A Regional Gravity Map for the Subduction-Collision Zone Near Taiwan

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ABSTRACT

To delineate the tectonic character of the subduction-collision zone in the marine area near Taiwan, we have constructed a regional gravity map by reconciling the shipboard data of 15 cruises that have surveyed the region of 20-26°N and 119-124°E over the past 20 years. Among the 15 cruises, three have known, reliable base-tie information. The absolute level for the other 12's cruises are adjusted in such a way that their crossover errors with respect to the other three are minimized. The root-mean-square difference of the totally 865 crossovers in the final data set is 6.0 mgal, representing an acceptable quality considering the multi-agency nature of the source and the rugged seafloor. The distribution of the ship tracks is uneven, with the better resolution around Taiwan but a progressive undersampling toward the east and northwest. To make a regional map, we interpolate both the marine data and the 640 free-air anomaly measurements on Taiwan and its offshore islands into 5 minute spaced grids using a minimum curvature technique. The SEASAT altimetry derived gravity values are placed on part of the map's boundary as an additional constraint in the minimum curvature calculation. On the map, the free-air anomaly ranges from -250 to 350 mgal, primarily reflecting the topography, with the maximum and minimum at the high mountains of Taiwan and the Ryukyu Trench-Taiwan intersection, respectively. The Lutao-Lanyu 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. The Hengchun Ridge shows a much more

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subdued gravity anomaly than that of the volcanic arc at a similar elevation. The map also delineates the North Luzon Trough as a forearc basin to the west of the arc, the Nanao Basin at the Ryukyu Trench, and to a less extent the Gagua Ridge at 123°E. To illustrate how the marine gravity data constrain crustal structure, a 2-D gravity analysis is performed with a free-air anomaly profile across the Ryukyu Trench taken from this map.

(Key words: Crossover errors, Free-air anomaly)

1. INTRODUCTION

Gravity measurement and analysis are particularly useful as a reconnaissance mapping tool for a large tectonic region. On the island of Taiwan, over 600 gravity stations have been established during the past few years (Yen et al., 1990), and models of isostasy and crustal structure of the island are explored using this data set later. This modeling work is, however, restricted by the short horizontal dimension of the island, which is about 100 km across the main structural trend, leaving the upper mantle properties unconstrained. On the other hand, the most important tectonic fabrics pertaining to the subduction-collision system, such as the volcanic arc, accretionary wedge and oceanic trenches, are present under seas. A high resolution marine gravity map is required to help decipher their tectonic signature (Figure 1). There is, therefore, a need to compile a gravity map that emcompasses the entire collision-subduction tectonic region. This task was not possible until recently because of a few cruises with reliable base ties placing dense tracklines of gravity observations offshore Taiwan. In 1984, the French launched two cruises, the POP 1 and 2, primarily surveying the Okinawa Trough and the Manila Trench, and providing some constraints in the vicinity of Taiwan (Sibuet et al., 1987). Additionally, in 1990, the U.S. ship R/V Moana Wave achieved a reconnaissance mapping in southern offshore with the cruise MW9006, covering major undersea ridges and troughs there with east-west traversing lines. Both of these recent shipboard measurements are accurately calibrated at land stations in the IGSN 71 system, facilitating the construction of a regional map that includes both land and marine data.

The strategy in this study for the construction of the regional map is to search for good quality shipboard data, with or without base-tie, and calibrate them via crossing a common, well base-tied cruise. Most data are retrieved from the archive of the National Geophysical Data Center (NGDC) in the National Oceanic and Atmospheric Administration (NOAA), United States. The NGDC archive receives geophysical data from contributing institutions world-wide and currently holds marine gravity data from as far back as early 1960. Because for most cruises information of base-tie is not clearly documented, it has to be tied to the 3 cruises mentioned above through the crossover analysis. Cruises with isolated tracklines that barely intercept others in and around the region of study were dropped. Under this strategy, most gravity lines are tied to the MW9006 in the southern area and to the POP 1 and 2 to the northeast of Taiwan. We include the land-based data to complete a regional map, but this paper focuses on describing the compilation of the marine gravity data. In the following, we introduce how we adjust each cruise's absolute level, give examples of the adjustment, and show a simple modeling work with a gravity profile taken from the final product of this study.
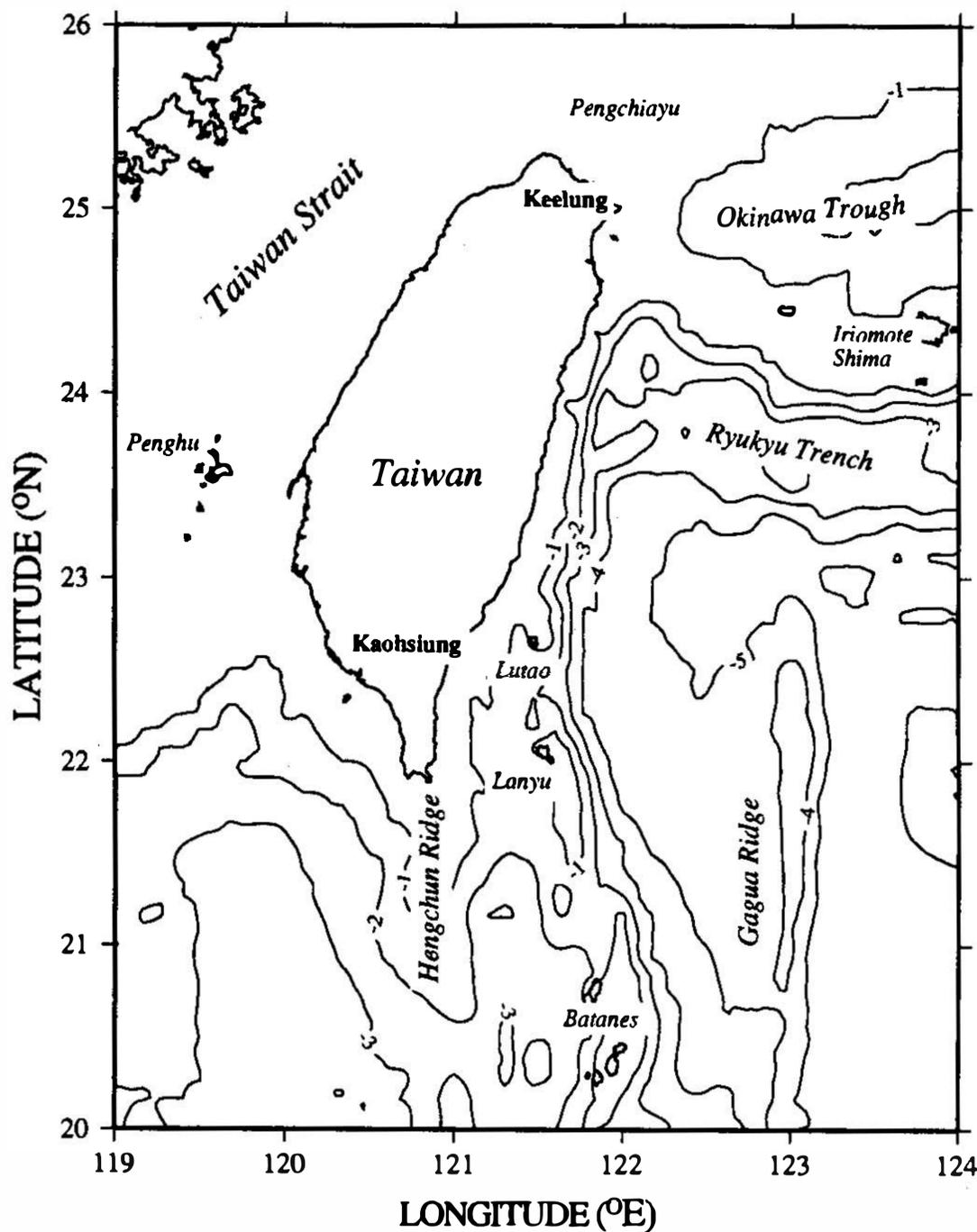
Fig. 1. The topography/bathymetry map of the subduction-collision zone of Taiwan, taken from the global data set ETOPO 5. The global data set lacks the detail resolution for the Taiwan area and is contoured at 1000 m interval to only depict the main tectonic elements described in this paper.

2. THE MARINE DATA

There are several tens of cruises in the NGDC archive that have underway gravity recordings in the area between 20 and 26°N and 119 and 124°E. Those with obvious noise, large time gaps and suspicious glitches or drift in the digital records are first rejected. All the acceptable cruises were post 70's, meaning that the navigations were at least dead reckoning with the Transit satellite or GPS fixes. Any cruise without a base tie is useful only if it yields consistent crossover differences with all intercepting, calibrated cruises. This means that for the crossover differences, the root-mean-square (rms) deviation from the mean must be small compared to the mean itself. Fifteen cruises, including 13 from the NGDC and 2 from the Chinese Petroleum Corporation, are retained as suitable for this study (Table 1). As the quality of navigation and measurement varies from cruise to cruise, the accommodation process starts with what is believed to have the highest quality and known, reliable base ties: the MW9006 and POP 1 and 2. We then include the Japanese cruises for which the base-ties must be corrected. Data from other cruises are last to be incorporated.

Table 1. Cruises used in this study.

