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Comparison of gravity anomaly between mature and immature intra-oceanic subduction zones in the western Pacific

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ABSTRACT

The western Pacific hosts major subduction systems such as Izu–Bonin–Mariana and Tonga–Kermadec, but also less conspicuous systems such as Yap, Mussau and Hjort trenches which constitute the young, incomplete, or ultraslow-member in the evolutionary spectrum of subduction zones. We used satellite-derived gravity data to compare well-developed and immature subduction systems. It is shown that at spatial resolution >10–20 km or so, the satellite data have accuracy comparable to ship-board gravity measurements over intra-oceanic subduction zones. In the isostatic residual gravity anomaly map, the width of non-isostatically-compensated region of the mature subduction zones is much wider than that of immature ones. More importantly, when the gravitational attraction due to seafloor is removed, a large difference exists between the mature and immature subduction zones in the overriding plate side. Mature subduction zones exhibit broad low gravity anomalies of ~200–250 mGal centered at distances of 150–200 km from the trench which are not found over immature subduction zones. The cause of the broad low gravity anomalies over mature subduction zones is debatable due to lack of information on the deep crust and upper mantle structure and property. We discuss the following four causes: (1) serpentinization of the upper mantle beneath the forearc; (2) presence of partial melt in the mantle wedge caused by release of volatiles from the slab, frictional heating and distributed by mantle circulation; (3) difference in density structure between the overriding and subducting plates caused by difference in age and thermal structures with and without compositional stratification between crust and mantle; and (4) anomalous thickness of the arc not explained by isostasy. Our analysis suggests that serpentinization cannot explain the observed gravity anomaly which appears ~150–200 km from the trench. Although the extent and distribution of partial melt within the mantle wedge remain in question, to our best estimate, partial melting contributes little (<50 mGal) to the total negative gravity anomaly. The difference in density structure reflecting temperature difference can only explain less than half of the low gravity anomaly. The sinking of lighter crustal material produces a large negative anomaly in the forearc but its location does not match the observed gravity anomaly. It appears that one cannot explain the total difference in gravity anomaly without invoking anomalous thickness of the arc. Although we could not identify the sole or combination of factors that give rise to the low gravity anomaly in mature subduction zones, the comparison of gravity anomalies between mature and immature subduction zones is likely to provide an important constraint for understanding the evolution and structure of subduction zones as more complementary evidences become available.

1. Introduction

Subduction zones are one of the most dynamic and complex regions in our planet. Sinking of oceanic lithosphere not only recycles near-surface materials, but is also the primary force driving plate motion (Forsyth and Uyeda, 1975; Conrad and Lithgow-Bertelloni, 2002). Geological phenomena such as earthquakes, explosive arc volcanism and back-arc spreading are closely linked with subduction. In spite of their importance, early stages in the development of subduction zone are poorly understood, largely due to the rarity of modern analogues. As a result, much of our insights on the development of subduction are based on idealized or conceptual models with little observational constraints (Cloetingh et al., 1989; Toth and Gurnis, 1998; Hall et al., 2003; Gurnis et al., 2004). Despite such difficulties, understanding the early-stage development of subduction zone is one of the remaining key questions of plate tectonics.

One of the early questions on how subduction zones begin is whether they can be produced spontaneously by the load of thick sediments at old passive margins. Studies (e.g., McKenzie, 1977; Mueller and Phillips, 1991) showed that the strength of this lithosphere is orders of magnitude greater than needed for lithospheric rupture leading to

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subduction. The consensus is that it is difficult to start a new trench on a pristine plate. Instead, intra-oceanic regions containing lithospheric weaknesses such as major faults or transform faults are considered to be favorable places for subduction to start.

Recently, Stern (2004) classified the subduction zones into those with modes of formation that are induced or form spontaneously. The former generally develops by compression due to collision or changing plate motions, while the latter begins when gravitationally-unstable lithosphere collapses into the asthenosphere. As noted above, spontaneous formation requires very low lithospheric strength. Stern (2004) argued that Izu–Bonin–Mariana (IBM) and Tonga–Kermadec subduction zones may be Cenozoic examples of spontaneous formation. On the other hand, the Mussau trench in equatorial western Pacific was considered as an example of induced nucleation of a subduction zone. However, there are at least two other examples of immature intra-oceanic subduction zones in the western and southwestern Pacific, including Yap and Hjort trenches. These subduction zones differ morphologically from well-established subduction zones such as IBM and Tonga–Kermadec trench systems. By comparing the gravity anomalies of the immature subduction zones with those of well-developed ones (IBM and Tonga–Kermadec), one may gain a new set of constraints that future models of subduction development need to satisfy.

It is unclear whether the three immature subduction zones that we identified, Yap, Mussau and Hjort, will eventually mature or halt. However, that may not be an important issue in our study because these poorly developed subduction zones exhibit features that are expected when two oceanic plates converge. Whether these subduction zones successfully develop into mature subduction zones or not will depend on how they interact with surrounding plates, which will likely be determined by later events and conditions. In any case, a range of evidence suggests that these three compression zones are snap-shots of early-stage subduction including morphology. For example, in the case of Yap trench, the trench–arc distance (~30 km) is much shorter than in IBM (100–150 km). Also magmatic arcs are poorly developed with no clear evidence of subduction-related volcanism, and earthquakes occur less than 50 km deep (e.g., Fig. 1 of Fujiwara et al., 2000).

Gravity measurements, despite ambiguity, can be useful for resolving deep crustal and upper mantle structures. According to our experience, gravity can be quite effective for constraining structures within 100 km or so beneath the earth at intra-oceanic subduction zones. Yet little attention has been given to comparative investigations of various developing convergent margins using gravity. One of the reasons for the lack of gravity investigations may be a long-held belief that, like bathymetry and multi-channel seismic data, accurate gravity data had to be collected directly by ship. However, as we shall demonstrate in this study, the resolution of gravity data from global satellite altimetry database (Smith and Sandwell, 1997) is comparable to shipboard measurements in deep open oceans.

Here we quantify and compare the gravity anomalies over mature and immature subduction zones in the western Pacific, using the IBM and Tonga–Kermadec subduction zones as mature examples and the Yap, Mussau, and Hjort convergence zones as immature examples. The effects of some of the major sources of the low gravity anomaly for the two subduction zone end-members are examined, one characterized by a deep and geophysically-obvious subduction zone, the other by a shallow and ill-defined subduction zone. We envisage that evolution of subduction zone may be characterized by a narrow negative gravity anomaly over immature subduction zones broadening with time as the subduction zone evolves. This suggestion implies that the variation of gravity anomaly as subduction zone evolves is an important clue for elucidating subduction process.

2. Geological settings

We examine subduction systems from seven different regions in the western and southwestern Pacific (Fig. 1). Yap, Mussau and Hjort arc-trench systems (ATS) are considered as regions of the upper plate associated with immature subduction, whereas IBM and Tonga–Kermadec ATS represent mature subduction zones.

Before we examine the gravity anomalies along ATS-perpendicular profiles, it is important to discuss the different geological settings of each region. IBM and Tonga–Kermadec ATS have existed for more than tens of millions of years as shown from our geological records and demonstrated in recent plate reconstructions (e.g., Hall, 2002). Also, their dimensions and morphological characteristics (development of active arc, existence of Wadati–Benioff zone and wide trench–arc distance, etc.) are quite different from immature ATS considered in this study. Some recent references on IBM and Tonga–Kermadec ATS can be found in Stern et al. (2003) and Smith and Price (2006) and references therein, respectively. Hence, we shall not provide a separate review. Instead attention is given to the Caroline plate and three less well-known regions of immature subduction zones.

2.1. Caroline plate

The Yap and Mussau trenches lie in the northwestern and southeastern corners of the Caroline plate, respectively (Fig. 1). The Caroline plate itself is an enigmatic plate which was once considered as a part of the Pacific plate. However, detailed investigations by Bracey (1975) and Weissel and Anderson (1978) revealed that it is a separate plate, rotating counterclockwise with respect to Pacific plate. For instance, the seafloor of Caroline plate stands higher than the surrounding Pacific plate to the north and east, and the Philippine Sea plate to the west. According to DSDP 62 (Winterer et al., 1971), which drilled the magmatic rise in the middle of the Caroline plate, the basement is determined as Oligocene in age.

