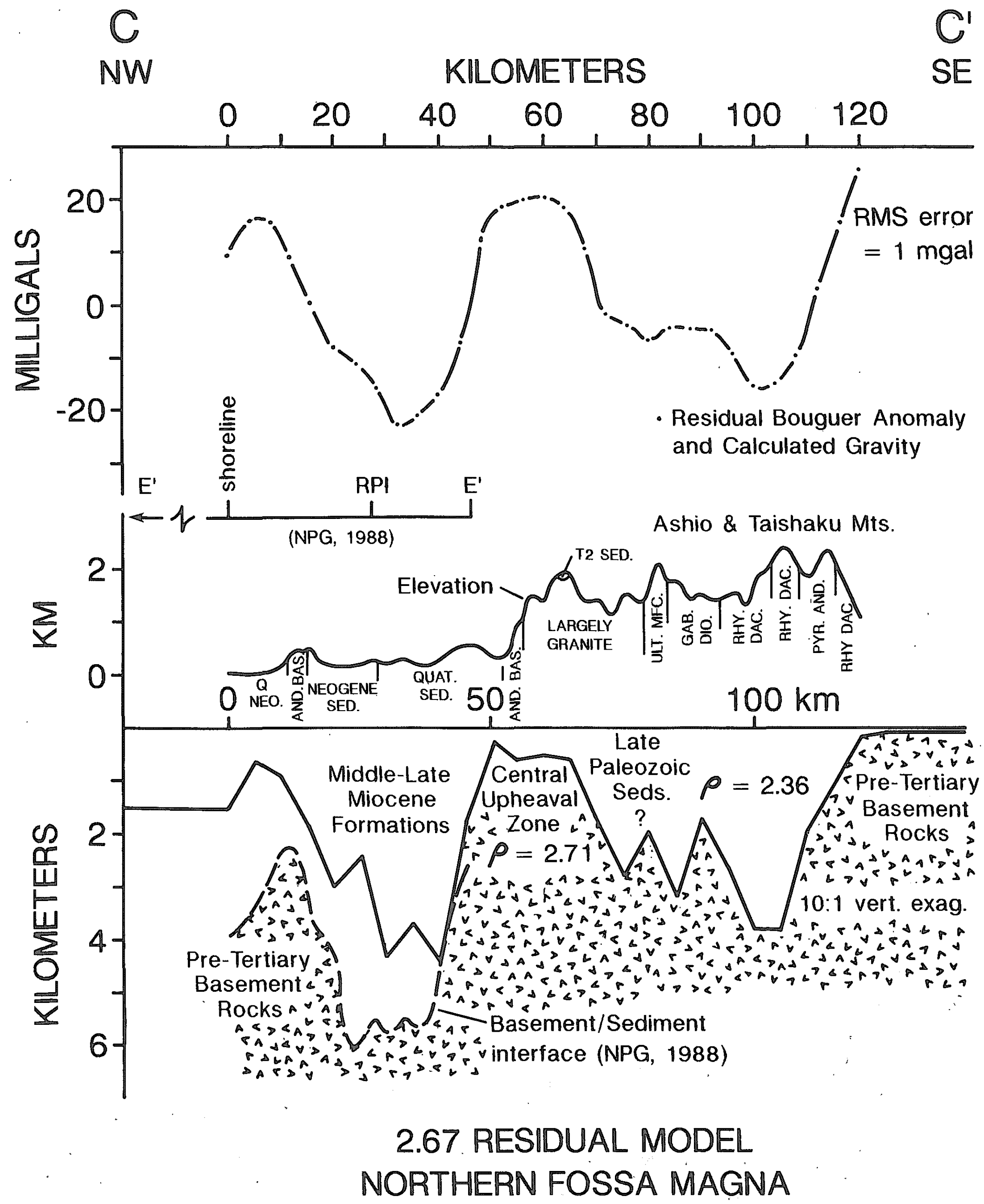


Fig. 10 The density model (bottom) was derived from the (2.67) residual Bouguer gravity (top) along profile CC' (Fig. 1) across the northern part of Fossa Magna. Elevation variations along the profile are shown in the middle of the figure along with surface geologic units exposed along the profile (Geological Survey of Japan, 1987). The residual was derived from the (2.67) Bouguer gravity data presented by Kono *et al.* (1990). The interpreted configuration of the basement along section EE' (Fig. 9) presented by the Niigata Prefectural Government (1988) is plotted for comparison to the derived model.

