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Two-dimensional crustal structures of Taiwan from gravity data

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Abstract. To delineate the tectonic character of Taiwan, an island-wide gravity survey of Taiwan was conducted between 1980 and 1987. The Bouguer anomaly map shows that, in general, isogals trend NNE in consonance with the overall structural trend of the island. With seismic and other geophysical data as constraints, the subsurface density structures were modeled along three profiles across the major structural trends. The gravity data are consistent with average continental Moho depths of 26 km in the Coastal Plain and the Western Foothills, 28 km underneath the Coastal Range in eastern Taiwan, and 33 km under the Central Range. A lack of significant correlation of the Bouguer anomalies with the topography implies dynamic, rather than isostatic, support of topography in the Taiwan region.

1. Introduction

The Central Range of Taiwan, reaching nearly 4000 m in elevation at its highest point, is an area where few gravity measurements were made before 1980 [*Chang and Hu*, 1981]. To achieve an improved overall understanding of the tectonics of Taiwan, an island-wide gravity survey, especially in the mostly inaccessible mountain range, was initiated in 1980 and completed in 1987. In total, 603 gravity stations were surveyed (Figure 1). Efforts were made to provide as uniform a coverage as physically possible. A Bouguer anomaly map was constructed from the newly collected data [*Yen et al.*, 1995b] and differs significantly from previous maps, which were based on insufficient data in the Central Range. To illustrate how the gravity data constrain crustal structures, a two-dimensional gravity analysis was performed with three gravity profiles across the major structural trends taken from the gravity anomaly map.

Using available information from surface geology, shallow (<10 km) seismic data, and the known Moho depths as constraints, we modeled three cross-island profiles in terms of crustal density distributions. Although such an interpretation is still far from being unique, it does provide a guide as to the overall structures under Taiwan. Not to be neglected is the fact that gravity data also enable us to investigate the state of isostatic equilibrium.

2. Gravity Anomaly Map

Two LaCoste-Romberg microgal gravimeters (D-47 and D-48) were used in our surveys. Gravity measurements were made at benchmarks of the first-order leveling network, at triangulation points, and at topographically salient points on 1:10,000 scale photomaps. Details of gravity survey procedures have been described by *Yen et al.* [1990]. The measurements are based on International Gravity Standardization Net 1971, and the Bouguer anomaly is referenced to Geodetic Reference System 1967. Bouguer and terrain corrections were made over a distance range of 100 km using an average density of 2.57 g/cm^3. A multicolor contoured version of the Bouguer anomaly map on a scale of 1:500,000 was published by *Yeh and Yen* [1992]. This map differs significantly from the previous map, which was based on insufficient data in the Central Range. As Figure 2 shows, the isogals trend generally NNE-SSW in consonance with the structural trends of the island. Negative anomalies cover a major part of the island; positive anomalies dominate in the eastern part of the Central Range, the Coastal Range, and the northern extremity of the island. Conspicuous gravity lows are found in west central and southwestern Taiwan over Tertiary and Quaternary sedimentary basins. It is important to note that the high mountains on the island lie in a zone of high Bouguer gradient. The Bouguer anomaly of Taiwan does not reflect the topography of the island. This suggests that the Central Range is not isostatically compensated on a local scale. The positive anomalies of the steep gradient zone (3 mGals/km) in the eastern part of the Central Range and the Coastal Range trend parallel to regional structures. The highest anomaly value is up to 100 mGals along the east coast. This rapid increase is obviously related to the suturing of the island arc (underlain by oceanic crust) to the continental shelf in the vicinity of the Longitudinal Valley.

Recently, a regional free-air anomaly map for the subduction zone near Taiwan was constructed by reconciling the shipboard data of 15 cruises [*Yen et al.*, 1995a]. On the marine gravity, the Lutao-Lanhsu volcanic arc is manifested as a prominent, continuous high from the southern border of the map, merging northerly with the Coastal Range in eastern Taiwan. A conspicuous low is over the Hoping Basin in the north and Hualien Canyon in the south, with a minimum value of -230 mGals. The low seems to extend southerly for about 50 km to