Cruise	Year	Operating Agency	Country
DME06	1971	Academy of Science	USSR (Former)
C1404	1971	Lamont-Doherty Geological Observatory	USA
V2817	1971	Lamont-Doherty Geological Observatory	USA
C1710	1974	Lamont-Doherty Geological Observatory	USA
KH7605	1976	University of Tokyo	Japan
C2006	1976	Lamont-Doherty Geological Observatory	USA
DME24	1980	Academy of Science	USSR (Former)
V3613	1980	Lamont-Doherty Geological Observatory	USA
CPC	1982	Chinese Petroleum Corporation	ROC
POP1	1984	IFREMER	France
POP2	1984	IFREMER	France
HT8402	1984	Hydrographic Department	Japan
HT8403	1984	Hydrographic Department	Japan
MW9006	1990	University of Hawaii	USA

2.1 MW9006 and POP 1, 2

The ship tracks of the MW9006 with useful gravity recording is shown in Figure 2. The survey covers the main tectonic elements of the arc-continent collision such as the Hengchun Ridge, a believed submarine accretionary wedge (e.g., Reed *et al.*, 1992), the North Luzon Trough as a forearc basin and part of the Manila Trench and Lutao-Lanyu volcanic arc (Figure 1). The cruise is base-tied at the Kaohsiung Harbor in the IGSN 71 system and navigated with GPS fixes for over 1/3 of the time each day. The digital recording is given each minute. The Eötvös correction is calculated by averaging the ship's heading and speed over a 5-minute window and applied to the gravity readings with a 5-minute latency. The corrected values of the readings are then referenced to the GRS 67 to obtain the free-air anomaly (FAA). When the ship makes a turn, the gravimeter is disturbed, which takes 10-15 minutes to settle down. Thus, the data in this time window during a large course change (Figure 2) are discarded. The cruise has 122 internal crossing points, and the mean (μ) of the crossover errors is virtually zero with a root-mean-square deviation from the mean (ε) of 4.0 mgal (Figure 3). There is no identifiable variation in the crossover errors with time, indicating no significant drift of the instrument (Figure 3). In fact, the gravimeter had been calibrated at Guam two weeks before the ship heaved to Kaohsiung; no gravimeter drift had been detected during that period. Some crossover errors exceed 10 mgal, most of which occur at steep bathymetric slopes, e.g., the wall of the North Luzon Trough or the Lutao-Lanyu volcanic arc. An ε of 4.0 mgal represents good accuracy considering that it surveys a high relief region and that many tracks cross each other at sub-parallel angles. This cruise, therefore, serves to tie other intercepting cruises charting the same area.

Another major data set in the vicinity of Taiwan is the 1984 French cruise POP 2 (Figure 2). With a base-tie at Keelung, a port in northern Taiwan, and for its 56 internal crossovers, μ=0 and ε=4.6 mgal (Figure 4). Similar to the MW9006, no obvious drift in the gravimeter is seen from the crossover errors as a function of the separation time.
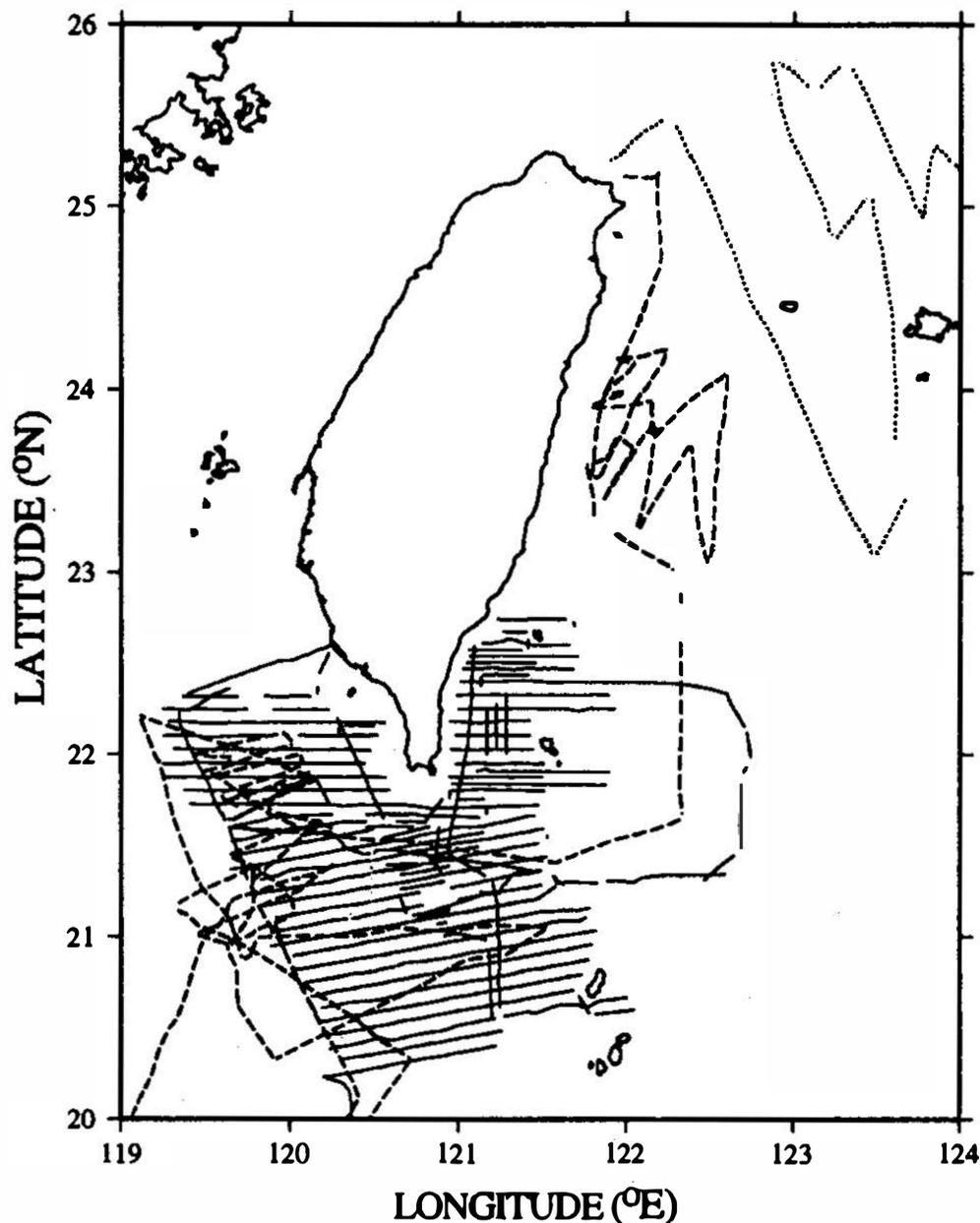
Fig. 2. Ship tracks with useful gravity data of the MW9006 (solid), POP 1 (dotted) and POP 2 (dashed). Data at large course changes were eliminated for the instrument disturbance. These tracklines form a basis for determining the absolute constant of other cruises.

There are 86 crossings between the MW9006 and POP 2, for which μ=0.2 and ε=4.3 mgal (Figure 5). This implies that these two data sets are calibrated to the same absolute gravity system. Although the POP 1 does not cross the POP 2 or MW9006, it was also base-tied at Keelung and we believe that the POP 1 has the same quality as the POP 2. This is verified in the following paragraph.

2.2 The Japanese Cruises

We include 3 Japanese cruises which primarily surveyed the Ryukyu Trench and Okinawa Trough (Figure 6). Two of them, the HT8402 and HT8403, reportedly have conducted base-tie at the port of Tokyo. The HT8402 has 59 internal crossings, with μ=0.0 and ε=4.6 mgal, and the HT8403 has 50 internal crossings; μ=-0,5 and ε=7.3 mgal. For the 130 crossovers between the two cruises, μ=2.2 and ε=5.4 mgal. We believe that they are consistent with each other because μ is not statistically different from zero although their common absolute level is not known. As these two Japanese cruises do not intercept the MW9006 and POP 2, the third Japanese cruise, the KH7605, which crosses all four of them (Figure 6) has to be taken advantage of. The crossover calculations for the KH7605 with respect to HT8402, HT8403, MW9006 and POP 2 show that μ=14.2, ε=3.5; μ=12.0, ε=5.6;