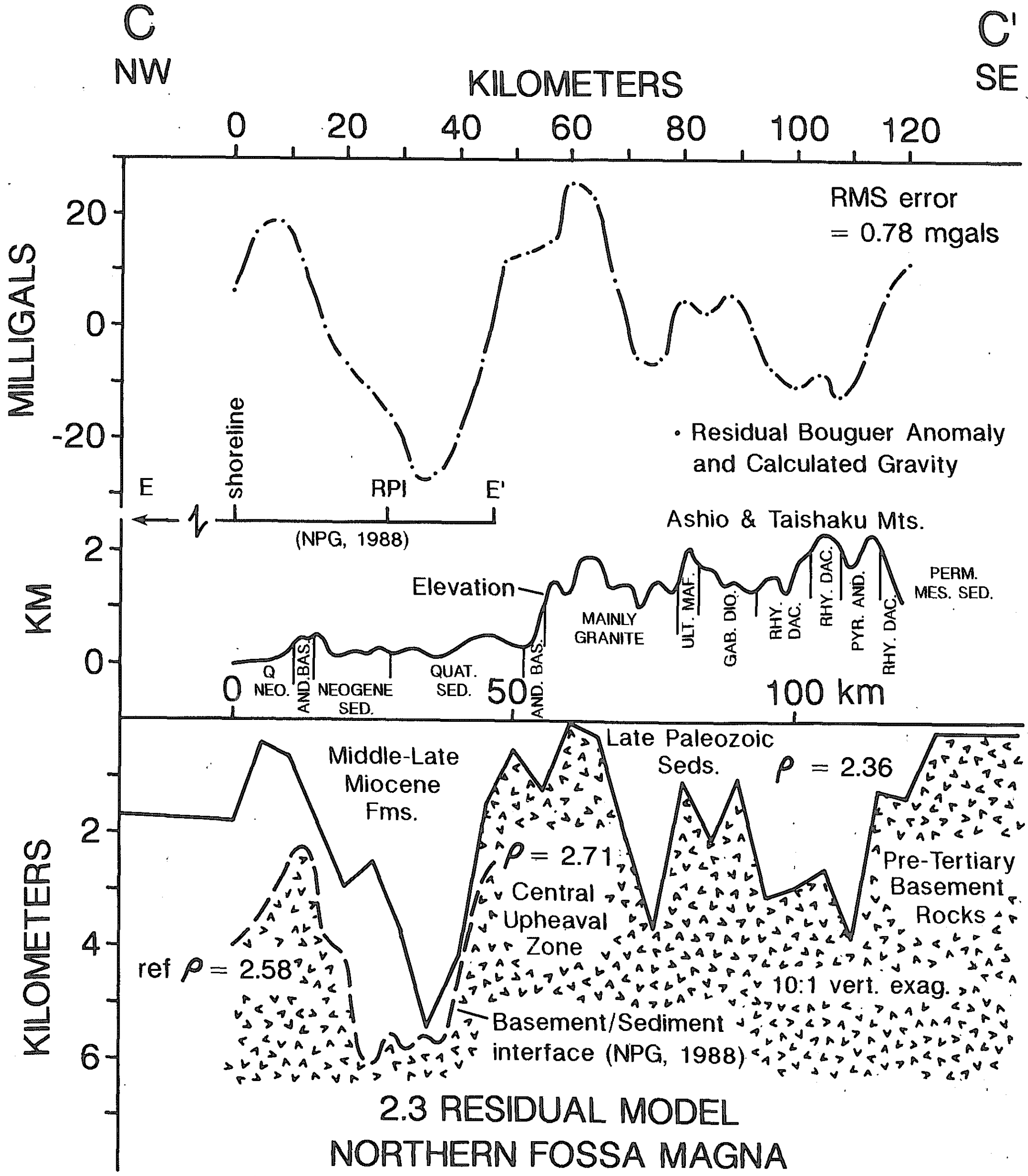


Fig. 11 The density model (bottom) was derived from the (2.3) residual Bouguer gravity (top) along profile CC' (Fig. 1) across the northern part of the Fossa Magna. Elevation variations along the profile are shown in the middle of the figure along with surface geologic units exposed along the profile (Geological Survey of Japan, 1987). In this case, the residual was derived from the (2.3) Bouguer gravity data presented by Komazawa *et al.* (1987). The interpreted configuration of the basement along section EE' (Fig. 9) presented by the Niigata Prefectural Government (1988) is plotted for comparison to the derived model.

presented in the models.