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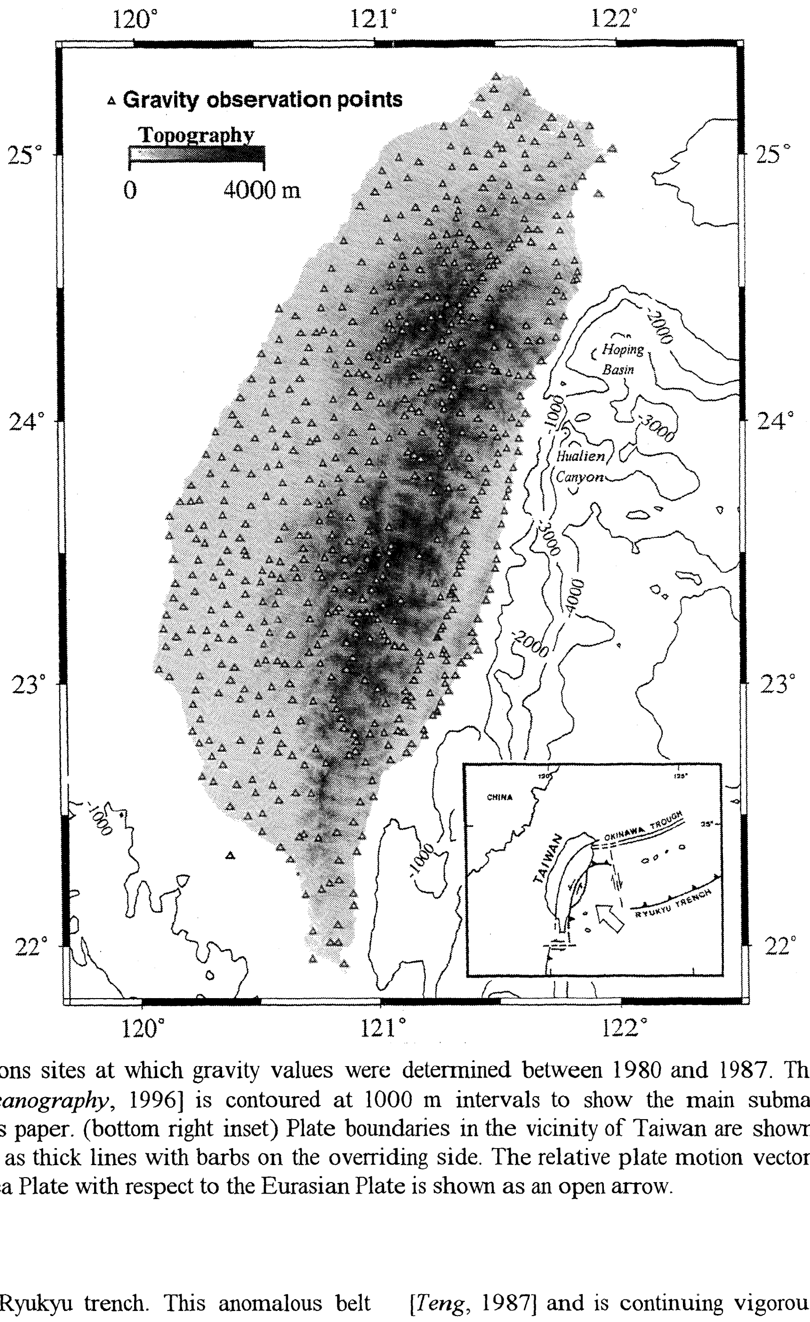


Figure 1. Stations sites at which gravity values were determined between 1980 and 1987. The bathymetry [*Institute of Oceanography*, 1996] is contoured at 1000 m intervals to show the main submarine features mentioned in this paper. (bottom right inset) Plate boundaries in the vicinity of Taiwan are shown. Subduction zones are shown as thick lines with barbs on the overriding side. The relative plate motion vector (7 cm/yr) of the Philippine Sea Plate with respect to the Eurasian Plate is shown as an open arrow.

the physical end of the Ryukyu trench. This anomalous belt could be caused by thickened sediments or subsidence of the oceanic crust, both indicating an enhanced downwarping of the edge of the Philippine Sea Plate via pushing against the eastern wall of the island [*Yen et al.*, 1995a]. We have compiled both the land gravity data (Bouguer anomaly) and the marine data (free-air anomaly) as shown in Figure 2. Marine gravity data may help us to understand the subsurface structures in eastern Taiwan where the subduction-collision zone is.

3. Tectonic Setting of Taiwan

The mountains in Taiwan are very young, geologically speaking, formed as a result of the collision between an island arc system and the Asian continental margin [*Wu*, 1978; *Ho*, 1982; *Tsai*, 1986]. The orogeny commenced about 5 m.y. B.P. [*Teng*, 1987] and is continuing vigorously. Seismicity on and around the island is quite high [*Wu et al.*, 1989]. Triangulation [*Yu et al.*, 1992], leveling [*Liu and Yu*, 1990] and recent Global Positioning System data [*Yu and Chen*, 1994] show that active deformation, rapid uplift (up to 2-3 cm/yr at some points), and convergence at a rate of over 7 cm/yr are taking place in and around Taiwan.