Monna Wave Cruise
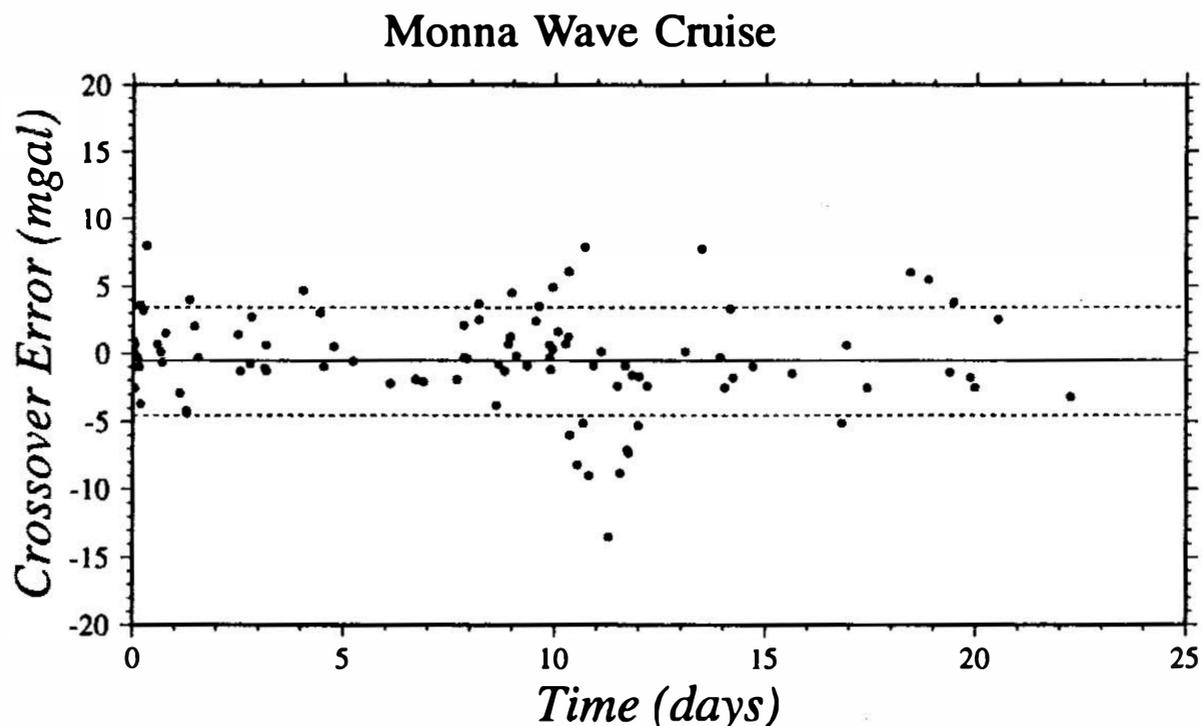
Fig. 3. Internal crossover errors of the MW9006 versus the separation time between two crossing tracks. The crossover errors show no systematic variation with time, implying no drift in the gravimeter. The mean (μ) (horizontal solid line) of the 122 crossover errors is nearly zero, and the rms deviation from the mean (ε) is 4.0 mgal (horizontal dashed lines). These statistics represent a high quality of navigation and measurements.

POP2 Cruise
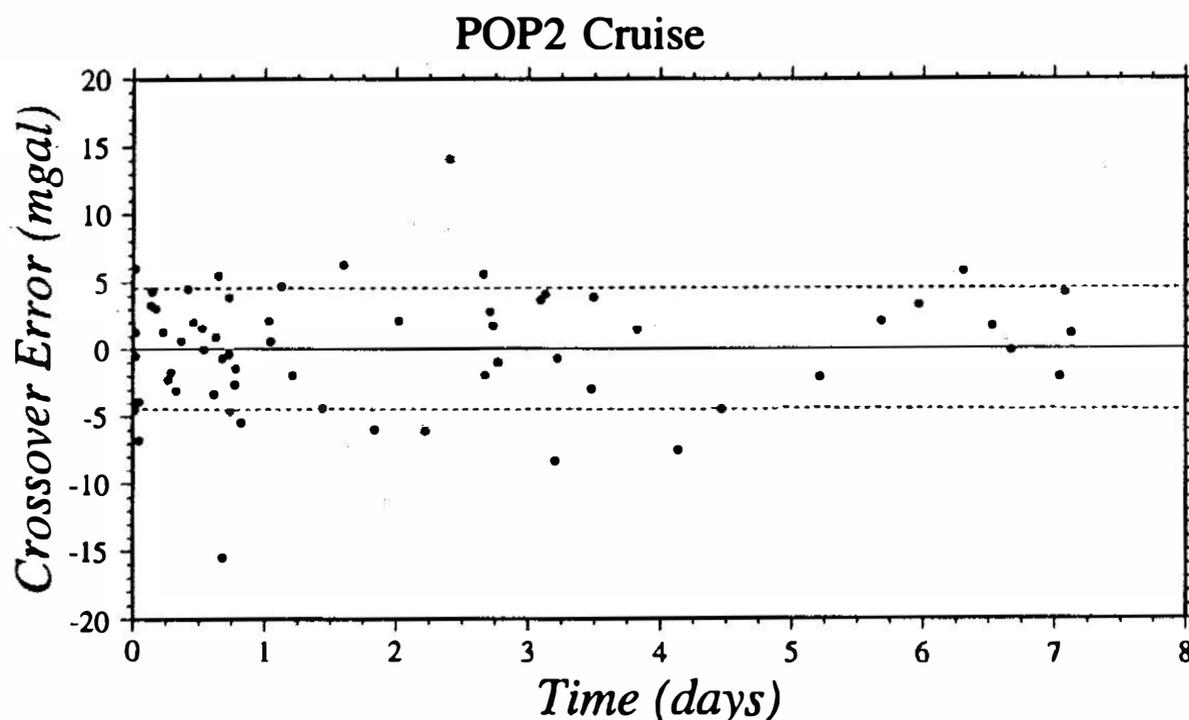
Fig. 4. Internal crossover errors of the POP 2. No drift of the meter can be seen from this plot. The horizontal solid line denotes the mean (μ=0.1), and the two dashed lines the rms error bound (ε=4.6 mgal). Some high crossover errors occur over the western Ryukyu Trench where the gravity and bathymetry show high slopes of change.

μ=8.1, ε=6.7; and μ=8.3, ε=4.3 mgal, for 6, 9, 32 and 8 crossing points, respectively. Although these statistics are not quite satisfactory, the result suggests that the FAA of the KH7605 is consistently misplaced at a higher level than the HT8402 and HT8403 by about 12-14 mgal and than the MW9006 and POP 2 by roughly 8 mgal. Taking HT8402 and HT8403 as one group and MW9006 and POP 2 as another, the means of the
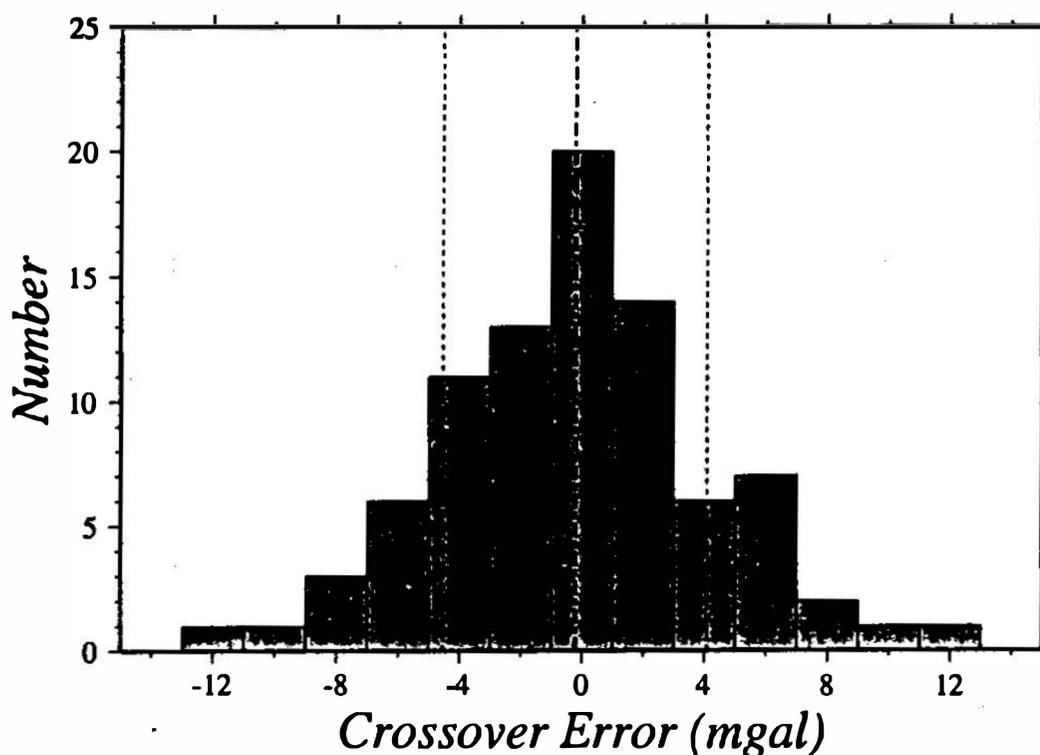
Fig. 5. Histograms of the 86 crossover errors between the MW9006 and POP 2. The solid line marks the mean (μ=0.2), and the two dashed lines the rms errors (ε=4.3 mgal).

differences for the two groups are 12.8 and 7.9 mgal. Therefore, it is determined that the HT8402 and HT8403 must be shifted upward by 4.9 mgal, and that the KH7605 downward by 7.9 mgal in order to join the MW9006 and POP 2 at the GRS 67 system. The corrected HT8402 and HT8403 together yield 18 crossings with the POP 1, showing μ=0.4 and ε=2.8 mgal, which suggests that the POP 1 has the same quality as the POP 2. The POP 1 is thus used to calibrate other cruises in the next category.