2.3 Profile CC'

Subsurface control along this profile is available only on its northwestern end. A well log derived cross section (section EE', Figs. 1 and 9) presented by the Niigata Prefectural Government (1988) across the northern Fossa Magna reveals the presence of a thick sedimentary basin northwest of the Central Upheaval Zone that reaches depths of up to 6 km. Projection of this cross section onto the gravity profile is shown in Figs. 10 and 11. The derived models (Figs. 10 and 11) reveal structure in the high-to-low density interface that is very similar to that observed on section BB' to the south. The low density regions inferred from the residual gravity are distributed into two basins, one on either side of the Central Upheaval Zone. However, basement relief estimated from the gravity data is in general about 1 and 1/2 km less than that observed in cross section EE'.

This discrepancy is partially resolved by refraction data from Ikami *et al.* (1986). The northernmost shot (Shot A1, Fig. 1) of their profile is located 4 km north of the gravity profile and provides additional information about the basin configuration and velocity structure in this area. Refraction velocities from this end of the profile (Fig. 2) reveal that the sedimentary section is characterized by two significantly different velocities rather than one as observed to the southwest. The sedimentary section is characterized by an upper layer with a velocity of 3.1 km/s, and a deeper layer with a velocity of 4.7 km/s. In the interpretation presented by Kato (1992) of Ikami *et al.*'s (1986) profile (Fig. 2), the interval with velocities of 3.1 km/s is correlated to Upper Miocene-Pliocene intervals, and the underlying high velocity (4.7 km/s) interval is correlated to the remainder of the Miocene sedimentary section.

The density model shown in Fig. 12 (bottom) combines the subsurface data from section EE' and densities estimated from the refraction velocities. Calculated gravity for this model agrees well with the residual gravity along the profile. The result supports the view that the gravity low along the northwest flank of the Central Upheaval Zone is primarily due to thick (4 km to 6 km) Neogene basins.

The gravity low on the southeast end of profile CC' along the flank of the Central Upheaval Zone is not, however, simply related to Neogene basins. In this case, the gravity low coincides with a structural break between the Ashio and Taishaku mountains, where a mixture of late Paleozoic to Quaternary formations are exposed. Hence, the gravity low does not represent a simple extension of the basin observed to the southwest on profile BB'.

Rapid uplifting of the Ashio and Taishaku Mountains occurred since the early Pliocene, and it is thought that the boundary faults

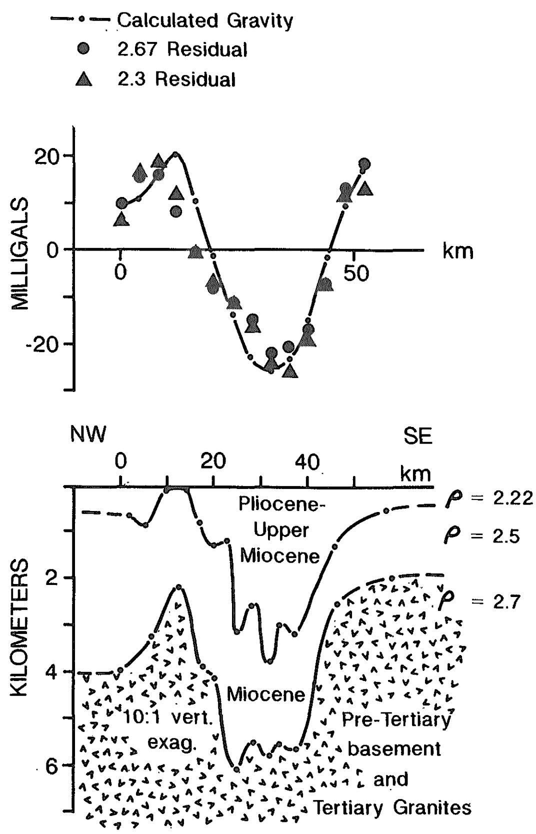


Fig. 12 The density model (bottom) is based on the geological interpretation of section EE' presented by the Niigata Prefectural Government (1988). Calculated gravity (top) for this model is compared to the 2.3 and 2.67 residual Bouguer anomalies. The calculation interval and sample interval are 4 kilometers.

between these mountains and adjoining basins, which cut even lower crust, were initiated during the early Pliocene (Editorial Committee of KANTO, 1986).