The geological structures of Taiwan trend mainly in a NNE-SSW direction as shown in the simplified geological map of Figure 3. These trends are parallel to the main topographic trends. The surface geology of Taiwan is dominated by Tertiary rocks, except on the east side of the Central Range where pre-Tertiary metamorphic complexes are exposed. They are most probably exhumed lower crustal rocks raised to the present level as a result of recent orogeny.

East of the metamorphic complex is the Coastal Range, where Miocene and younger rocks representing a former island

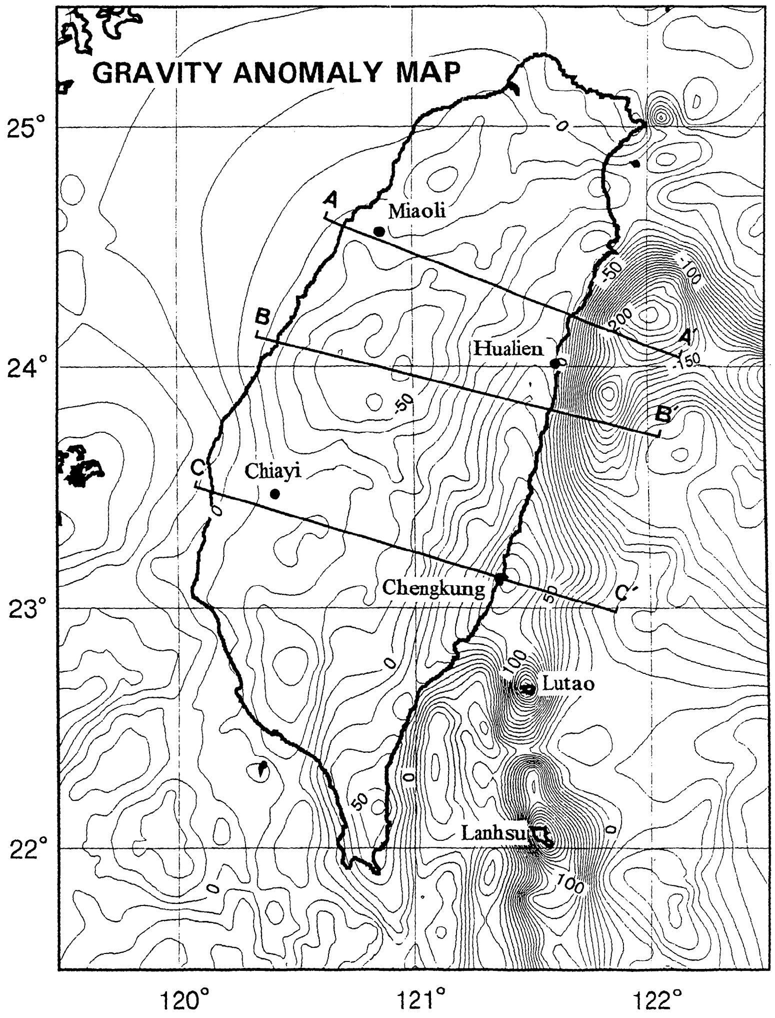


Figure 2. Gravity anomaly map in the Taiwan region (contour interval, 10 mGals). The thick lines mark the locations of the three gravity profiles (A-A', B-B', and C-C') modeled in this paper. The regional gravity is obtained by joining the interpolated land-based gravity data (Bouguer anomaly) with the marine data (free-air anomaly) on a 1/12° grid.

arc are found. These rocks are thrust up along a series of en echelon faults, striking about N30°E, at a slight angle to the dominant structural trend of the island. These thrust blocks were successively accreted to the island, beginning around 4-6 m.y. B.P. [*Lee et al.*, 1991].

The Longitudinal Valley (LV) separates the Coastal Range from the Central Range to the west. The LV is considered to be the suture that juxtaposes older continental rocks and young island arc materials. It also separates the highly seismic Coastal Range [*Wu et al.*, 1989] from the relatively aseismic Central Range.

West of the pre-Tertiary metamorphic complex are the main Central Range, the Foothills, and then the Coastal Plain. In northern Taiwan, the Central Range is composed of two ranges, the Backbone Range in the east and the Hsuehshan Range in the west, but the southern Central Range is a single range; the overall width of the Central Range is wider in the north than in the south. Whereas the pro-orogenic sedimentary rocks of the northern half of Taiwan were formed in relatively shallow shelf environments, as part of the passive margin of southeastern China, corresponding rocks of the southern half of western Taiwan were formed on the former continental slope. The Peikang high, where the pre-Tertiary basement is at the shallowest in western Taiwan, is a natural divide between north and south Taiwan. The Backbone Range is composed mainly of slates, but in the Hsuehshan Range alternating sandstone and shale layers dominate. Most of the older Tertiary rocks were derived from the Chinese mainland, but since the Late Pliocene, the sediments in the western Taiwan Basin have been derived from the Central Range [*Chou*, 1973], signifying the rise of the Central Range at that time. The Coastal Plain of western Taiwan is composed of Quaternary alluvial deposits, and the Neogene strata underneath are gently folded and thin to the west.