The Yap and Mussau trenches developed from the interaction of Caroline plate with the surrounding plates, although the timeline of their development remains unclear. It is thought that, due to the counterclockwise rotation of the Caroline plate, convergence has been occurring in the Yap and Mussau trenches while Ayu Trough (Fig. 2) has been spreading (Fujiwara et al., 2000; Lee, 2004). From the geometry of the Ayu Trough, Seno et al. (1993) inferred that the pole of the rotation between the Caroline and Philippine Sea plate at 134°E, 6°N. However, fine-scale sea floor fabrics revealed by recent multi-beam bathymetry surveys showed that Ayu Trough has opened obliquely (Lee and Kim, 2004; Park et al., 2006), and thus the pole of opening is apparently quite different from earlier suggestions and lies further east (Weissel and Anderson, 1978; Seno et al., 1993).

The rate at which the Caroline plate is rotating and deforming is another source of debate. Based on sediment thickness and other evidence, Fujiwara et al. (1995) suggested that Ayu Trough might be opening at a rate as low as 4 mm/yr. However, the sedimentation rate that they used comes from the center of Caroline plate, and therefore may not be representative of the Ayu Trough (Lee and Kim, 2004). Using a higher sedimentation rate would make the opening rate of Ayu Trough higher. In any case, however, the general morphology of Ayu Trough resembles that of slow and ultra-slow spreading centers (Park et al., 2006).

2.2. Yap trench

The Yap trench is located just south of Mariana trench where the Pacific-Caroline plate underthrusts beneath the Philippine Sea plate (Fig. 1). The subducting-plate side of the Yap trench is elevated seafloor called the Caroline ridge, which is divided roughly north and south into two, by the transtensional Sorol Trough (Fig. 2).

Much of the controversy on the origin and tectonics of Caroline plate stems from our lack of knowledge on the timing and style of collision between the Caroline ridge and the Yap ATS. According to McCabe and Uyeda (1983) and Fujiwara et al. (2000), the collision of the Caroline ridge with the proto-Yap-Mariana trench began at about

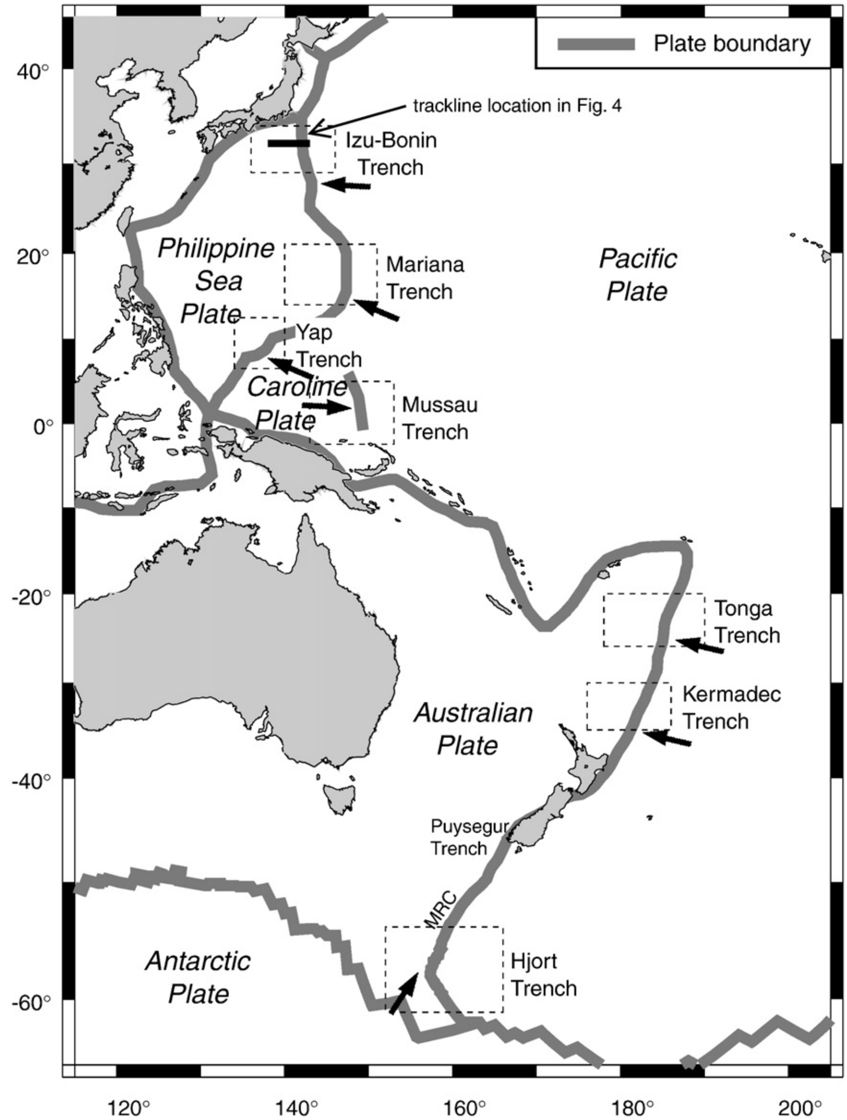


Fig. 1. Location map of major plate boundaries in western and southwestern Pacific. 7 sites were chosen for detailed comparison between mature and immature subduction zones. The former include Izu–Bonin, Mariana, Tonga and Kermadec trenches and the latter include Yap, Mussau and Hjort trenches. Boxes are areas where isostatic residual gravity anomalies were computed (Figs. 9 and 10). Solid black line in 32°15′N is the location of transect profile in Fig. 4. The location of Macquarie Ridge Complex is labeled as MRC. Relative plate motion is shown with arrows.

25 Ma. The collision caused a change of spreading direction in the Parece Vela basin whose opening lasted from 19 to 15 Ma (Okino et al., 1998). McCabe and Uyeda (1983) and Fujiwara et al. (2000) argued that the arcuate shape of the Mariana trench is a combined result of the opening of Mariana Trough (~5 Ma) and forearc erosion along the Yap trench by slow westward migration of Caroline ridge. However, their argument does not take into account the fact that the Caroline and Pacific are separate plates and that the differential motion has existed between the two plates. After noticing the division of Caroline ridge by Sorol Trough, Lee (2004) suggested the convergence could have occurred much later, perhaps by a few million years, or that subduction along Yap trench may have been reactivated. In this model, the Sorol Trough marks the boundary between the Caroline and Pacific plates, although farther east the boundary becomes obscure. An important question with this later argument is how the Pacific-Caroline convergence was accommodated prior to subduction along the Yap trench.

A number of observations suggest that Yap trench is a zone of incipient active subduction. They include: (1) deep trench (7000–8000 m), which would not exist if the Yap trench was a site of collision; (2) absence of active subduction-related arc volcanism; (3) lack of deep (>70 km) Wadati–Benioff zone; and (4) evidence of obduction of the overriding plate and exposure of the oceanic crust at the tip of the overriding plate along the forearc side of the trench as revealed by submersible dives (Fujiwara et al., 2000; Kobayashi, 2004).