Although the gravity low, in this instance, is not associated with a Neogene basin, it appears to be related to the structural break between the Ashio and Taishaku Mountains. It may be that the Neogene basin which lies along the southeast flank of the Central Upheaval Zone once extended continuously to the northeast through this area. The structural break between the Ashio and Taishaku Mountains may be the exposed floor of the earlier basin. Localized basement lows containing Neogene formations occur along the trend of this gravity low to the northeast beyond the Ashio and Taishaku Mountains.

3. Regional Basement Structural Interpretation

The preceding gravity models calculated approxinately are partially constrained by seismic refraction and subsurface data. The configuration of the sediment / basement interface derived from modeling of the gravity data is generally consistent with seismic refraction and subsurface data. This agreement suggests that the gravity lows on either side of the Central Upheaval Zone and along the Itoigawa-Shizuoka tectonic line provide a rough outline of Neogene-age basins. Our speculations about the distributions of these basins are presented on Komazawa *et al.*'s (1987) terrain corrected Bouguer gravity map of the region (Fig. 13).

3.1 Northwestern Basin

The northern half of profile A (Fig. 5) from Asano *et al.* (1969) trends close to the northwestern edge of the Central Upheaval Zone. The central portion of Ikami *et al.*'s (1986) Nagano refraction profile (Figs. 1 and 2) nearly coincides with the profile of Asano *et al.* (1969). Both these profiles indicate that, along the Central Upheaval Zone, there is little variation of the depth to the basement, which generally lies within a kilometer or so of the surface.

Ikami *et al.*'s (1986) refraction profile (A1-A5 in Fig. 2) trends at an angle across the Central Upheaval Zone into the basin on its northwest flank. The refraction profile reveals that the basement, northwest of the Central Upheaval Zone, drops off steeply, and is interrupted by a step-like feature that may be fault controlled (Fig. 2). In this same area, the Bouguer anomaly patterns (Fig. 1) shown for the 2.3 data set are interrupted (see 0 milligal contour lines). The gravity-low is offset in a right-lateral sense. In our interpretation (Fig. 13), this basin and the one to the southeast, are bent to conform with the observed pattern of gravity lows. Kono and Furuse (eds., 1990) also describe the gravity patterns across this area as a zone of steep horizontal gradient. They refer to this zone as the "Naoetsu-Choshi Line", and suggest that 30 km of offset may have occurred across it. However, the shift in the pattern of Bouguer anomalies appears to increase from northwest to southeast along this zone. To the northwest near Naoetsu, the shift, or possible offset, appears to be only 5 to 10 km or so, while to the southeast, along the Central Upheaval Zone, a shift or offset of between 10 and 20 km appears possible.

The location of the basin along gravity profile CC' (Figs. 1 and 13) coincides with the thicker part of the basin shown in cross section EE' (Fig. 9) (Niigata Prefectural Government, 1988) and also as inferred from the gravity models (Figs. 10 and 11). The Bouguer gravity low associated with this basin is observed on the offshore data of Kono and Feruse (1990) to extend into the offshore area north of Niigata. Given the long history of oil and gas production in the Niigata area, the extent of this basin suggested by the gravity data may be relevant to future resource exploration and development of the area.

3.2 Southeastern Basin

As mentioned above, seismic refraction data revealing the presence of a basin, southeast of the Central Upheaval Zone, is limited to the short segment of refraction profile B from Asano *et al.* (1969) (Fig. 5). This profile extends for about 5 kilometers beyond the southeastern edge of the Central Upheaval Zone along gravity profile BB' of Fig.s 1 and 13.