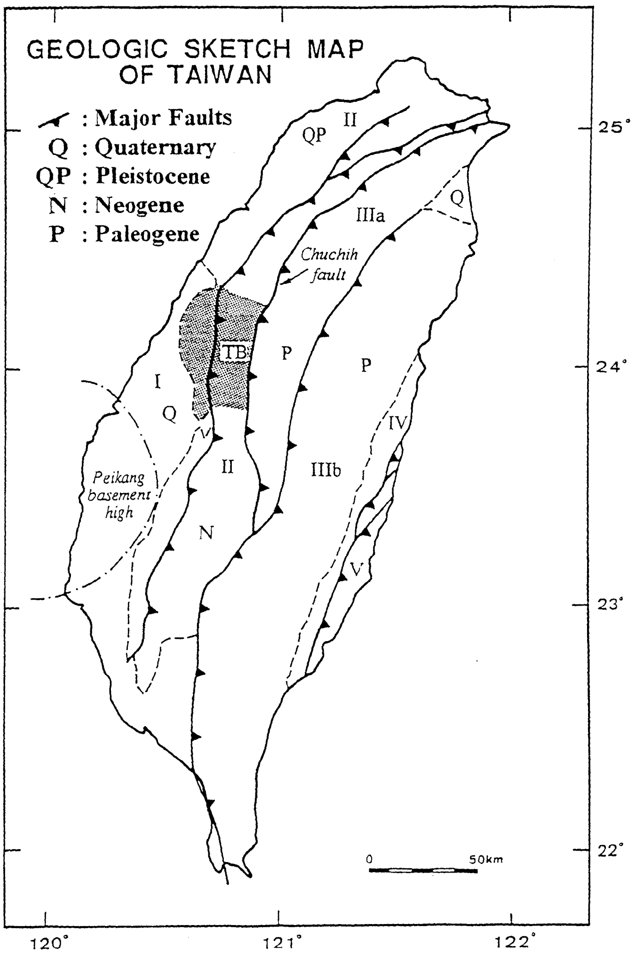


Figure 3. Simplified physiographic and geologic map of Taiwan [after *Ho*, 1982]. Abbreviations are as follows: I, Coastal Plain, II, Western Foothills, IIIa, Hsuehshan Range, IIIb, Backbone Range (IIIa+IIIb, Central Range), IV, Longitudinal Valley, V, Coastal Range, and TB, Taichung Basin.

4. Modeling of Subsurface Density Structure

The lengths of the structures along the strike of Taiwan are roughly 4 times their widths, and, as a first-order approximation, we can model them as two-dimensional structures based on cross sections perpendicular to the strike. In the modeling, available seismic, drilling, and other data are used wherever possible to constrain the geometries and/or densities. We also assume, for lack of more detailed information, that the structure consists of a small number of layers, the density within each layer does not change laterally, but that layer thicknesses may vary. This assumption is not used when seismic or drilling data are available as constraints. Constraints in terms of geological cross sections, well data, seismic profiles, and velocity information are relatively abundant in the Western Foothills and the Coastal Plain areas. However, there is a paucity of such data in the Central Range. Because of the inherent nonuniqueness of gravity interpretation, an attempt was made to keep the model relatively simple.