2.3 Other Cruises

In this category cruises have relatively isolated tracks, usually with few internal crossings and no base-ties. Two former cruises of the Soviet Union (FSU), two of the Chinese Petroleum Corporation (CPC) and five of the U.S. were collected. The tracklines of the FSU's cruise DME24 are shown in Figure 6, and the adjustment of its data level is illustrated in Figure 7. The DME24 crossesth e MW9006 at 5 points and the POP 1 at 5 points east of 124°E, together yielding a mean and rms error of 49.7 and 6.3 mgal. We therefore subtract 49.7 mgal from the DME24 data. The DME24 also intercepts the HT8402 and HT8403 together at 15 points. After the corrections are made to them, the DME24, and the 2 Japanese cruises give μ=0.4 and ε=5.0 mgal, casting a self-consistent system. The reason the Japanese cruises are not used to determine the DME24's level is that the Japanese cruises are themselves dependent on the MW9006 and POP 2. After a shift of 49.7 mgal, the DME24 yield much more reasonable crossovers with other isolated cruise tracks than before.

It is worth noting that two survey cruises of the Chinese Petroleum Corporation, the CPC 1C and 1F, 1982, are analyzed and included (Figure 8). The original digital data of the 1C and 1F are FAA at an unknown absolute level. As the data acquisition/processing of the 1C and 1F were completed by the same group of contractors (Western Geophysical Company/EDCON), it is assumed that the 1C and 1F have been referenced to the same absolute value, and they are considered as one data set despite their geographic separation. For the summed 78 internal crossovers, μ=0.0 and ε=0.2 mgal (Figure 9). The apparent
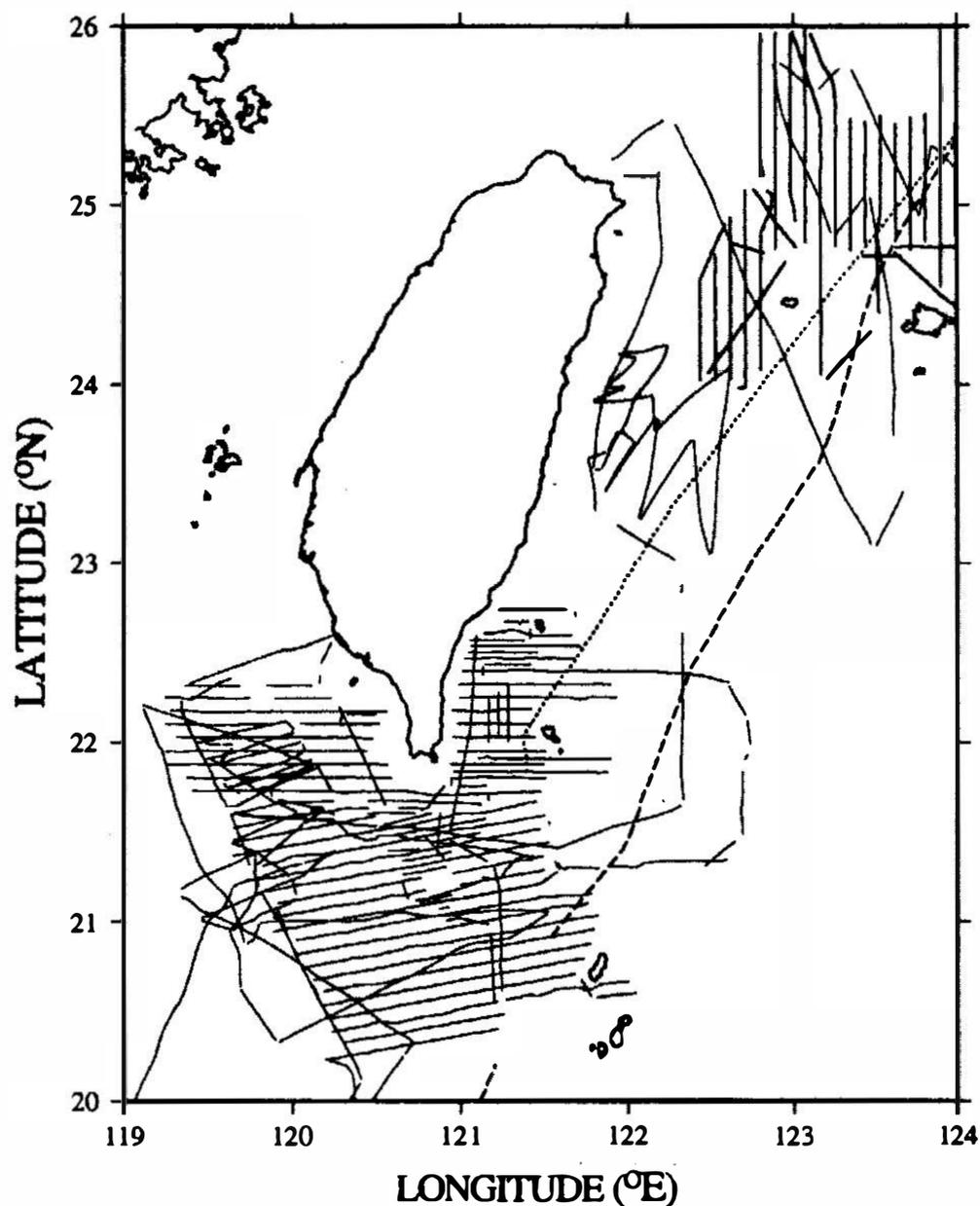
Fig. 6. Tracklines of the MW9006, POP 1 and 2 (thin lines), the same as in Fig. 5 and the HT8402, and HT8403 in the northeastern area (thick), KH7605 (dotted) and the DME24 (thick dashed). Although the HT8402 and HT8403 do not cross either the MW9006 or POP 2, they are tied to the MW9006 through the long track of the KH7605. This leads to the corrections to all three Japanese cruises. The corrected Japanese cruises are also consistent with the POP 1. The DME24 crosses the MW9006 at 5 points and the POP 1 at another 5 out of the map area. Its correction is shown in Fig. 7.

high performance is primarily due to the relatively quiescent sea and the nearly featureless seafloor in the Taiwan Strait. While the 1C is completely isolated, the 1F barely crosses the MW9006 at 7 points, showing μ=-47.2 and ε=2.6 mgal (Figure 8). Thus, 47.2 mgal is added to the data of both the CPC 1C and 1F. This correction is justified by the fact that the corrected CPC 1F crosses the C1710 at 18 points with μ=1.5 and ε=2.0 mgal.

Other cruises are adjusted depending on their crossover errors with the MW9006, POP 1 or 2 in the same manner, but are not described in detail here. All the gravity tracklines used in this study are shown in Figure 10. There are totally 865 crossovers, and the rms difference is 6.0 mgal. This represents a reasonably good quality for the marine data considering that all different data sets collected in the past two decades by a variety of agencies have been put together. Although it is believed that some cruises in the 70's may have had lower quality of data due to relatively poor navigation or less sophisticated recording systems, the crossover

DME24 Cruise
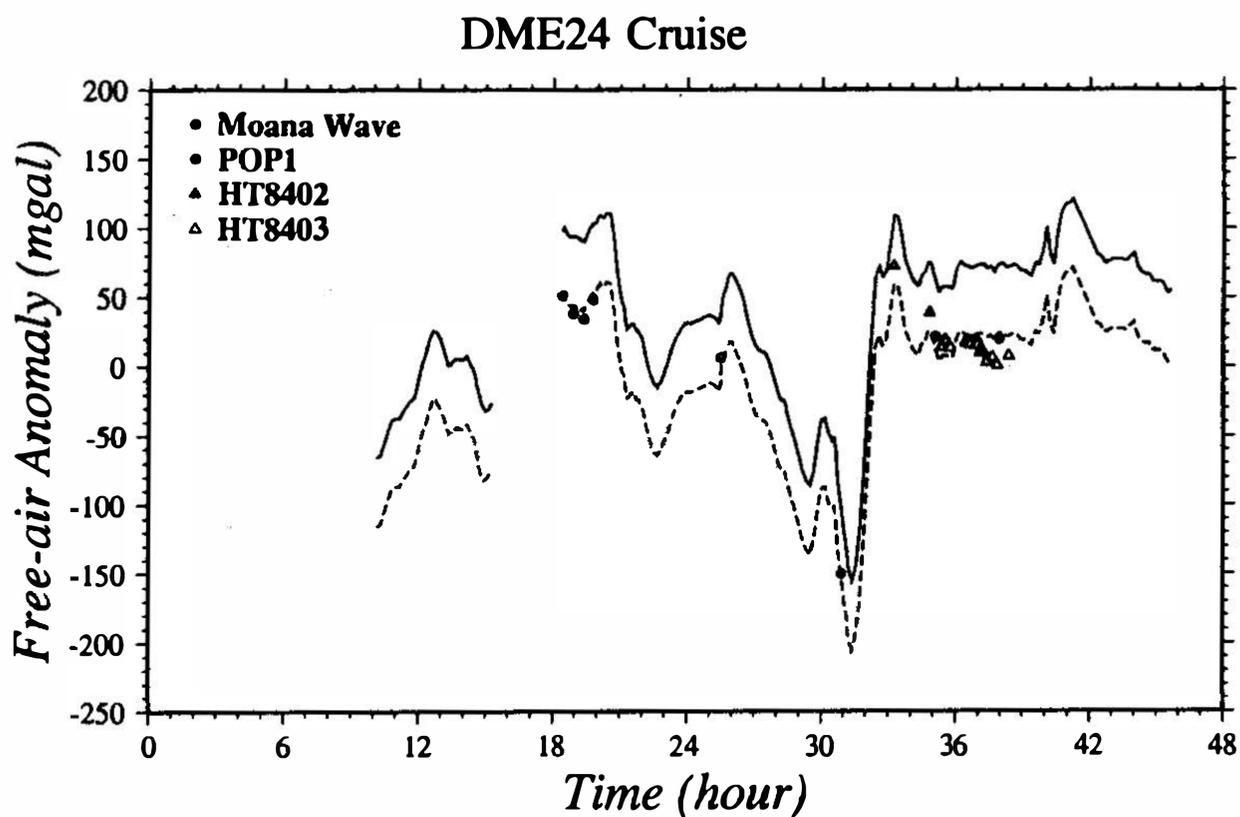
Fig. 7. The FAA along the track of the DME24 with increasing time toward the north-northeast (Fig. 6). Time zero is arbitrarily set. After a downward shift of 49.7 mgal, the data of the DME24 match the MW9006 (solid square) and POP 1 (solid circles). Crossing values of the HT8402 and HT8403 are plotted to justify the shift although these crossover errors are relatively scattered.