2.3. Mussau trench

The Mussau trench is another case where the history is not well understood. It is located along the eastern boundary of the Caroline plate (Fig. 1) and is an immature subduction zone where the Caroline plate is being thrusted beneath the overriding Pacific plate (Ryan and Marlow, 1988). Like the Yap trench, it also has a short arc-trench distance (~40 km); because there is no obvious arc, we select the highest point on the overriding plate to measure the arc-trench distance. Previous gravity, seismic and magnetic studies suggested that subduction started at ~1 Ma and at present 7–10 km of Caroline slab underlies beneath the Pacific plate (Hegarty et al., 1983; Hegarty and Weissel, 1988). Earthquakes are shallow and subduction-related arc

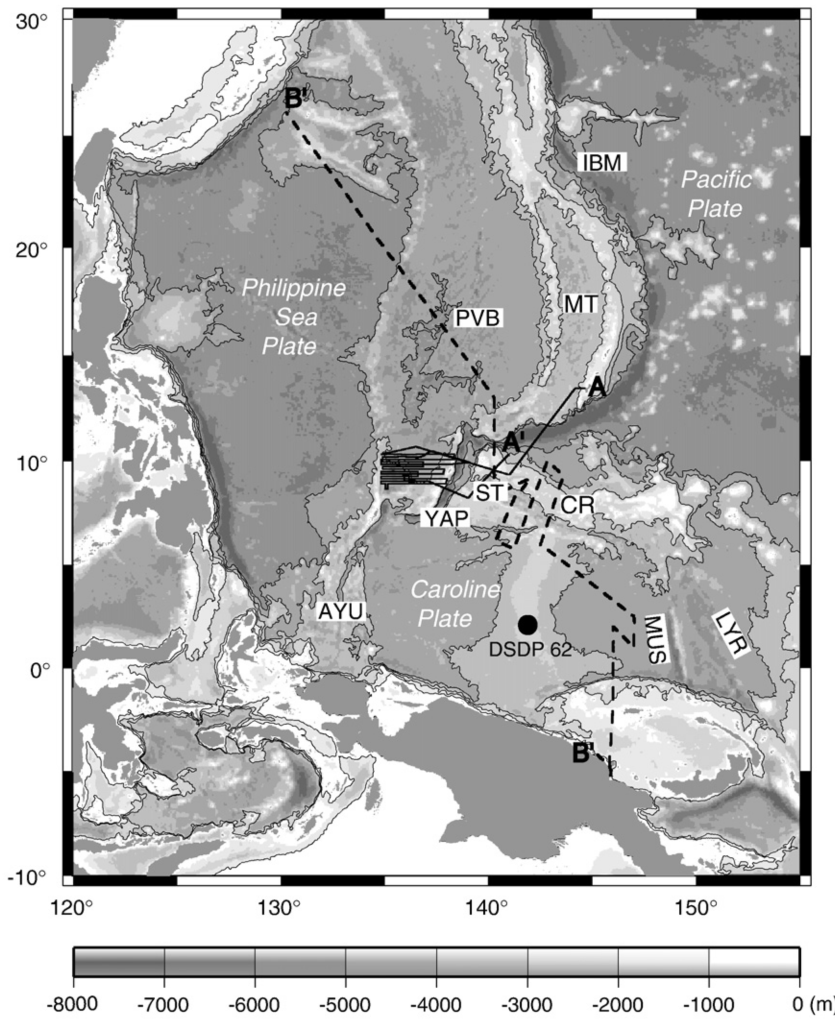


Fig. 2. Bathymetry map showing the ship tracks where gravity was measured by R/V *Hakuho-maru* in 2005 (solid line) and R/V *Onnuri* in 2002 (dashed line). AYU: Ayu Trough, CR: Caroline ridge, IBM: Izu–Bonin–Mariana trench, LYR: Lyra Trough, MT: Mariana Trough, MUS: Mussau trench, PVB: Palace Vela basin, ST: Sorol Trough, YAP: Yap trench. Black circle is the location of DSDP 62 hole and the contour interval of bathymetry map is 1000 m.

volcanism is absent, similar to the Yap ATS. To the east of Mussau trench lies the Lyra Trough (Fig. 2) whose origin is also controversial. One argument suggests that the Lyra Trough and its northward extension represent the old convergent boundary between the Pacific and Caroline plates (Hegarty and Weissel, 1988). If so, the Lyra Trough and its northward extension may have been the active boundary prior to the start of subduction along the Yap trench.

The Mussau trench may be a classic example of progressive strain localization within the convergent margin where numerous, widely distributed thrust faults develop into a few large thrust faults and then are localized to form a single trench. Hegarty et al. (1983) examined the thrust faults along the Caroline-Pacific boundary using seismic reflection profiling and argued that they are linked with the development of the Mussau trench. Recent high resolution multi-beam tracks, however, present a more complex picture where the strike of thrust faults differs from that of Mussau trench and is aligned with the Lyra Trough (Korea Ocean Research and Development Institute, 2002). An extensive bathymetric survey may be required to resolve the relationship between the various features in this area.

2.4. Hjort trench

The Hjort ATS is situated at the southernmost section of the Macquarie Ridge Complex (MRC), south of New Zealand (Fig. 1). Unlike the Yap and Mussau ATS, this region has been extensively surveyed thanks to the recognition that it represents a rather rare case of early stage of subduction. As a result, the timing and direction of subduction are relatively well-constrained. According to NUVEL-1A (DeMets et al., 1994), the convergence of Australia plate with the Pacific plate has occurred in an oblique manner along the MRC. The oblique motion has led to convergence along the pre-existing fracture zones and has triggered the subduction along the Puysegur and Hjort trenches north and south of the MRC, respectively (Meckel et al., 2003, 2005).

The Hjort trench in the southernmost part of the MRC is where intra-oceanic subduction is thought to have occurred during the last ~11 Myr (Meckel et al., 2005). The subduction rate is about 2–4 cm/yr along the Hjort trench (Meckel et al., 2005). The region is marked by shallow seismicity (<20 km). Focal mechanisms are consistent with strike-slip motion along the trench (Massell et al., 2000). There is some magmatism on the overriding plate side of the Hjort trench (Solander volcano; Reay and Parkinson, 1997), but its origin remains controversial. For instance, Meckel et al. (2003) argued that the eastern volcanic structure may be the result of an anomalous mantle melting and not of subduction-related arc magmatism, because it is simply too far away from the trench. Still, the volcano in that region erupts adakite which is thought to be a product of slab melting (Defant and Drummond, 1990).

The Hjort ATS exhibits a wide range of crustal deformation from north to south as a result of oblique convergence. Different stages of