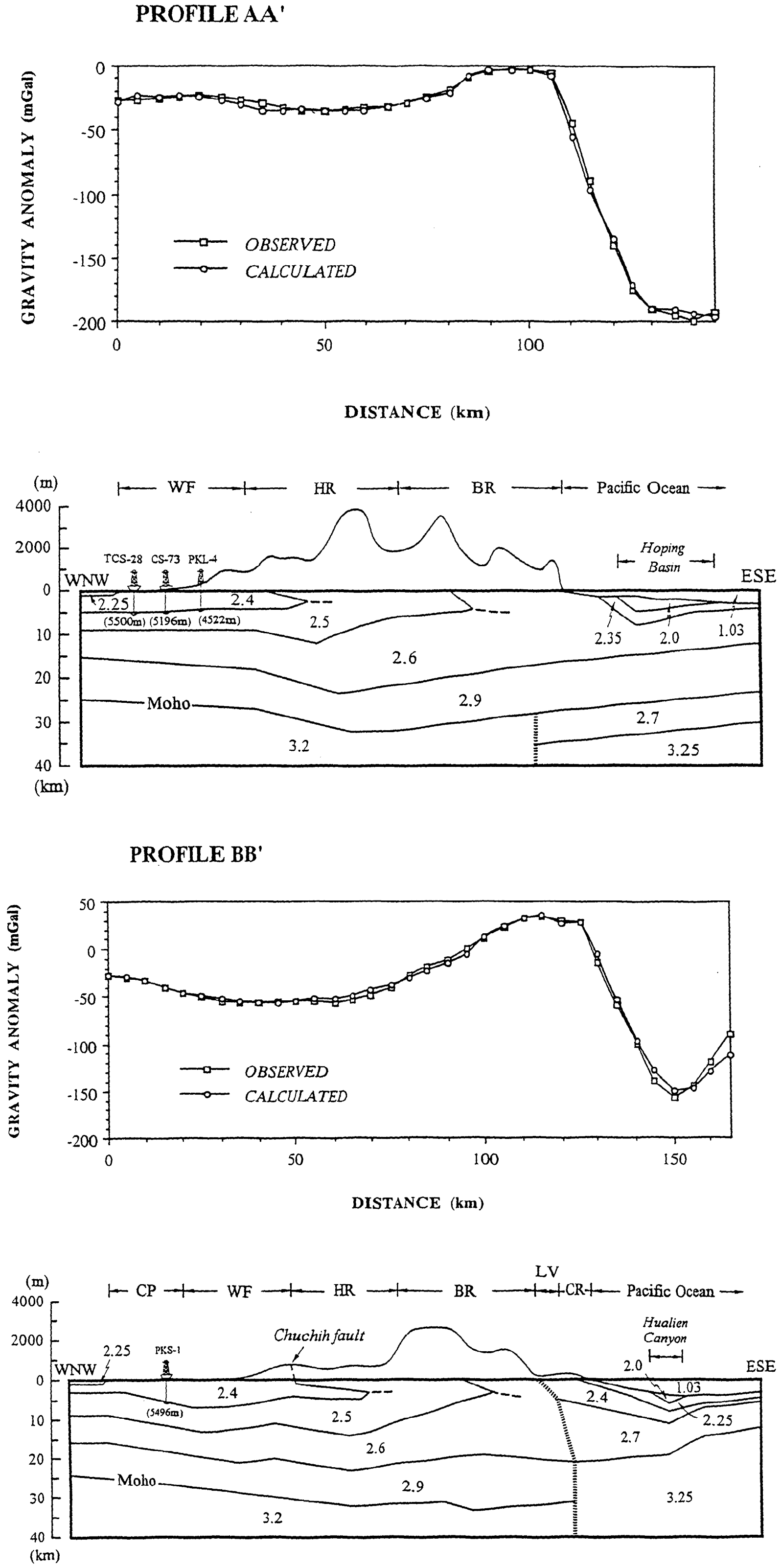
Three gravity profiles (AA', BB', and CC'), as shown in Figure 2, are selected for subsurface density modeling. The formulae of *Talwani et al.* [1959] are used for the theoretical calculations. The observed and calculated gravity values are matched by trial and error. In our models, the lateral variations of shallow subsurface layers are dictated by surface geology [*Central Geological Survey*, 1986], whereas the vertical column consists of three layers if no constraints are available and up to seven layers if well data and seismic information already exist in the vicinity. The density of each rock unit [*Nafe and Drake*, 1965; *Hsieh and Hu*, 1972; *Wu*, 1978; *Hu and Chen*, 1986] is mostly assumed to be constant during the iterations (Table 1). The depth of Moho, under the western edge of Central Range, is constrained by using seismograms from natural sources recorded by the Taiwan Telemetered Seismic Network stations [*Wu et al.*, 1991; *Rau*'s 1992].

The observed and calculated gravity anomalies, the topography along the profile, together with the differences between the observed and calculated values are shown in Figures 4a, 4b, and 4c. The main features of the models are as follows:

1. Profile AA' starts from Miaoli, crosses the Hsuehshan Range and the northern Backbone Range, and finally ends up south of the Hoping Basin. The gravity anomalies are characterized by a gradual increase at a rate of 0.7 mGals/km from the Hsuehshan Range to the east on land and a rapid decrease on offshore in eastern Taiwan. Here the topography has two peaks. The minimum value of the Bouguer gravity is nearly over the Hsuehshan Range, but the Backbone Range is in the transition zone. The general increase in the Bouguer anomaly toward the east is a result of the presence of the high-density, lower-crustal rocks (pre-Tertiary metamorphic rocks) at shallow depths, and the decreasing crustal thickness eastward. The obvious gravity low at the eastern end of the profile is due to the thick sediments in the Hoping Basin [*Lin*, 1994] and the presence of the northward subducting Philippine Sea Plate underneath the eastern side. The model (Figure 4a) shows that the continental Moho has a maximum depth of 32 km under the Central Range and is shallower on both sides. The depth of the Moho in the Western Foothills is 26 km.
2. Profile BB' cuts through the lowest Bouguer anomaly, located in west central Taiwan. The modeling result is shown in Figure 4b. The low is separated into the eastern and western parts by the Chuchih Fault. In the western part, this coincides with the Taichung Basin (TB, Figure 3), with more than 5000 m of Neogene sediments [*Sun*, 1982]. According to the modeling result, the maximum depth is about 7 km in the