analyses suggest that their data after a constant shift fit quite well with the data of the more recent cruises. Therefore, the 6.0 mgal should be a fair, representative quality measure for the marine data collected. Variations greater than 12 mgal may be regarded as real at the 95% confidence level, and any variations less than 12 mgal should not be interpreted. Despite the gaps on the map, especially on the eastern half, the ship track coverage shown in Figure 10 is, nonetheless, the most complete to date. Next the marine data are merged with the FAA observations on the island of Taiwan and its offshore islands to complete a regional gravity map.

3. THE MAP

The island-wide, 603 gravity stations have been established by Yen et al. (1990). Since then, several tens of measurements on the offshore islands, such as Penghu, Lutao, Lanyu and Pengchiayu, have been added to the data set. The total 640 land measurements are based on the IGSN 71 and the FAA is referenced to the GRS 67. Land and shipboard data are interpolated together into $1/12°$, or 5 arc minutes, spaced grids using a minimum curvature technique (Smith and Wessel, 1990). To maintain a reasonable extrapolation from the surveyed area toward the map's boundary where no ship tracks are present, the boundary is padded with the SEASAT gravity data (Haxby, 1987). These data, given at $1/4°$ grids, are derived from the SEASAT satellite geodetic mission, and are therefore characterized by relatively smooth variations. Only the map's southeast and northwest corners are allowed and necessary for this artificial treatment. In Figure 11, the contour map at 100 mgal intervals superimposed with the shiptracks is presented, in order to give a clear discrimination as to what features may be artificial. Figure 12 shows the shaded, contoured map at 25 mgal

(a)

(b)

LONGITUDE (°E)
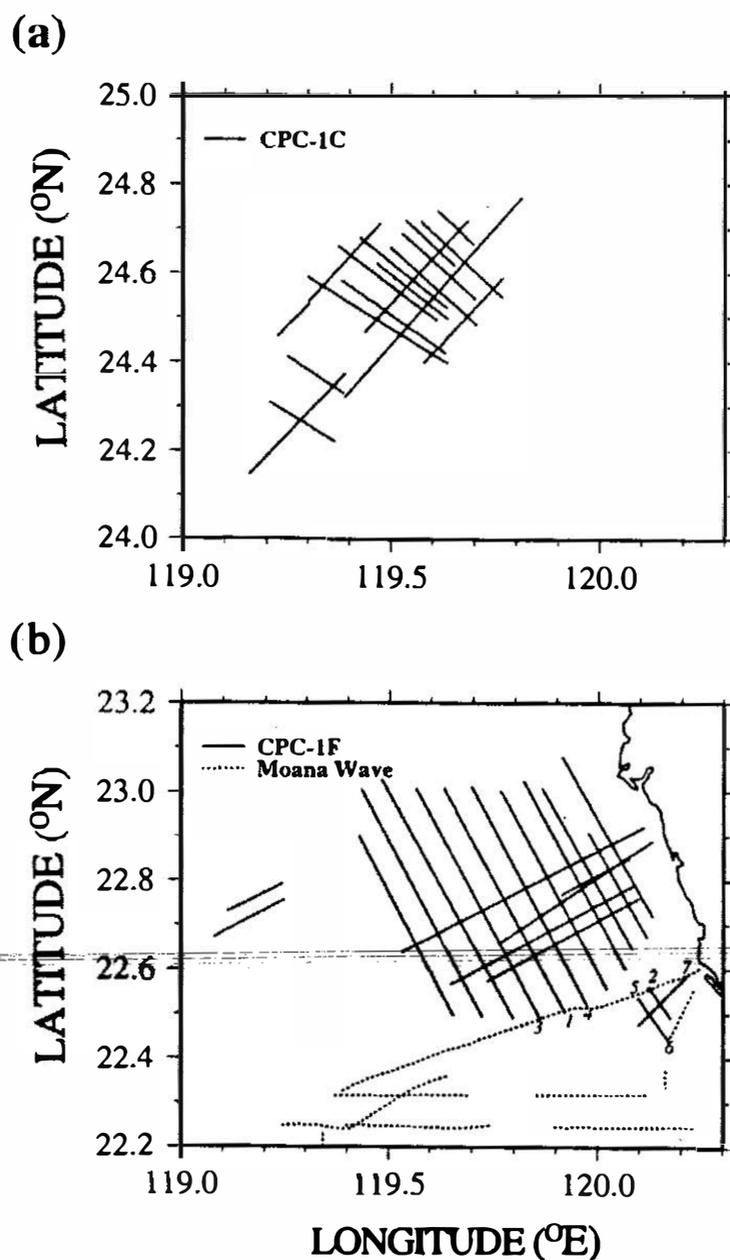
Fig. 8. Cruise lines of the CPC 1C (a) and 1F (b). 1F barely crosses the MW9006 at 7 points, making the determination of the absolute level of the 2 cruises possible.