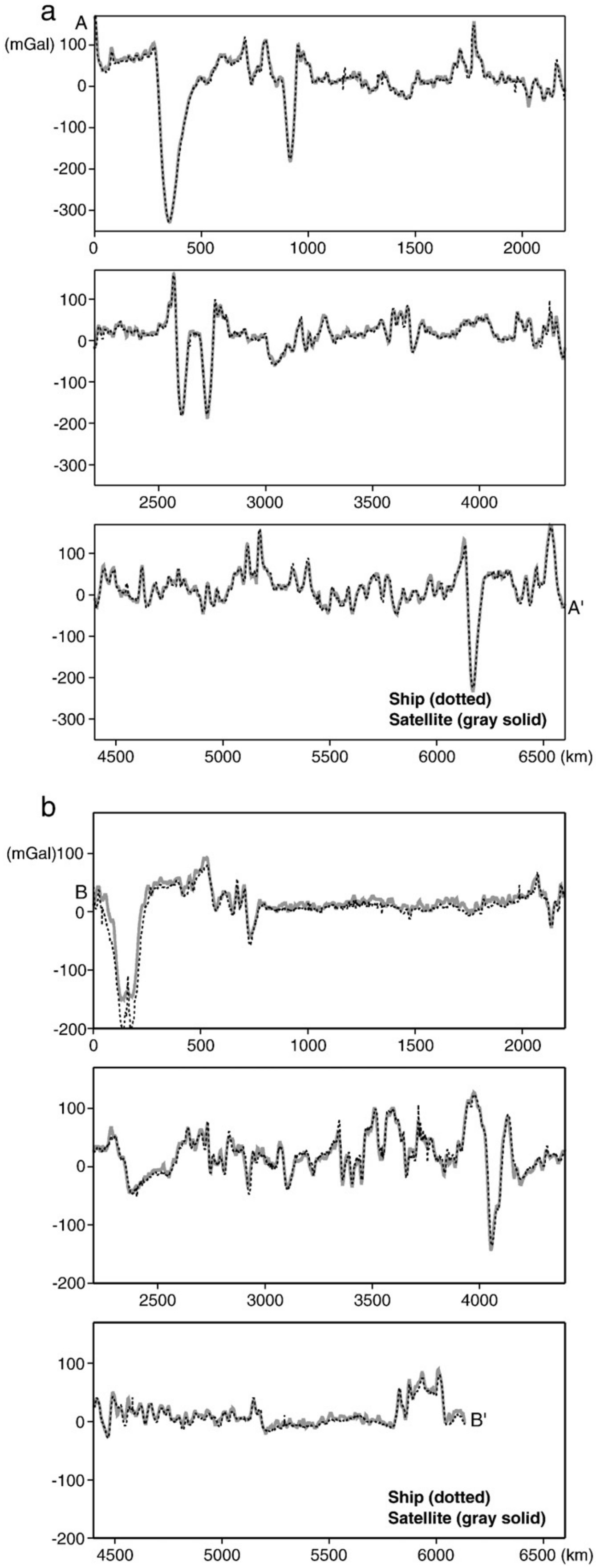


Fig. 3. Comparison between shipboard free-air gravity data (dotted) and satellite gravity data (gray solid) derived from satellite altimeters. Shipboard gravity data are obtained from (a) R/V *Hakuho-maru* and (b) R/V *Onnuri*. The ship tracklines are shown in Fig. 2.

young subduction may be observed along its length. In particular, Meckel et al. (2003) found from regional seismicity that both the dip angle and depth of trench become shallower from south to north.

3. Gravity data

The traditional means of obtaining gravity data at sea is using a shipboard gravimeter. Depending on maintenance and calibration, modern marine gravimeters have considerable accuracy (<a few mGal; Bell and Watts, 1986) but can be quite expensive to cover large areas. In the last couple of decades, we have seen the advent and improvement of marine gravity data derived from satellite altimeters (Neumann et al., 1993; Marks, 1996; Sandwell and Smith, 1997). The primary advantage of satellite-derived gravity is that it provides global, uniform coverage, and in some cases, information about the seafloor topography. However, there are concerns about using satellite-based gravity data to determine or compare seafloor topography between regions because free-air gravity and seafloor topography may not match in certain areas where the sediment is thick such as continental margins or the crust is abnormally thick such as plume-affected regions. As a result, scientists in general have been reluctant to use satellite-derived gravity data as a substitute for direct shipboard bathymetric and gravity measurements and mostly use satellite-derived gravity for reconnaissance purpose.

In this study, we use satellite-derived gravity data to compare various intra-oceanic subduction zones. It is not possible to compare different subduction zones using shipboard gravity measurements alone. We argue that, far away from geologically anomalous regions, the satellite-derived gravity measurements are accurate enough for comparative studies of tectonic features at regional scales generally greater than few tens to hundreds kilometers. To demonstrate that satellite-derived gravity data are accurate enough for our study we compare them with two recent shipboard gravity profiles in the western Pacific. Fig. 2 shows the trackline during those two recent cruises.

The first comparison was made in the Parece Vela basin in the southern Philippine Sea plate (Fig. 3a). The shipboard gravity data were obtained on board R/V *Hakuho-maru* (KH05-01-Leg 3) in June 2005. The survey area included the Yap ATS and back-arc region and the Sorol Trough. The gravity field was measured by Dynamic Gravity Meter D-004 and ZLS GyroPack (GG-49). The calibration tie was performed at the Ocean Research Institute of University of Tokyo before the cruise. It is obvious that shipboard and satellite measurements coincide almost exactly (Fig. 3a). In fact, in some ways, the satellite gravity data are preferable because they do not contain errors and spikes due to sudden ship turns and speed change in the free-air gravity anomaly.

The second comparison was made using shipboard gravity data acquired by R/V *Onnuri* in 2002 (Fig. 3b). The gravimeter used was Lacoste-Romberg S-118. Again satellite gravity matches well with shipboard gravimeter. However, compared to R/V *Hakuho-maru* case, the agreement is not good. Still for wavelengths greater than 10–20 km, the satellite and marine data sets show extremely good agreement.

4. Gravity data reduction

Two types of data reduction were performed for satellite-derived free-air gravity data: (1) seafloor Bouguer gravity anomaly (SBGA) was calculated after subtracting the gravitational effects of seafloor topography from the free-air gravity anomaly, and (2) isostatic residual gravity anomaly (IRGA) to examine how well the assumption of isostasy explains the observed gravity field. The former may provide us information on the density structure below the seafloor, whereas the latter may tell us about the relative importance of flexure versus isostasy.

Another important set of data that we used was bathymetry which was derived from ETOPO2 global dataset (NGDC, 2001). To make sure that the bathymetry data do not contain artifacts stemming from interpolation and inferred values from the satellite free-air gravity data, we cross-checked ETOPO2 data with the actual ship track and depth information obtained by echosounders in our study areas when possible. Our examination showed that the bathymetry data that we used are correct and reliable.

We used 1.0, 2.9, and 3.3 g/cm^3 as the density of water, crust, and mantle, respectively (Carlson and Raskin, 1984). Gravitational effects due to undulation of various interfaces were computed in the Fourier domain using the method of Parker (1972) which was later extended to the 3-D case. When calculating IRGA, the choice of depth of compensation can be a debatable issue. In this study, we used 45 km as the depth of compensation. A change of compensation depth by several tens of kilometers has a minimal effect on the resulting IRGA, and therefore a different choice of compensation depth does not seriously alter our results.

In addition to regional 3-D SBGA and IRGA calculations, we also performed detailed 2-D forward gravity calculations where deep structural information was available from seismic observations. Unfortunately, there are few cases where the velocity structure was imaged across the subduction system deep enough to be useful for gravity modeling. One such case was the deep seismic refraction survey by Suyehiro et al. (1996). The ocean bottom seismic experiment of Suyehiro et al. (1996) was conducted along 32°15′N across the Izu–Bonin arc. It provides fairly good seismic velocity information above 25 km.

To better constrain the density of the crust and upper mantle, we converted the velocity values to density and calculated the gravity anomaly resulting from such 2-D structure (thin solid line in Fig. 4a).

The density was derived from P-wave velocity using the following relationship by Christensen and Shaw (1970) which was derived from rocks dredged from the Mid-Atlantic Ridge (22°N, 4°S):

$$\mathrm{Vp(km/s)} = 2.53\rho\left(\mathrm{g/cm^3}\right) - 0.76$$

where, Vp is compressional wave velocity and ρ is density. For the density of the mantle, we used 3.37 g/cm^3 (Afonso et al., 2007). The gravitational effects were calculated using GM-SYS (2001), a commercial software based on methods suggested by Talwani et al. (1959) and Talwani and Heirtzler (1964). The forward calculations were compared with observed gravity anomaly extracted from satellite-derived gravity data (Fig. 4).

5. Gravity anomaly comparison

Figs. 5–8 show the SBGA over immature (Yap, Mussau and Hjort ATS) and mature subduction zones (IBM and Tonga–Kermadec ATS). A systematic difference can be found between the two groups in the overriding plate region. For example, the mature subduction zones (IBM and Tonga–Kermadec ATS) exhibit much lower SBGA by 200–250 mGal in the overriding plate than the immature subduction zones (Yap, Mussau and Hjort ATS). The probable cause of such differences in SBGA will be the main topic of our discussion in the following section.

A careful examination reveals that there are some variations of SBGA in the subducting-plate side. These variations are especially notable in the immature subduction zones. They are local variations which can be explained by local geological peculiarities and thus do not alter the main purpose of our study, namely the difference between mature and immature subduction zones. For example, for the Yap ATS, the SBGA profiles display ~80 mGal variation across the subducting-plate profile (first 4 profiles in Fig. 5b). The variations are in large part due to the fact that the subducting plate side of the Yap ATS consists of ridges and troughs roughly parallel to the transect lines, and consequently, some of the lines that we drew were along the trough while others were parallel to the ridges. Also the SBGA across the Mussau ATS is low by 50–80 mGal towards the west compared the east (bottom 4 profiles in Fig. 5b). Such low values are probably due to thicker crust beneath the Caroline ridge. Finally, the low SBGA on the subducting plate side of the Hjort ATS (Fig. 6b) generally coincides with the locations of fracture zones.