The southeastern margin of the Central Upheaval Zone revealed by the refraction profile

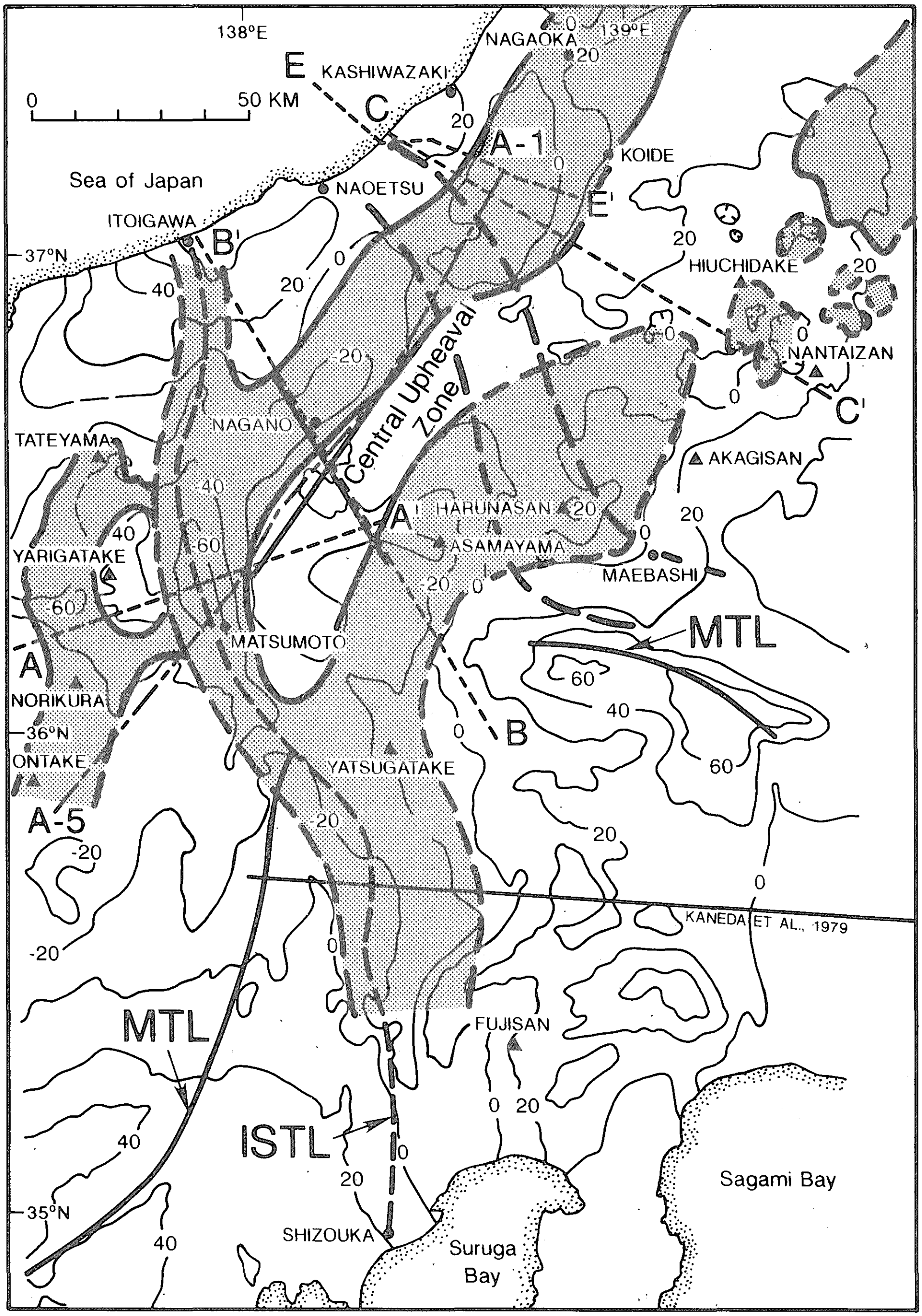


Fig. 13 An interpretation of the areal extent of the basement structures inferred from the gravity models derived from the residual Bouguer anomalies along profiles AA', BB', and CC', and the supplementary data sets discussed in the text and located above. This interpretation is made on the (2.3) Bouguer anomaly data set compiled by Komazawa *et al.* (1992). Heavy dashed lines between Naoetsu and Maebashi locate interpreted cross-fault zone. MTL= Median Tectonic Line. ISTL=Itoigawa-Shizuoka Tectonic Line.