CPC Data

Time (days)
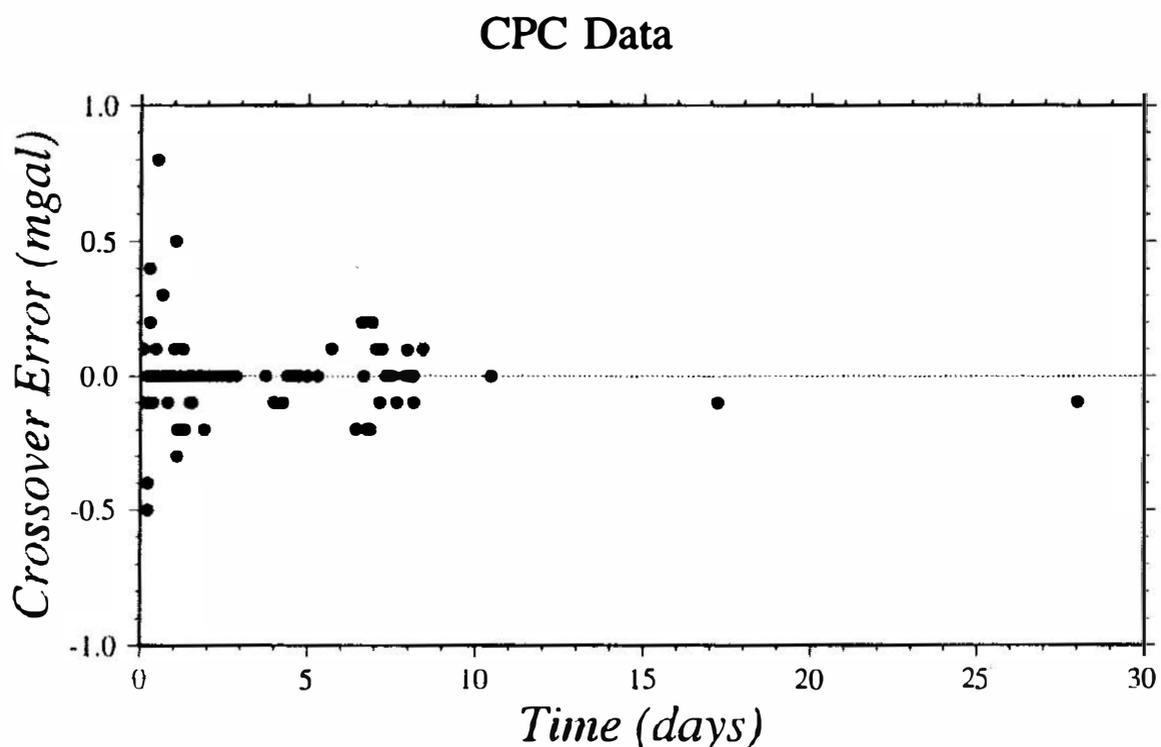
Fig. 9. The crossover error analysis of both the CPC 1C and 1F. The high quality of data (μ=0.2, ε=0.1 mgal) compared with other cruises in this study reflects primarily good sea conditions and little relief of seafloor in the Taiwan Strait as opposed to the southern and eastern offshore.
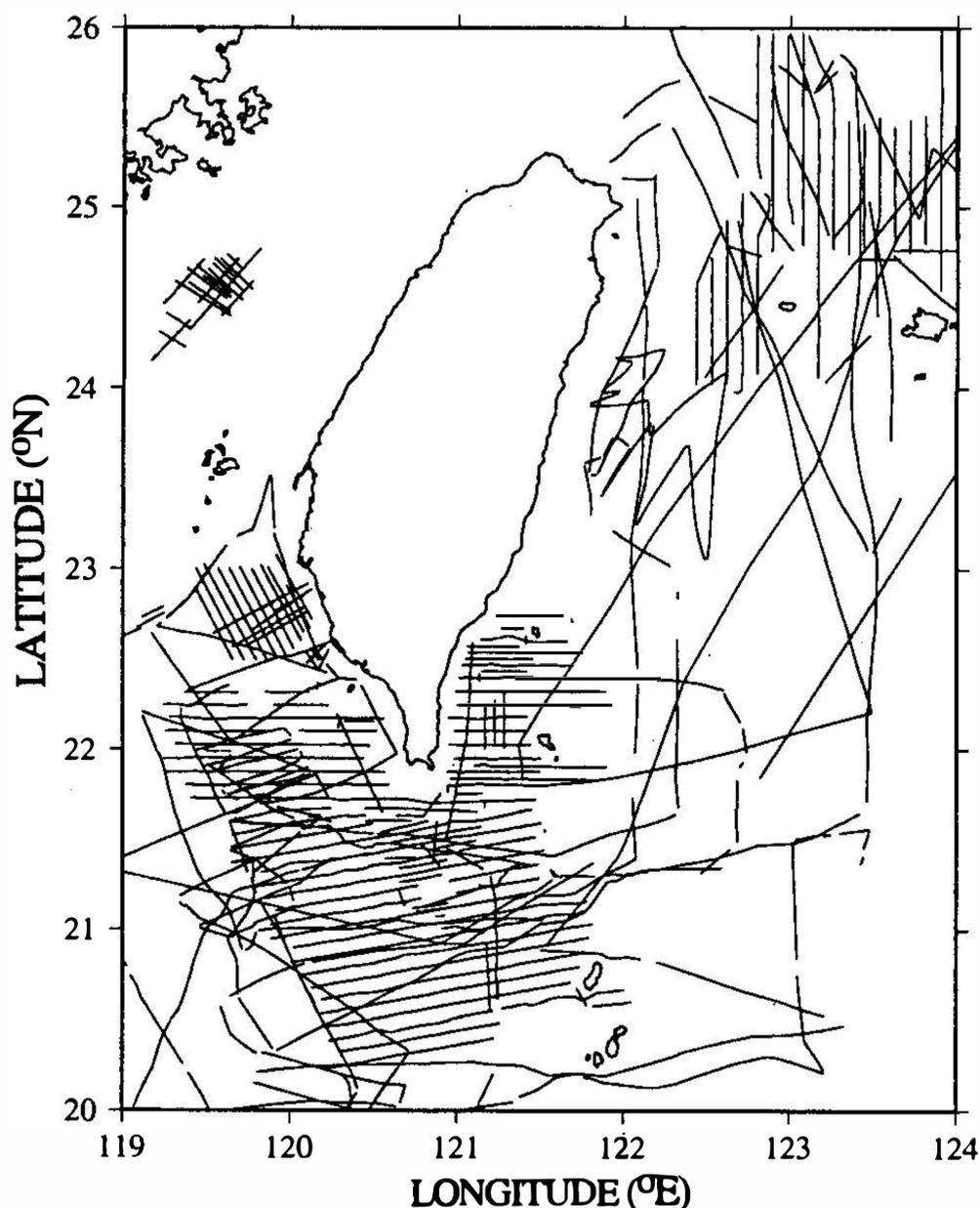
Fig. 10. Ship tracks of useful gravity data of all the cruises analyzed in this study. The uneven sampling for different tectonic zones should be noted. The gravity data on these tracklines are interpolated with land observations into 1/12° grids to complete a regional map. Dots are the SEASAT data used to constrain the extrapolation toward the southeastern and northwestern margins.

intervals to better illustrate the variations of the FAA. We emphasize that deciphering the map should always be done in accompaniment by the trackline chart (Figure 11).

The FAA ranges from about -250 to 350 mgal in this region with the maximum at the Central Range of Taiwan, and the minimum at the western truncation of the Ryukyu Trench against Taiwan. The gravity character on land has been examined and published elsewhere (Yen et al., 1995). Here, we will focus on the description of the marine gravity field. The FAA's variations are dominated by the seafloor topography. The Lutao-Lanyu volcanic arc exhibits an FAA high continuing along the 25 mgal contour from the bottom of the map (20°N) to the Coastal Range in eastern Taiwan (Figure 12). Because there is no observational control on the Batanes, the local maxima there are off the islands, an artifact of interpolation. To the west of the arc, the North Luzon Trough, which is thought to be a forearc basin, is evident as a gravity low. Seismic reflection interpretation indicates that the North Luzon Trough is filled with sediments as thick as 2000 m (Jiang, 1991; Reed et al., 1992), giving rise to a lower FAA than is expected from its bathymetry. The Ryukyu Trench is characterized by a low continuous at the -100 mgal level, lying about 50 km north of the trench. It is a common phenomenon that the lowest gravity anomaly mirrors the crust-crust boundary of
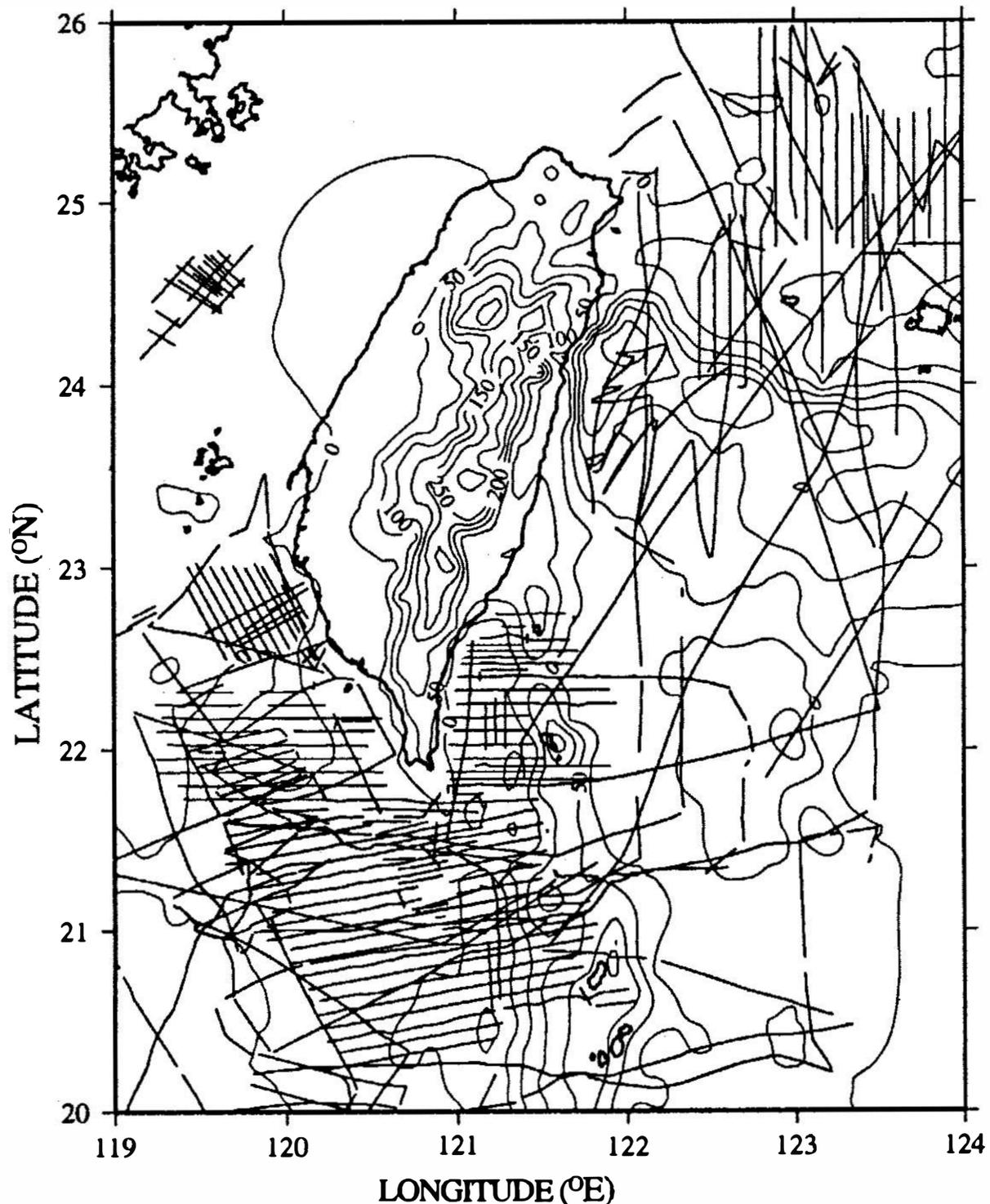
Fig. 11. A contour map with shiptracks superimposed to distinguish the features constrained by shipboard data from those created by interpolation and extrapolation.

the two converging plates, usually beneath the accretionary wedge, rather than the crust-wedge boundary that marks the position of the trench on the seafloor. These overall large-scale features are well constrained by real data. On the northwest corner of the map, the gravity field is almost flat, as a result of extrapolating the data on Taiwan under the minimum curvature requirement guided by the SEASAT data assigned on the Chinese mainland. With the limited resolution east of 122°E, the Gagua Ridge is manifested as gravity highs like hummocks distributed slightly west of the ridge, in contrast to the ridge's physical elongated shape (Figure 1). A roughly north-south oriented low lies to the east of the ridge instead. Although the overall pattern for the Gagua Ridge is constrained by the available shiptracks, more shipboard data are required to delineate a more detailed variation.