Table 1. Densities for Modeling in This Study and Their Relative Rock Layers

Rock Layers	Density, g/cm^3
Recent sediments	2.0
Quaternary sediments	2.25
Neogene sediments	2.35~2.45
Paleogene sediments	2.5
Granitic layer (include metamorphism)	2.6
Oceanic crust	2.7
Basaltic layer	2.9
Upper mantle	3.2~3.25


PROFILE AA'

PROFILE BB'

Figure 4. Subsurface density structures obtained from the modeling of three gravity profiles: (a) AA' profile, (b) BB' profile, and (c) CC' profile. Abbreviations are as follows: CP, Coastal Plain, WF, Western Foothills, HR, Hsuehshan Range, BR, Backbone Range, LV, Longitudinal Valley, and CR, Coastal Range.

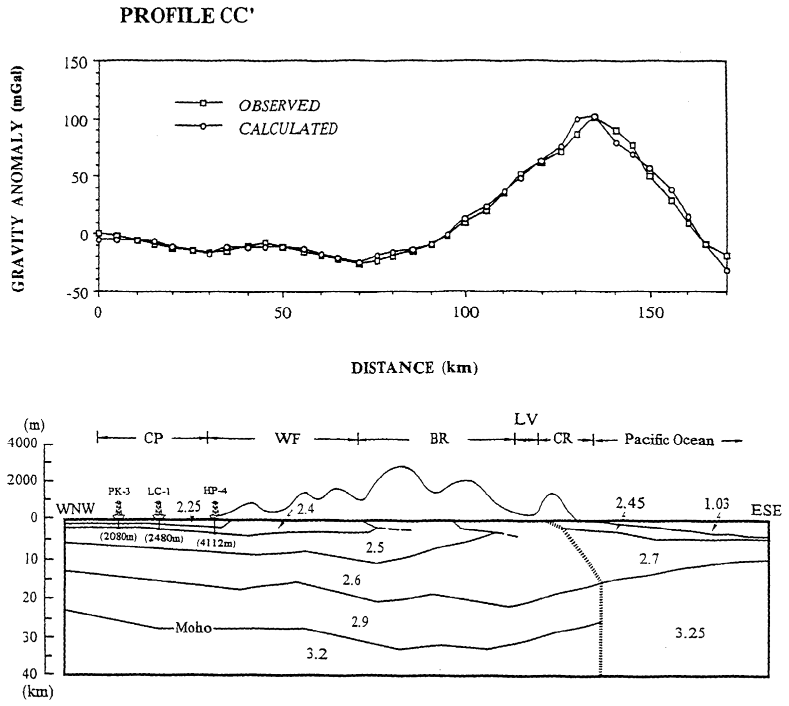


Figure 4. (continued)

middle of the TB. Farther east, we observe that the high negative Bouguer values do not diminish although the Neogene sedimentary rocks grade into exposures of denser, lightly metamorphosed Paleogene sandstone and slate. Hence the Paleogene rocks have been thrust westward a distance of 20 km over the Neogene units. This inference based on the modeling explains the lowest Bouguer anomaly on Taiwan. The depth of the continental Moho is 24-28 km under the Coastal Plain and the Western Foothills and 29-33 km under the Central Range. The topography here has only one peak, located in the zone of steep Bouguer gradient. The continental Moho is convex upward underneath this peak. The oceanic crust thickens as it approaches the collisional boundary, reaching up to 20 km, and the high-density oceanic mantle is juxtaposed with the lower-density crustal rocks; both factors contribute toward the high Bouguer gradient in this area. This transition is interpreted as the contact of the Philippine Sea Plate and Eurasian Plate. The striking gravity low at the eastern side of the profile is caused by the Hualien Canyon, filled with recent sediments [*Lin*, 1994].

3. The profile CC' is from the Peikang basement high to Chengkung which has the highest anomaly value on the island. The depth of the continental Moho shows a shallowing toward both sides of this section (Figure 4c). The depth of the continental Moho is 24-28 km in the Coastal Plain, 28-30 km in the Western Foothills, 31-33 km in the Central Range, and 28 km underneath the Coastal Range in eastern Taiwan. The thickness of the oceanic crust here is about 15 km. The higher anomalies along this profile in comparison with those of profile BB' may be caused by the thinner oceanic crust. The contact of the Philippine Sea Plate and the Eurasian Plate causes the Bouguer anomaly to rise sharply.