We also compared the IRGA between mature and immature subduction groups to see if there were any notable features (Figs. 9 and 10). It is obvious that regions immediately around the trench are not isostatically balanced as evidenced by large IRGA values. In regions close to the trench, the plates are highly curved, and therefore flexure plays an important role in supporting the topography (Watts and Talwani, 1974).

In both groups, the large variation in IRGA, with low anomalies along the trench and high anomalies over the arc and backarc regions, attests that subduction zones are far from being isostatically

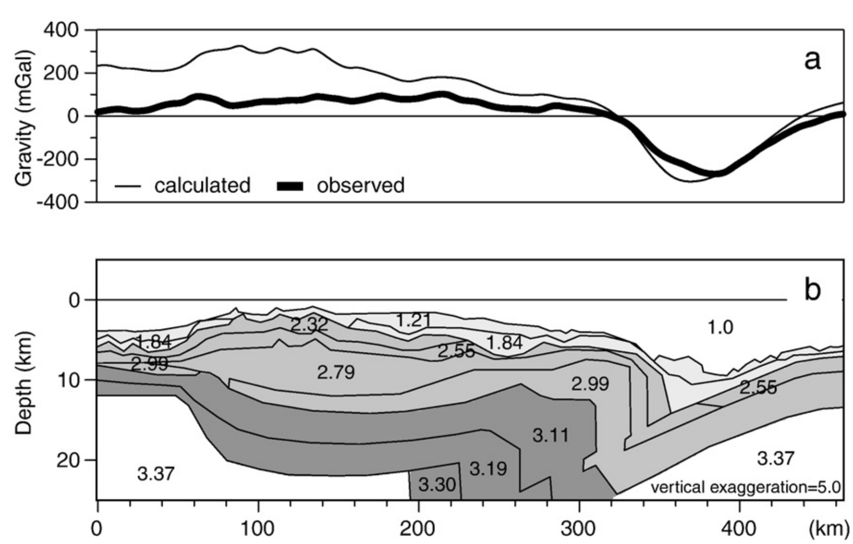


Fig. 4. (a) The comparison of calculated and observed gravity anomalies along 32°15′N of Izu–Bonin trench (see the location of trackline in Fig. 1). Calculated gravity values are computed using GM-SYS (2001) software and observed free-air anomalies are derived from the satellite gravity data (Smith and Sandwell, 1997). (b) Density values above 25 km are obtained from conversion of P-wave seismic velocities (Suyehiro et al., 1996) and are in g/cm^3.

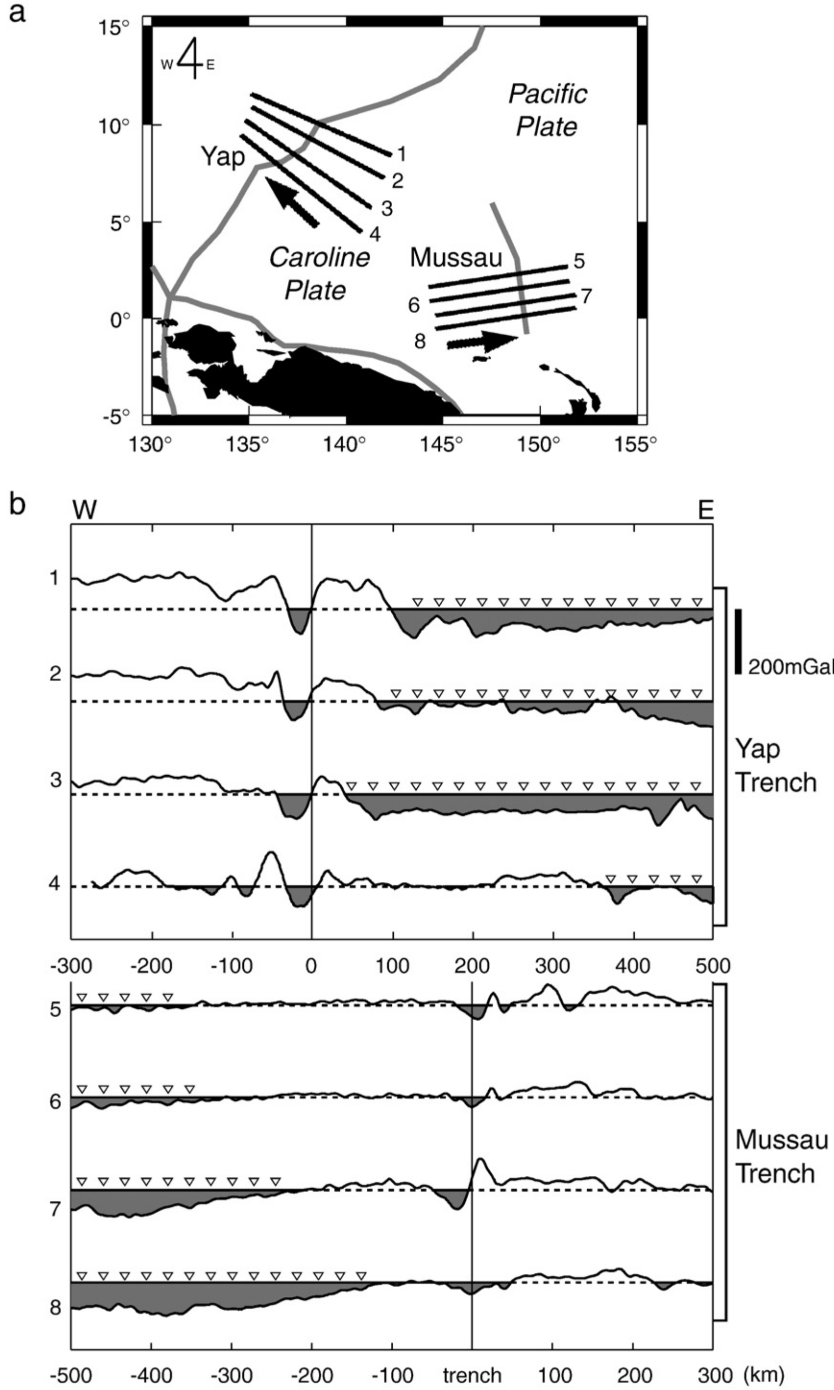


Fig. 5. (a) Location of the cross sections across Yap and Mussau trenches and their numbers. (b) Profiles of seafloor Bouguer gravity anomaly (SBGA) corresponding to cross section numbers in (a). Inverted triangles denote portions showing a large variation in the subducting plate (see text).

compensated (Figs. 9 and 10). A major difference between mature and immature subduction zones seems to be that the width of non-isostatically compensated region is relatively narrow for immature subduction zones (<50 km), whereas it is several times wider in the case of mature subduction zones (150–200 km). One likely cause of the difference is that the high-density slab penetrates deeply into the mantle in the mature subduction systems whereas such effect of the slab is absent for immature cases.

In general, subduction systems and overlying ATS have complex internal structure, and therefore a simple test was conducted to check if the complexity of crustal and upper mantle density structure alone may explain the observed free-air gravity anomaly or if additional sources are needed. As mentioned earlier, despite numerous seismic surveys conducted in the western Pacific subduction zones (LaTraille and Hussong, 1980; Hino et al., 1991), very few cases actually image lithospheric structure deep enough to be useful for gravity modeling. In this study, we use the deep seismic results of Suyehiro et al. (1996) which represent a profile along ~500 km of Izu–Bonin ATS across 32°15′N (Fig. 1). A 2-D gravity calculation, after converting P-wave velocity to density, was conducted to see if the gravity anomalies can be explained by density distribution in the crustal and upper mantle section, and if so, to what extent.