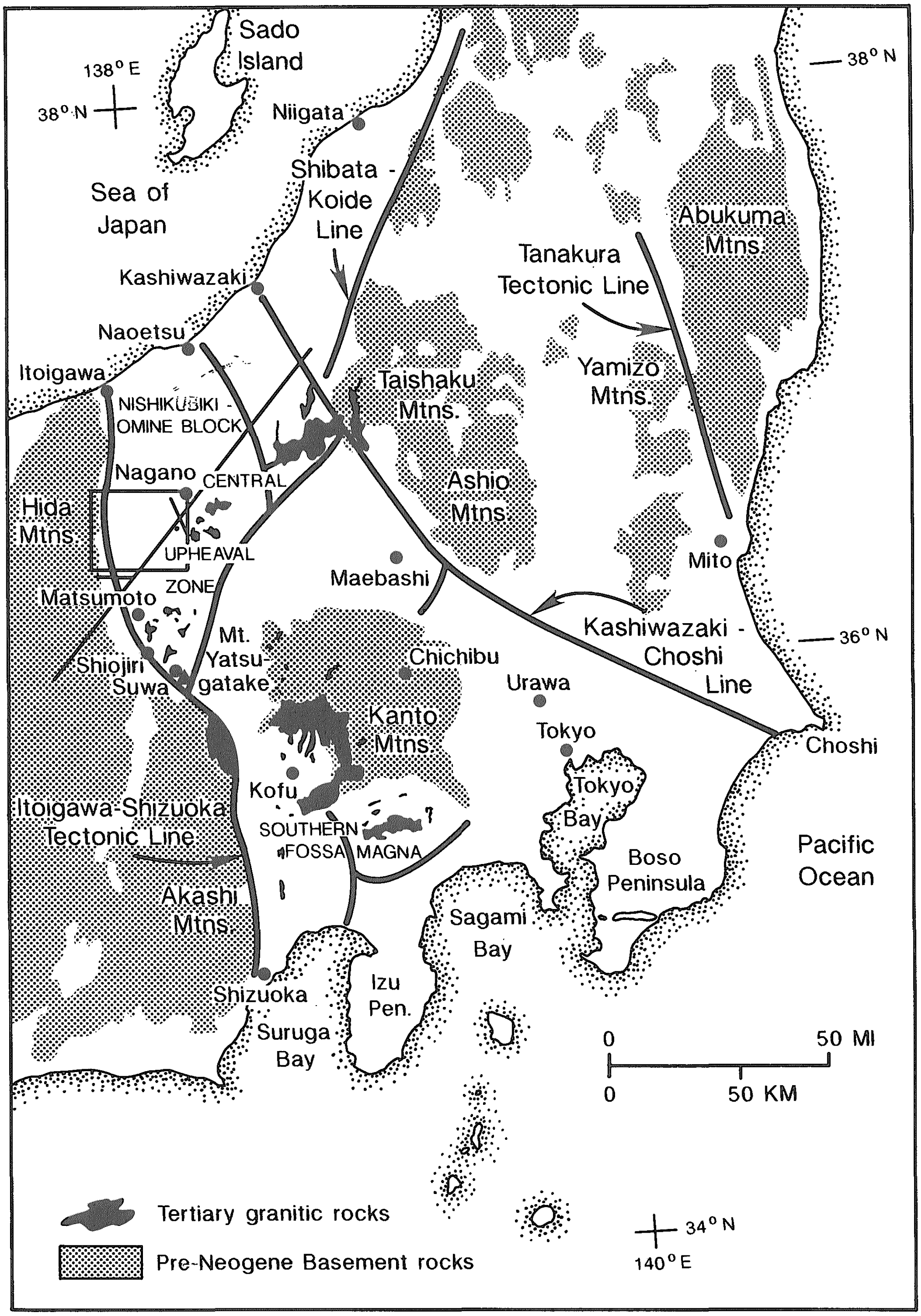


Fig. 14 Tectonic map of central Japan (taken from Kato, 1992).

coincides with the edge of another gravity low in both the 2.67 and 2.3 residual Bouguer anomalies along profile BB' (Figs. 7 and 8 respectively). This gravity low is also interrupted between profiles BB' and CC' (Figs. 1 and 13) in a right-lateral sense as noted for the gravity low northwest of the Central Upheaval Zone. A right-lateral offset of 30 km or so is suggested by the bend in the Bouguer gravity. This basin may be much less continuous, and the right-lateral offset, more abrupt, than suggested in our interpretation (Fig. 13).