The results of the subsurface structure modeling in this study can be summarized as follows: (1) The lowest Bouguer anomaly is caused by the presence of a sedimentary basin. (2) The depth of the continental Moho reaches a maximum of 33 km beneath the Central Range and is shallower on both sides; the average depth of the continental Moho is 26 km under the Coastal Plain and the Western Foothills and is 28 km underneath the Coastal Range in eastern Taiwan. (3) The contact of the Philippine Sea Plate and the Eurasian Plate is inferred to lie under the Coastal Range. (4) Beneath the Coastal Range, the thickness of the oceanic crust in the south is thinner than in the north. (5) The distribution of the Bouguer anomalies and the modeled subsurface structures do not clearly reflect the topographic variations.

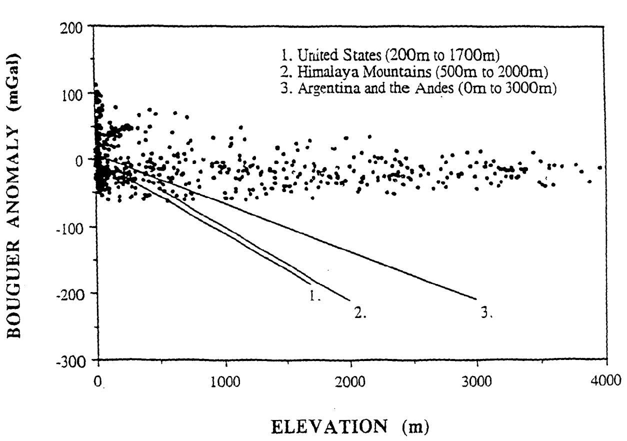


Figure 5. Plot of Bouguer anomalies with respect to station elevations. Three lines represent the relation of 1° × 1° mean Bouguer anomaly to mean elevation in different areas [*Woollard*, 1969].

5. Isostatic Adjustment Under Taiwan and Mountain Building

We have already observed that the highest topographic peaks are located in the transition zone where the Bouguer anomalies increase sharply toward the east. According to an antecedent study by *Yen et al.* [1990], it is quite clear that the free-air anomalies closely mimic the topography, but in contrast, the Bouguer anomaly map does not show any significant correlation with elevation [*Yen et al.*, 1995b]. Figure 5 shows the general relation between elevation and Bouguer anomaly at the 603 stations. The lack of correlation between these two quantities, in comparison to the negative correlation between Bouguer anomalies and mean elevation (in 1°x 1° area) on a world-wide basis for areas having attained various degrees of isostatic equilibrium, clearly indicates that Taiwan is quite far from this state.

When the equilibrium is under the Airy hypothesis with isostatic support at the Moho, the incremental crustal thickness should be [e.g., *Sharma*, 1986]

$$h_a = h \cdot \left(\frac{\rho_c}{\rho_m - \rho_c} \right)$$

where h is the elevation above sea level, ρ_c is the average crustal density, and ρ_m is the density of the substratum. If ρ_c for the average crustal column is taken to be 2.57 g/cm^3 which is equal to the Bouguer reduction density and ρ_m for the mantle is 3.2 g/cm^3, then $h_a = 4 \times h$. Figure 6 shows adjusted crustal thickness variations according to the Airy model. It is clear that the present maximum thickness of 33 km derived from seismic modeling and consistent with the gravity data is quite a bit thinner than that obtained by the Airy model. It can be concluded that the isostatic adjustment has not been achieved in the Taiwan region. Although there is evidence that a nascent root is present, it is certainly not well developed. The state of disequilibrium is most probably related to the fact that the mountains are so young that the crust has not yet had time to respond.