Fig. 4 compares the observed and calculated gravity anomaly for the Izu–Bonin ATS across 32°15′N. Note that we do not consider the

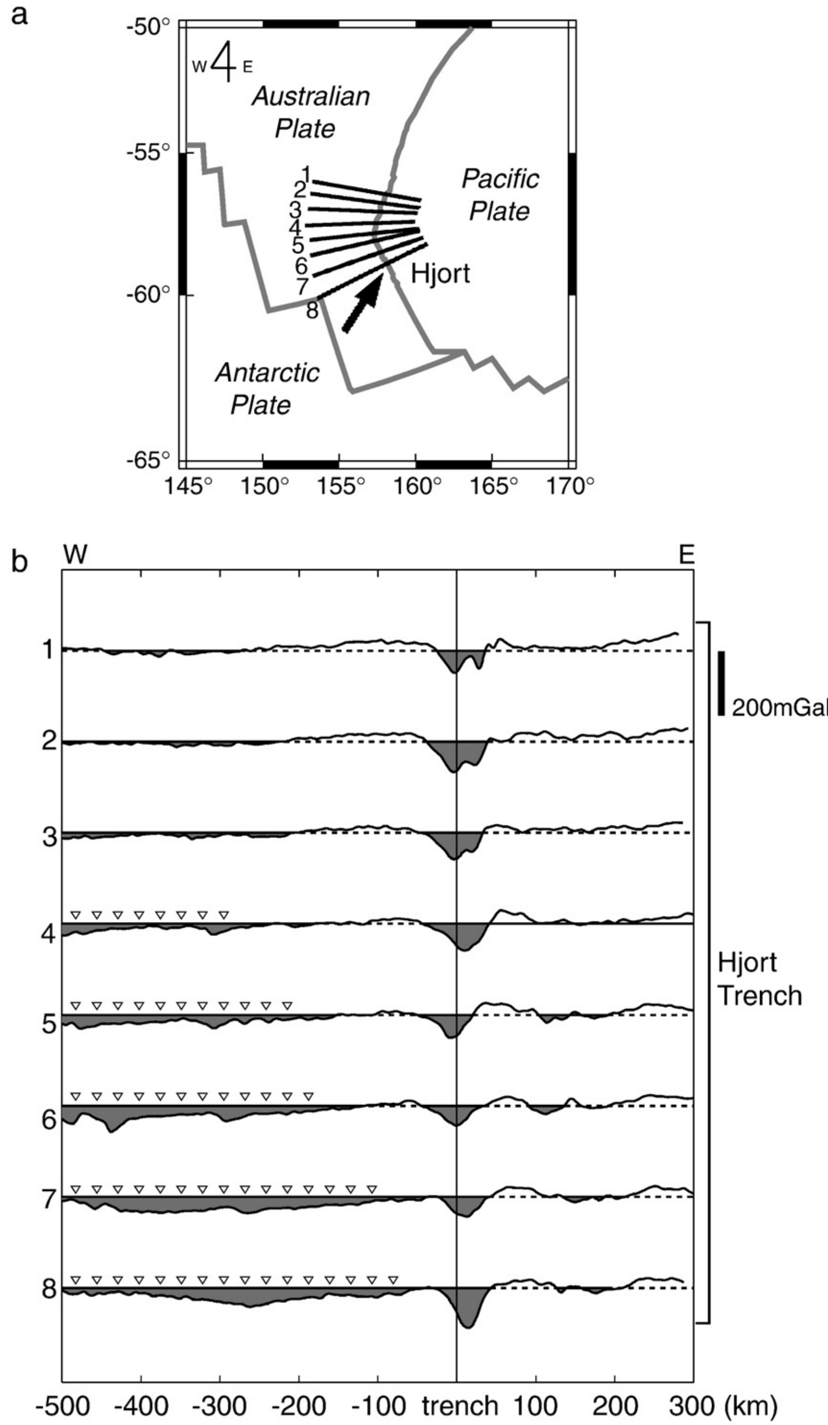


Fig. 6. (a) Location of the cross sections across Hjort trench and their numbers. (b) Profiles of seafloor Bouguer gravity anomaly (SBGA) corresponding to cross section numbers in (a). Inverted triangles denote portions showing a large variation in the subducting plate (see text).

effect of the slab in this calculation. The observed and calculated gravity anomalies differ by ~200–250 mGal. Therefore, it is clear that density structure of the crust and upper mantle for the profile by Suyehiro et al. (1996) cannot explain the observed values and thus additional sources of gravity anomaly are necessary.

6. Discussion

A substantial difference in the SBGA was found between mature and immature subduction zones (Figs. 5–8). A low gravity anomaly of 200–250 mGal is found over the overriding plate of mature subduction zones 150–200 km away from the trench axis (Figs. 7 and 8). Such a broad and large low gravity anomaly is not seen over the immature subduction zones (Figs. 5 and 6). The gravity anomaly at ATS results from the undulation in seafloor topography and variations in the density structure below the seafloor. The SBGA is obtained by calculating the effect of seafloor undulations and subtracting it from the total gravity anomaly. Hence, the SBGA provides us the means to constrain the density variations, in particular, those within 100 km or so below the seafloor.

Gravity anomaly over the subduction zone has been investigated by Marotta et al. (2006, 2007). However, the region they examined is