There are some interesting features evident from the map. Along the low anomaly zone north of the Ryukyu Trench, three close-contoured lows < -150 mgal, centered at 122°, 122°40' and 123°15'E, appear where the tracklines are concentrated (Figures 11, 12). We, therefore, question whether this is a real pattern or an artifact due to uneven
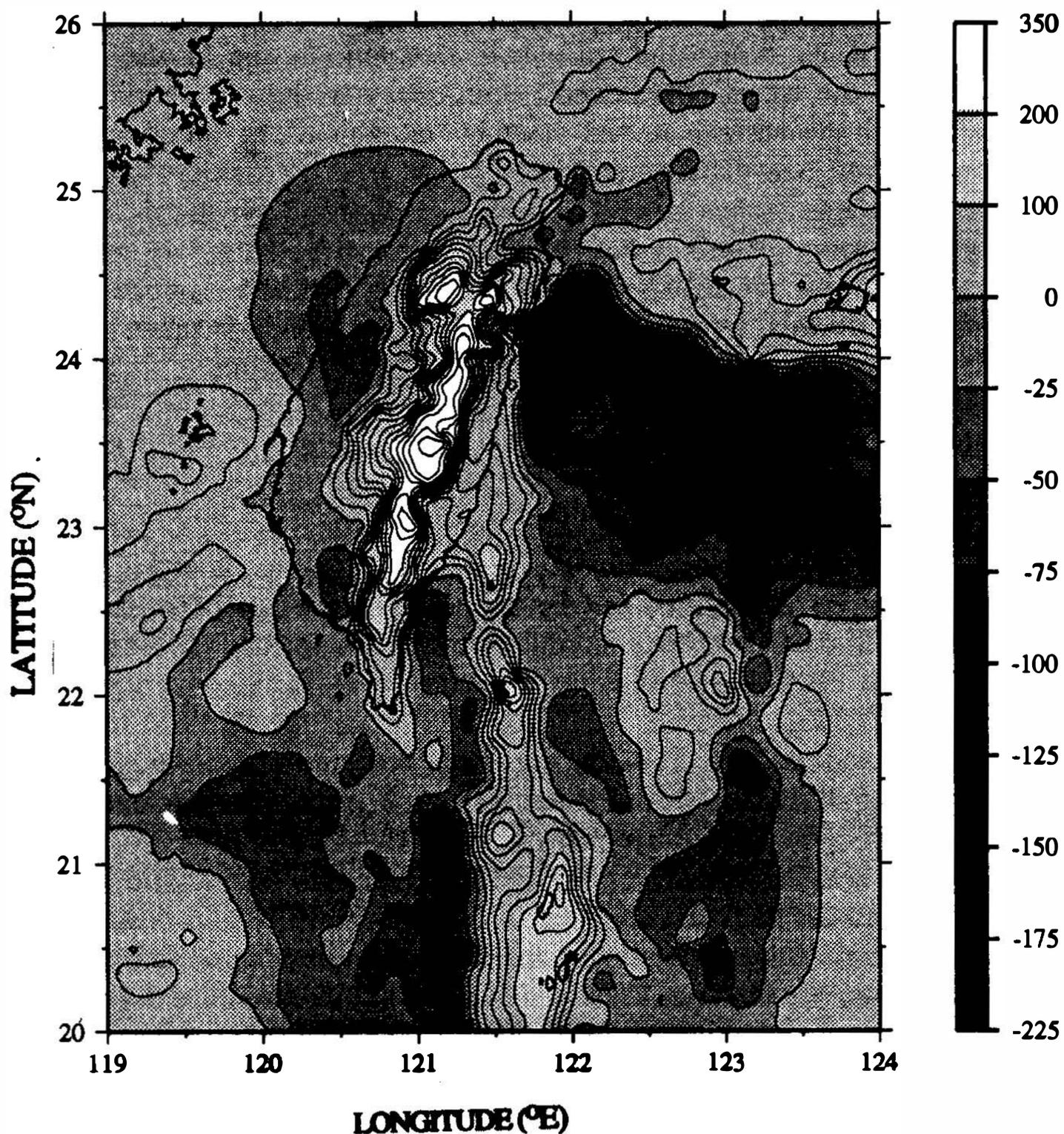
Fig. 12. The regional FAA map of Taiwan contoured and shaded at 25 mgal interval below zero. The Ryukyu Trench is associated with a prominent low north of it. The Lutao-Lanyu arc and the North Luzon Trough are both pronounced features. The Gagua Ridge is delineated as a hummocky high with present shiptracks.

sampling. Although the bathymetric map in Figure 1 does not suggest the presence of the three separated lows, local data are investigated for clues. The high resolution bathymetry map and the seismic profiles of Lin (1994) indicate that the low at 122°40'E corresponds to the Nanao Basin, a close contoured topographic low filled with sediments. This suggests that it is probably a true close-contoured feature. On the bathymetric map compiled by Marsset *et al.* (1987), there are basins centered at both 122°40' and 123°15'E, supporting the presence of the easternmost gravity low too. However, the shape of the easternmost gravity low may be dictated by the extrapolation toward an unprescribed boundary, and therefore still remains to be verified in the future. The 122° low seems to extend southerly for about 50 km to 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. Over the Hengchun Ridge where the seafloor is elevated (Figure 1), the FAA remains low, implying that either the ridge, a believed accretionary wedge, is composed of much low density material near the surface or the crust is "thickened" by attaching the crust of the subducted South China Sea plate underneath (Jiang, 1991). Tackling these issues requires different quantitative approaches as well as a high resolution bathymetric map, making these subjects beyond the scope of this paper. Instead, in the following, we intend to show, with a simple experiment, how the marine gravity data compiled here impose constraints on the crustal structure. To do this, a profile across the Ryukyu Trench is taken from the map, and the 2-D gravity analysis is performed in a simple, forward fashion.

4. DISCUSSION

In this simple experiment, a profile is taken along 122°40'E between 22°40' and 25°20'N (Figure 13a). It should be noted that a 2-D gravity analysis in the vicinity of this longitude cannot be entertained on the trackline data alone because no individul ship tracks in the available data base have straddled the trench for such a long distance between 122 and 123°E. The FAA extracted from the map is, in fact, constrained by the data of the POP 1 and 2, HT8402, HT8403, KH7605, V2817 and the DME24 to different extents. The profile is characterized by a 150-200 mgal low centered at the wedge. The bathymetry is taken from the 3.5 KHz and 60- channel reflection profile demonstrated in Lin (1994). Talwani *et al*'s (1959) method is used to calculate the theoretical FAA for a 2-D density structure. With the non-uniqueness of the modeling under consideration, what is first depicted is a simple crustal structure in which, except for the Nanao basin, only the crustal thickness, or equivalently the geometry of the Moho, is allowed to vary (Figure 13b). This simple model explains the observed FAA to a satisfaction that the fit can be further improved easily with a detailed modification of the geometry of the Moho.