As noted above under the discussions of gravity profile CC', a structural break between Ashio and Taishaku Mountains coincides with the extension of the gravity low northeastward across profile CC'. This interruption is suggested in our interpretation (heavy dashed lines in Fig. 13). However, coincidence of localized basement lows with lows in the Bouguer gravity further northeast are observed and suggested in our interpretation.

Several Quaternary aged volcanic deposits are present at the surface along the trend of this gravity low. However, there is a lack of any clear relationship between the areal extent of volcanic deposits and the areal extent of the gravity low. Profile BB' for instance crosses near the southern margin of Quaternary aged pyroxene andesites associated with Asamayama (Yamada *et al.*, 1982). However, the Bouguer anomaly, rather than decreasing northward toward the peak of this volcano, actually increases (Figs. 1 and 13).

The effect of these low density volcanic deposits is more noticeable in the 2.67 data set (see Kono and Furuse, eds., 1990). However, in the 2.3 data set, some of these volcanic deposits actually lie on local highs, as is the case for Harunasan and Asamayama (Fig. 13). Akagisan (Fig. 13) also sits on a local high (see detailed map of Komazawa *et al.*, 1987). Quaternary aged pyroxene andesites are also distributed in places along the gravity high along the Central Upheaval Zone (see Yamada *et al.*, 1982), and are not restricted to the gravity low areas.

3.3 Matsumoto Basin

The low over the Matsumoto basin is interpreted to be associated with a deep, fault-bounded basin. In Fig. 13 the sense of motion along these marginal faults is noted as reverse along the southwest and normal along the northeast. This interpretation is based on the results of the models shown in Figs. 3 and 4, and is consistent with the geologic history of the region (Kato, 1992).

The areal extent of the basement structure underlying the Matsumoto Basin shown in Fig. 13, is drawn to coincide with the ISTL. The regional northeast-southwest trend of the Bouguer anomalies along the Central Upheaval Zone is interrupted by the ISTL. With the exception of its northernmost end, the Bouguer gravity usually swings to a trend along the ISTL, forming a relative low along its length.

Our models (Figs. 3 and 4) also indicate the presence of a shallow low density region beneath the Hida Mountains. This gravity low is a prominant part of the central Honshu gravity low, also includes the Matsumoto Basin. Tateyama, Yarigatake and Norikura all lie within or on the flanks of the gravity low beneath the Hida Mountains suggesting that the low may be associated with a low density pluton beneath the area. A possible connection between the Hida and Matsumoto basins is suggested by the pattern of gravity contours (Fig. 13).

4. Summary

The gravity model studies presented in this paper suggest the presence of extensive basin-like structures in the Pre-Tertiary crust or basement rocks of central Honshu. Basement structure inferred from the gravity models is consistent with available seismic refraction and a well log derived cross section from the area.

Structures outlined by the Bouguer gravity include two basins, which extend northeast through the Fossa Magna along the flanks of the Central Upheaval Zone from the Itoigawa-Shizuoka Tectonic Line. Disruptions of the gravity anomaly patterns in the northeastern Fossa Magna are interpreted to be associated with a cross fault zone. This zone passes between the eastern margin of the Nishikubiki-Omine block and the Kashiwazaki-Choshi

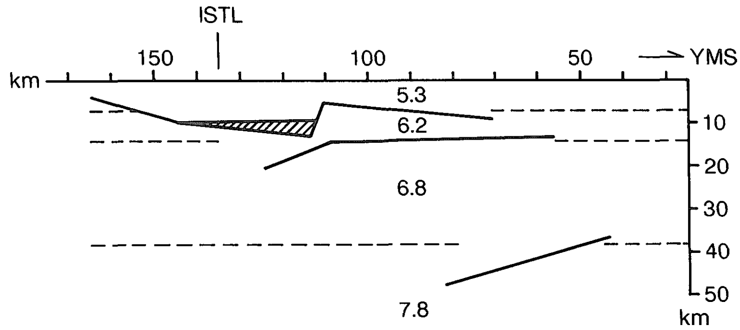


Fig. 15 Velocity model derived from explosion seismic reflection profile across the western Kanto District (from Kaneda *et al.*, 1979). Location of profile is shown on Figs. 13 and 14. ISTL=Itoigawa-Shizuoka Tectonic Line.

tectonic line (Fig. 14). Apparent offset implied by the disruption of the gravity contours is right-lateral and decreases to the northwest. Whereas Kono and Furuse (1990) suggest that there is 30 km of offset along the northern end, our correlation of gravity models and other geophysical data to the pattern of Bouguer anomalies suggests that only about 10 km of offset may occur across this area. The disruption in the Bouguer anomaly contours further to the southeast suggests that this right lateral offset may extend into the southern Fossa Magna along the southern end of the Kashiwazaki-Choshi tectonic line (Fig. 14) and the northern margin of the Kanto syntaxis marked by the Median Tectonic Line (MTL) (Fig. 13). Based on the pattern of Bouguer anomalies, a right-lateral offset of over 30 km seems possible in this area.