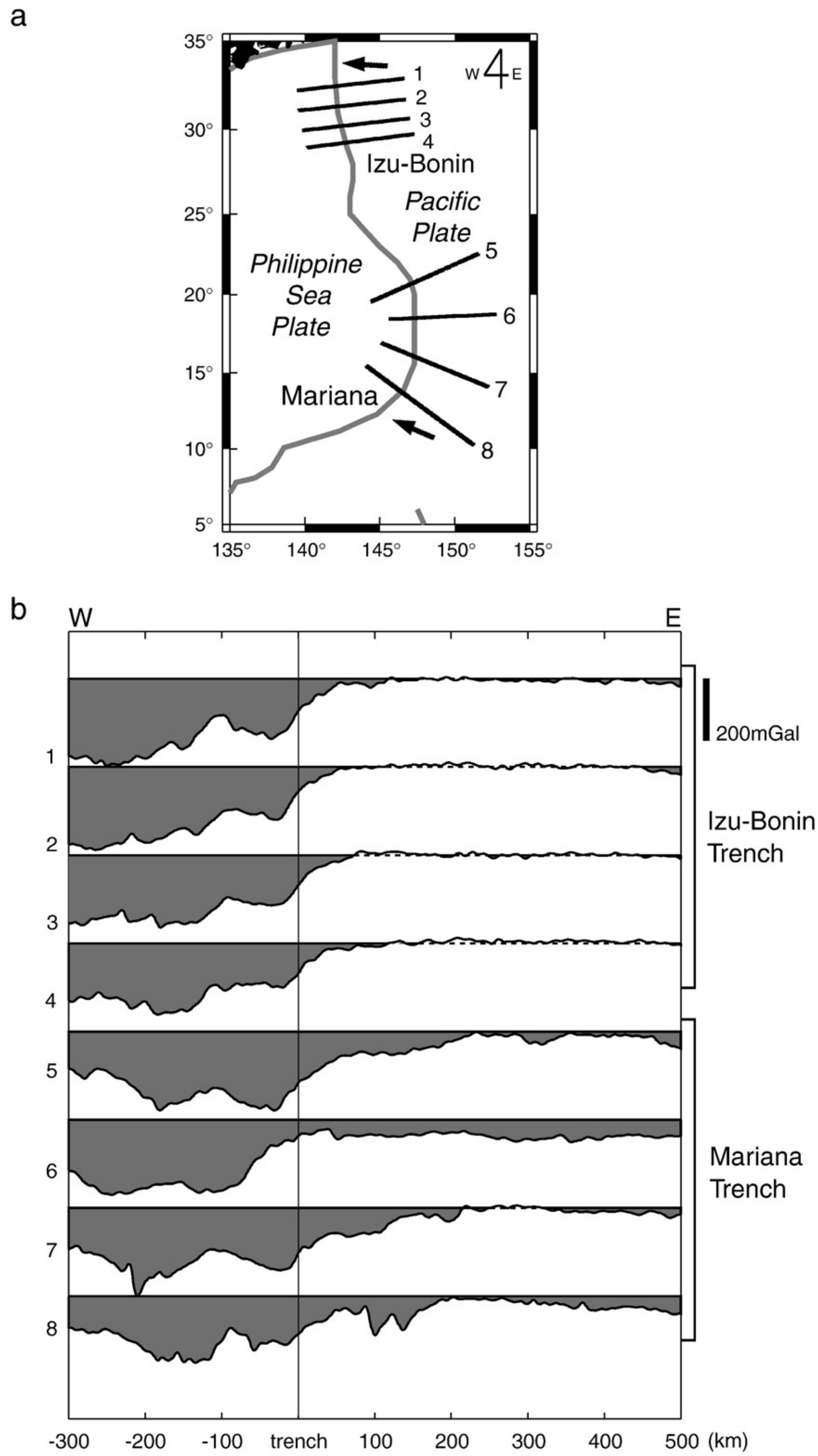


Fig. 7. (a) Location of the cross sections across Izu–Bonin and Mariana trenches and their numbers. (b) Profiles of seafloor Bouguer gravity anomaly (SBGA) corresponding to cross section numbers in (a).

around the trench axis (generally within 100 km). Our study differs from theirs in that the gravity anomaly that we are trying to explain is quite broad whose center lies 150–200 km away from the trench axis. However, some of our results, such as gravity anomaly due to difference in the thermal age of two plates, is quite consistent with Marotta et al. (2006).

The IRGA maps (Figs. 9 and 10) represent the degrees of isostatic compensation. The non-isostatically compensated region of mature subduction zones (~150–200 km) is several times wider than that of immature ones (<50 km). Such wide-band high anomaly region over mature ATS is considered to be related to the low gravity anomaly in SBGA and perhaps to the existence of low-density materials under the arc–backarc region. Other than that, not much can be said about the IRGA, especially in regards to its fine-scale features. However, we note some interesting ones. For instance, immature subduction zones exhibit high IRGA close to the trench (denoted as 'A' in Fig. 9b, d and f).

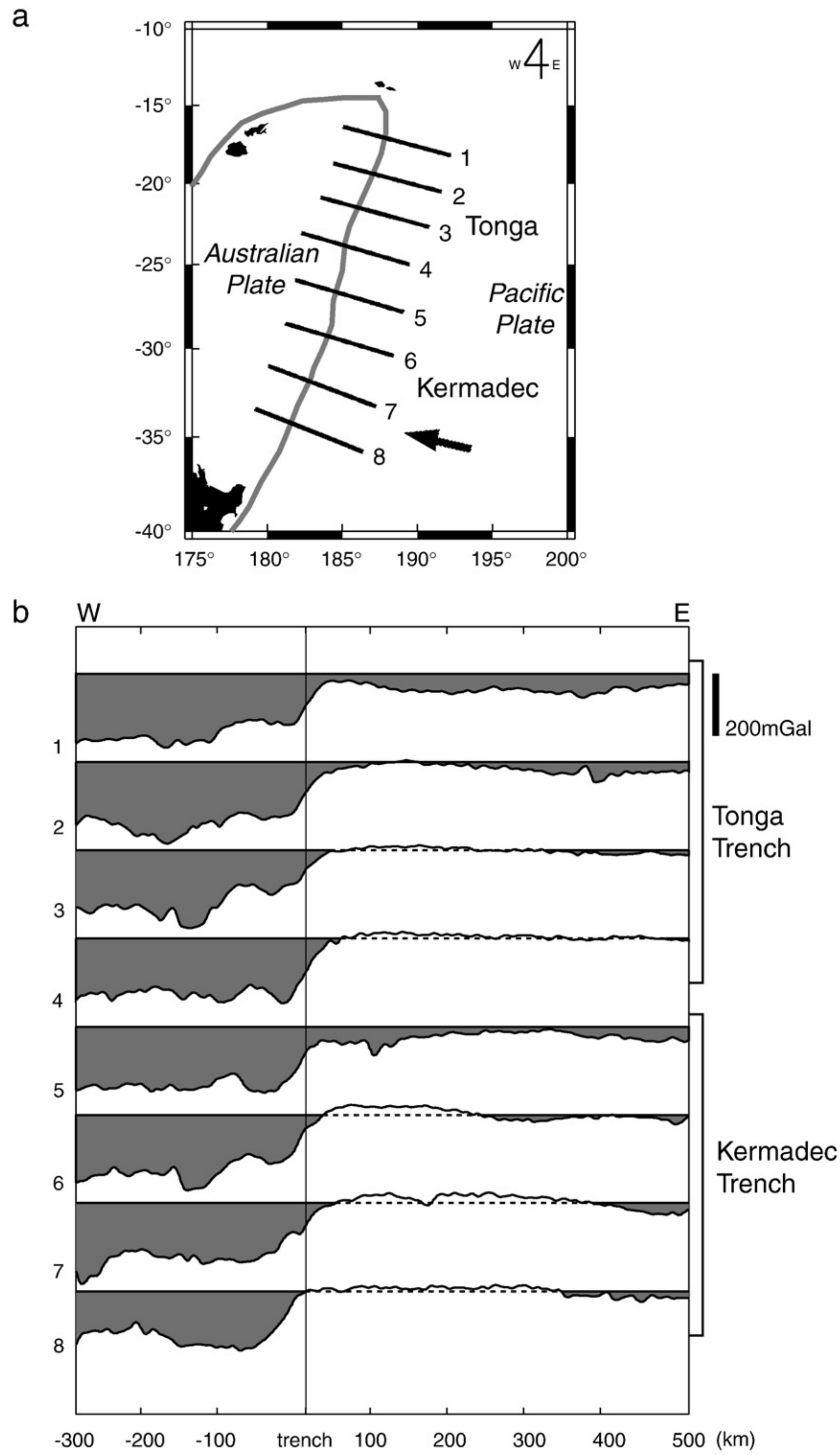


Fig. 8. (a) Location of the cross sections across Tonga and Kermadec trenches and their numbers. (b) Profiles of seafloor Bouguer gravity anomaly (SBGA) corresponding to cross section numbers in (a).

They are thought to be associated with the uplift and/or the increase in thickness as a result of thrusting of the overriding plate.

It appears that evolution of subduction zone from immature to mature involves widening of low-gravity-anomaly zone in the overriding plate. Considering diverse processes that take place after subduction starts, such as continued penetration of the slab, subsequent dehydration and melting of the slab, changes in the circulation pattern of the mantle and development of the arc, our finding, though new, could have been predicted to a certain extent. Understanding the cause or the combination of the causes that produced the low gravity anomaly would be the next question. The answer to this question requires a lot of new information about the deep structure of ATS and its properties such as density. Unfortunately, our knowledge is limited regarding the processes and structure of the crust and upper mantle of subduction zones. Still, one can make reasonable assessments on some of the major causes that are considered as important contributors to the low gravity anomaly.