In the second model, we consider a more complicated structure of crust which is meant to reflect the interpretation of the seismic refraction data by Kimura (1986) and the general knowledge about subduction tectonics. The subduction of the Philippine Sea Plate is represented by the underthrusting of an oceanic layer with a density of 3.27 g/cm^3 (Figure 14b). The geometry of the plunging crust is within the resolvable range of the observed seismicity. The model consists of an apparent accretionary wedge as suggested by Kimura (1986). The front half of the wedge is assigned a density of 2.2 g/cm^3, smaller than the rest of the wedge and the marine sediment to simulate its probably unsolidated nature. This, as well as the deeper structure, is arbitrarily assigned anyway. The calculated FAA nearly perfectly fits the data (Figure 14a). In both models, the effect of the cold slab is ignored. This simplication may introduce a significant, long wavelength bias on the position of the Moho or upper mantle properties. In view of the uncertainty of the slab model itself, we rather sacrifice the "reality" to retain the simplicity of the experiment here. The two models represent end members in the spectrum of the non-unique gravity interpretation. While the first model is at odds with the general understanding of the subduction tectonics, the second is probably overparameterized, thus losing its statistical credit. Given the constraints from Kimura (1986), Lin (1994) and the seismicity, the presence of a subducting crust, the Nanao Basin and an accretionary wedge of a slightly low density seem to be justified. A model with these elements, perhaps conceptually between the two styles of modeling in Figures 13 and 14 may be preferrable at the present time. Despite the intrinsic ambiguity in the gravity
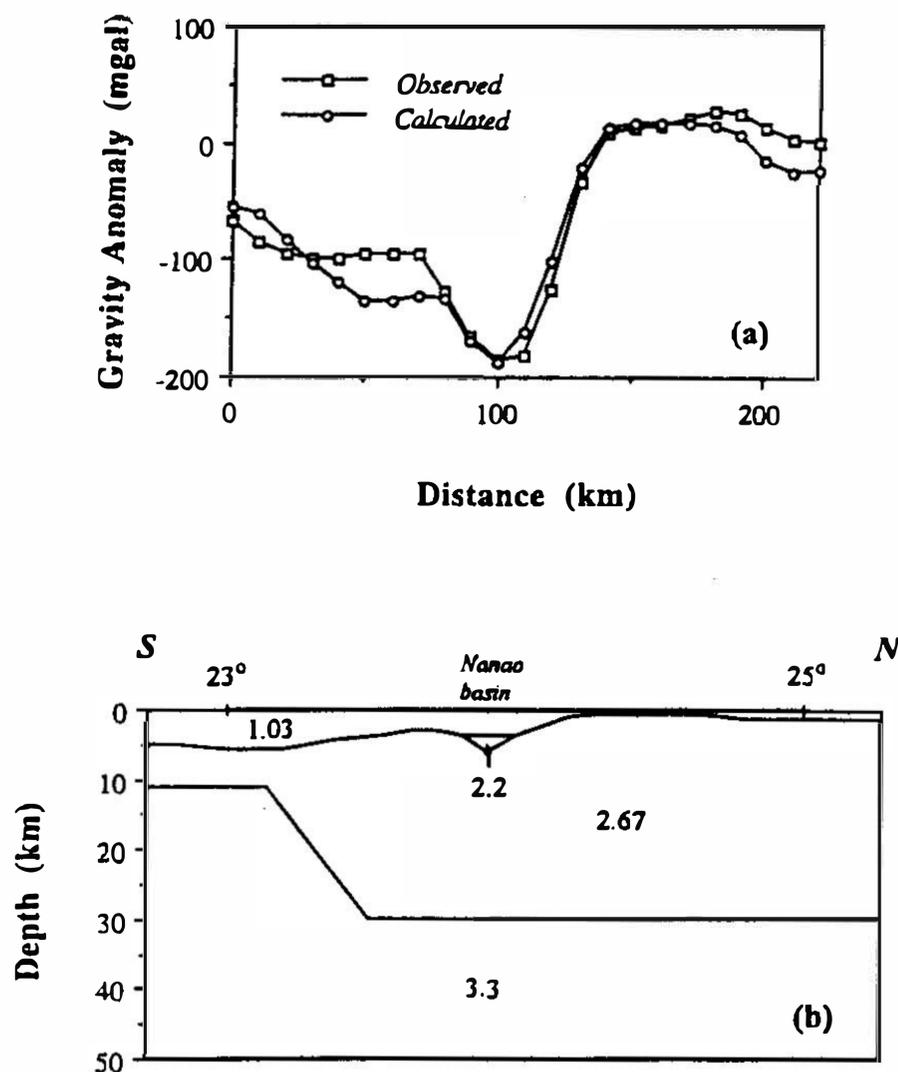
Fig. 13. The modeling of crustal structure across the Ryukyu Trench along 122°40'E (a) The observed and calculated FAA. (b) The simple crustal model consisting of the Nanao Basin (e.g., Lin, 1994) and the geometry of Moho that reflects different crustal thicknesses across the trench. The simplistic model explains most of the FAA variation, though there is room for refinement.

analysis, the work in this example can never be realized without a comprehensive regional map.

While the Okinawa Trough and southern offshore Taiwan are heavily charted, most of the area east of the Lutao-Lanyu volcanic arc is left blank. As few of the shiptracks straddle the arc evenly on both sides, the average response of the lithosphere to the volcano's loading cannot be fully described from these ship data. We are, thus, inept in quantifying the mechanics of the lithosphere through the conventional gravity/topography spectral analysis which requires many continuous, through-going profiles (Mckenzie and Bowin, 1976; Louden and Forsyth, 1982). The difficulty may be alleviated, however, by taking profiles from the regional map, on which the constraints on the eastern side of the arc are improved with many segments of gravity control from different cruises combined. To accomplish the spectral analysis, it is better to have a more detailed bathymetric map than the ETOPO 5 shown in Figure 1. As the 3.5 KHz lines in the NGDC archive are much longer than the gravity lines, a high resolution bathymetric map is attainable in this region.

The resolution of the map may also be enhanced in the future. For example, recently, the Russian cruise PG15, 1994, with underway gravity recording favorably surveyed the blank area on the map in Figure 11, particularly from the eastern coast of Taiwan to 123°30'E. These new data, however, are not readily available. Meanwhile, efforts should be devoted to utilizing the latest Geosat and ERS-1 satellite gravity observations as additional constraints
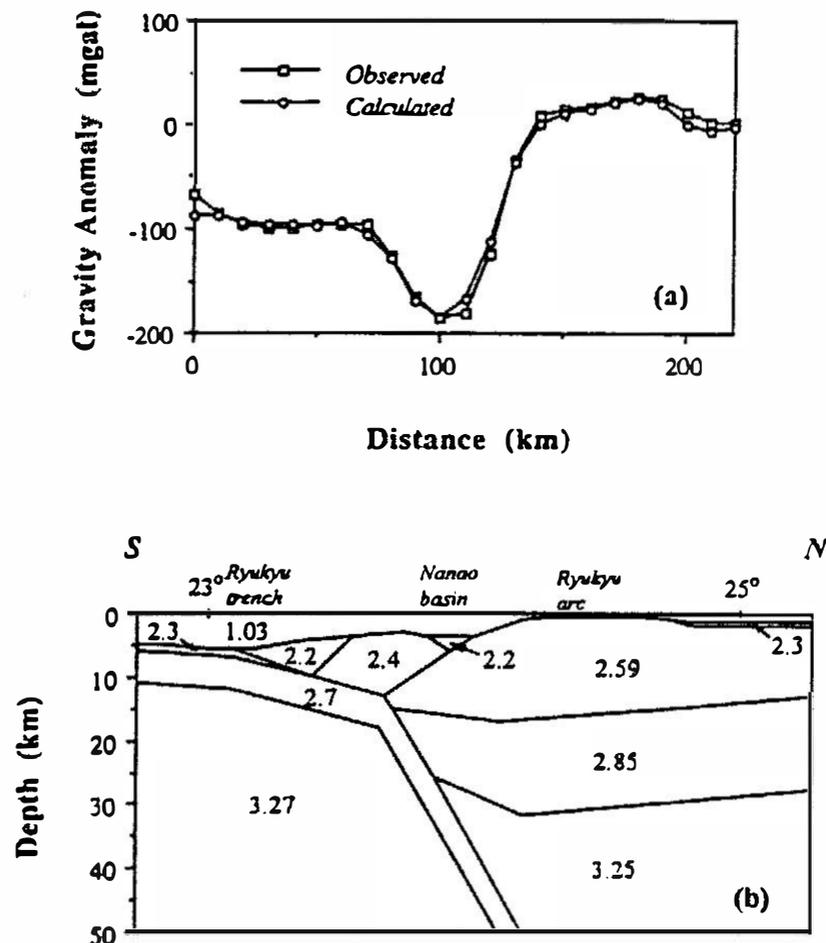
Fig. 14. A more complicated crustal model for the same gravity profile as in Fig. 13. (a) Observed and calculated FAA. (b) Extended from the seismic interpretation by Kimura (1985) and our general idea, the model consists of an underthrusting crust, accretionary wedge, the Nanao Basin, several layers of crust beneath the Ryukyu arc and sediments on the seafloor. This model and the simplistic one in Fig. 13 represent the non-uniqueness of the gravity analysis.

in compiling the regional map (e.g., Hwang *et al.*, 1994). These new geodetic missions possess much higher horizontal resolving power than the SEASAT and, therefore, will merge more smoothly with the shipbornes. Seismic reflection and refraction experiments should also be planned to systematically provide shallow structure information so that a gravity analysis can be used to retrieve deep crustal or upper mantle properties. The much more expensive refraction experiment can be designed to perform at critical locations to image the geometry of the Moho. With the depth of the Moho seismically defined at one spot, the Moho elsewhere in the marine region may be mapped to the first order from the regional marine data using a 3-D gravity modeling technique (e.g., Kuo and Forsyth, 1988).

5. CONCLUSION

The difficulty in making a marine regional gravity map from highly heterogeneous sources is to reconcile data on different absolute levels. In principle, at least one cruise must be reliably calibrated to the known absolute system, so that others can tie to it through a crossover analysis. We find it timely now to attempt a regional map for the Taiwan collision zone because the recently available MW9006, POP 1 and 2 are accurately base-tied. The quality of the regional map of Taiwan presented in this study is characterized by a root-mean-square error of 6.0 mgal for the 865 crossovers, indicating that a variation of more

than 12 mgal can be considered real. The Ryukyu Trench, north Luzon Trough and the Lutao-Lanyu volcanic arc stand as pronounced anomalies on the map. The current map contains artificial features, which can be easily revised when new data fill in. The map facilitates crustal structure modeling in locations where tracks are few or discontinuous for individual cruises and also helps reveal interesting phenomena where the underlying structure may be anomalous.

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