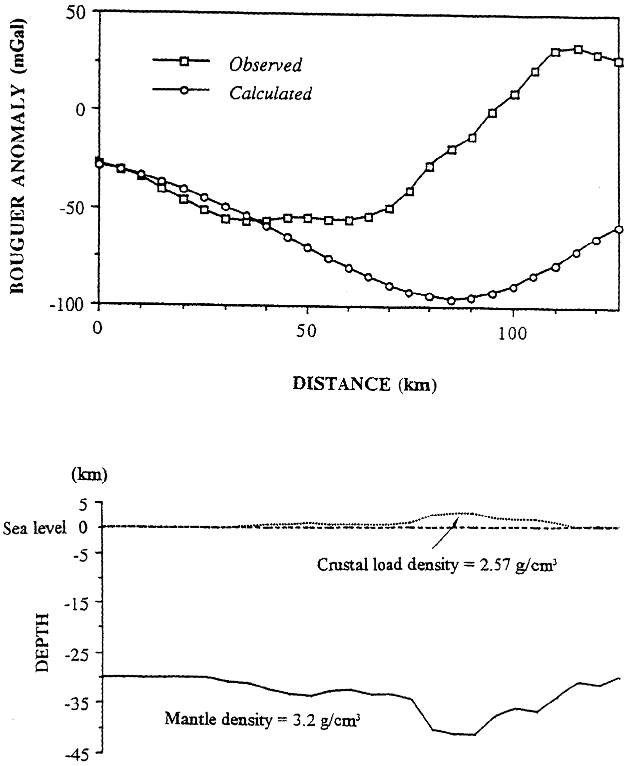


Figure 6. The gravity effect of the adjusted crust according to the Airy model along profile BB'.

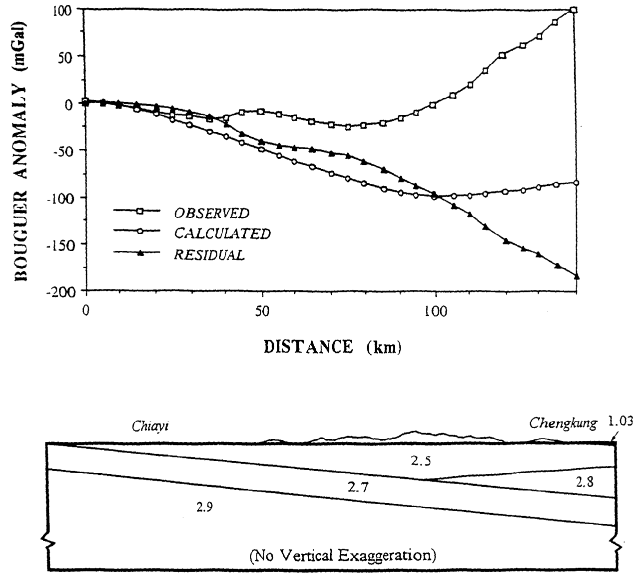


Figure 7. Gravity effect of the double-sided wedge model and the difference between the observed and the calculated values. The crustal structure is redrawn from *Suppe* [1981].

This new gravity data set allows for the testing of the commonly cited mountain-building model of Taiwan as proposed by *Suppe* [1981], since his model (Figure 7) can be assigned densities. Inherent in this model are the assumptions that an eastward subducting continental lithosphere decollement exists and that the mountains were created by deforming the "critically tapered wedge" made out of Tertiary and Quaternary sedimentary deposits [*Dahlen et al.*, 1984]; the materials below the decollement are not subject to deformation. Furthermore, in the model, the Coastal Range is viewed [*Suppe*, 1981] as a wedge of oceanic crust that is being pushed under the Tertiary sediments, as shown in the model cross section from Chiayi to Chengkung (Figure 7). Translating this model to a two-dimensional density profile by assuming reasonable densities (Table 2), we obtain the results shown in Figure 7. Since the observed and calculated Bouguer anomalies are quite different, we conclude that this relatively simple model does

Table 2. Assumed Densities for Testing *Suppe*'s [1981] model

Layers	Density, g/cm^3
Fold and thrust belt	2.5
Upper crust	2.7
Lower crust	2.9
Philippine Sea Plate	2.8

not agree with the gravity data. Because the crust has thickened somewhat, the deeper part of the lithosphere must have participated in the mountain-building process.

6. Conclusions

The subsurface density structures along three profiles across the major structural trends are obtained from a newly constructed Bouguer anomaly map. The depth of the continental Moho is a maximum of 33 km beneath the Central Range and is shallower on both sides; the average depth of continental Moho is 26 km under the Coastal Plain and the Western Foothills and is 28 km underneath the Coastal Range in eastern Taiwan. The lowest Bouguer anomaly (down to -60 mGals) in west central Taiwan is caused by the presence of a sedimentary basin. The high positive anomalies in eastern Taiwan may be caused by the oceanic crust. The contact of the Philippine Sea Plate and the Eurasian Plate is inferred to lie under the Coastal Range.

The Bouguer anomalies do not show any significant correlation with elevations (Figure 5). Furthermore, the distribution of Bouguer anomalies and the modeled subsurface structures do not clearly reflect the topographic variations. These results all point to the fact that the young mountains in Taiwan are not in isostatic equilibrium. Further details of the depression in the Moho as well as the timing of the rise of the Central Range will be useful in modeling the whole mountain-building process in terms of mechanical deformation and the viscoelastic response of the crust.

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