During the opening of the Japan Sea, a deep basin was formed along the length of the ISTL. Displacements along the ISTL and other faults were generally normal throughout the Miocene and Pliocene resulting in the formation of a deep basin along the boundary between northeast and southwest Japan. However, recently during the Pleistocene, the sense of motion along the ISTL is believed to be reverse in response to compressional stress along the boundary between northeast and southwest Japan. The relative uplift of southwest Japan is believed to be associated with incipient subduction of northeast Japan beneath southwest Japan (Nakamura, 1983; Kobayashi, 1983; Seno, 1983). The models presented above along profile AA' (Figs. 3 and 4) are consistent with this hypothesis. The present-day southwest dip predicted for the southwest flank of the Matsumoto basin suggests a reverse sense of offset for the bordering Hida Mountains area relative to the Fossa Magna.

With the exception of the northernmost end of the ISTL, the Bouguer gravity patterns usually trend along the ISTL forming a relative low in the Bouguer gravity along its length. In our interpretation, we suggest that the deep basin observed in the Matsumoto area extends along the length of this trend. Furthermore, we extend this structure into the southern Fossa Magna based on the reflection seismic profile presented by Kaneda *et al.* (1979) (Fig. 15). This profile crosses the southern part of the ISTL (Fig. 13) and reveals a structural depression in the basement along the border of the southern Fossa Magna with southwest Japan. This depression (Fig. 15) is much wider than that observed across the Matsumoto Basin.

Whether the ISTL developed initially in the early Neogene, or is a reactivation of structures developed during earlier episodes of deformation, it seems likely that development of the ISTL predates the development of upper crustal structures in northeast Japan, which terminate against it or merge into it.

5. Conclusions

At the outset of this paper, we ask the question whether gravity anomalies in central Japan, or for that matter within Japan as a whole, can be related (in a meaningful way) to subsurface structure, given the complexity of the surface geology and the use of a constant density for the Bouguer plate and terrain corrections. The results of our studies suggest that:

1) Inverse gravity models of the residual terrain corrected Bouguer gravity are consistent with explosion seismic and a well log derived geologic cross section.

2) Correlation of lows in the terrain corrected Bouguer gravity with upper crustal basins, confirmed in places using refraction seismic and subsurface data, implies the presence of a pair of basins, which trend southwest-to-northeast through the Fossa Magna region on either side of the Central Upheaval Zone.

3) A basin is also interpreted to extend along the boundary between northeast and southwest Japan.

4) Gravity models across the basin between northeast and southwest Japan suggest that the southwest wall of the basin is overturned.

5) Elimination of long wavelength components from the Bouguer anomaly reduces the influence of above-sea-level density contrasts as well as those associated with the deeper crust.

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北部フォッサマグナの重力モデルの研究

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要　旨

本論文では北部フォッサマグナ地域の基盤構造の解釈がインバース重力モデルに基づいて提案されている．更にその結果は地震屈折法による速度構造断面やボーリングデータによる地質断面図などによって検討されている．重力モデルは北部フォッサマグナにおける第一級の地質構造の１つで中期中新世以降の隆起帯である北東―南西性の中央隆起帯の北側で，それに並走する２つの新第三系堆積盆の存在を示唆している．それらは幅 30―50km で低ブーゲー異常の分布に対応する．これらの堆積盆は鮮新世以前には東北日本弧に沿って延び，切断されてはいなかった．初期鮮新世における帝釈・足尾山地の隆起によって南西方向への延長が阻止されている．また，糸魚川―静岡構造線以西にも延びていない．西頚城―大峰地塊といわゆる銚子―柏崎線の間で北西―南東方向に重力異常の不連続線がみられ，これが上記２つの堆積盆をみかけ右横ずれに変位させている．