While gravity may be a powerful tool for demonstrating the difference between mature and immature subduction systems, it alone may not be as effective in identifying the main cause or causes due to its

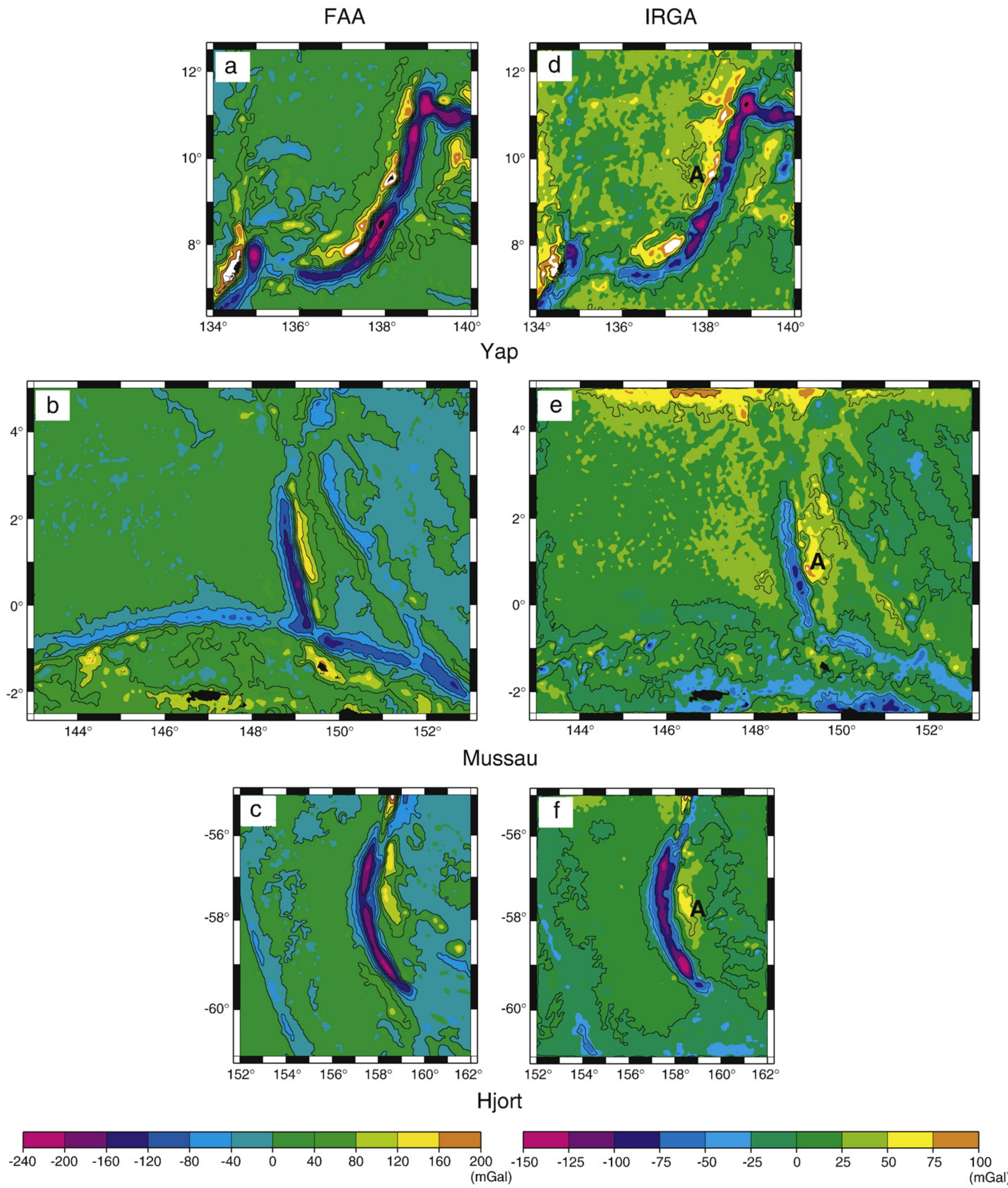
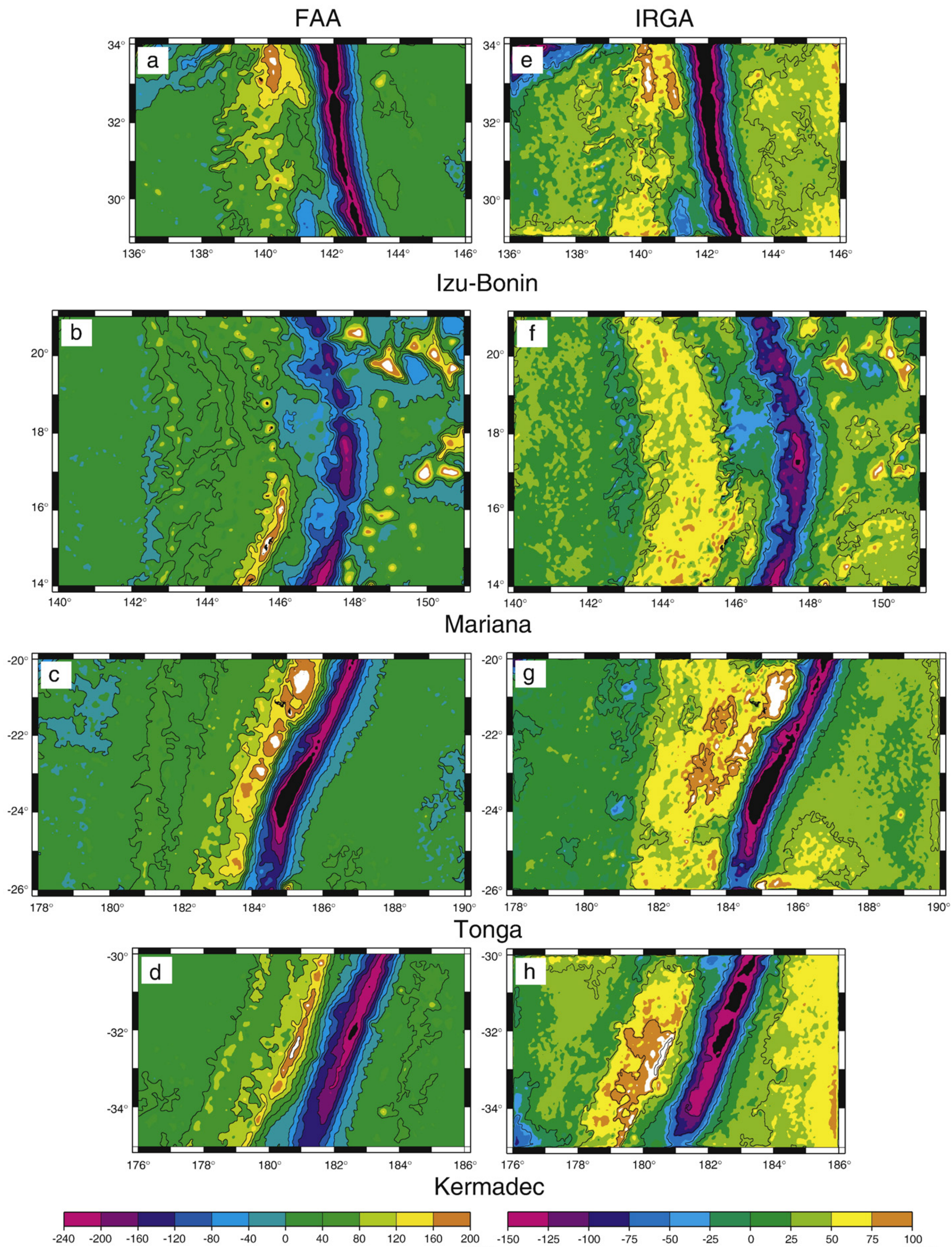


Fig. 9. (a–c) Maps of free-air gravity anomaly derived from satellite altimeters (FAA) for Yap, Mussau and Hjort trenches considered as immature subduction zones (see Fig. 1 for locations). (d–f) Maps of isostatatic residual gravity anomaly (IRGA). 'A' indicates the region showing high anomaly. The contour intervals are 40 mGal.

ambiguity. Other tools and information are needed such as the deep seismic information. However, as we mentioned, there are few seismic surveys that penetrated structures deep enough to help us interpret gravity data. Even if seismic data were available, the conversion of seismic velocity into density can be an additional source of error. Though limited, we can still make some useful inferences on possible causes based on our present state of knowledge about subduction systems.


FAA
IRGA
a
b
c
d
e
f
g
h
Izu-Bonin
Mariana
Tonga
Kermadec
34°
32°
30°
136°
138°
140°
142°
144°
146°
20°
18°
16°
14°
148°
150°
-20°
-22°
-24°
-26°
178°
180°
182°
184°
186°
188°
190°
-30°
-32°
-34°
176°
-240 -200 -160 -120 -80 -40 0 40 80 120 160 200
(mGal)
-150 -125 -100 -75 -50 -25 0 25 50 75 100
(mGal)

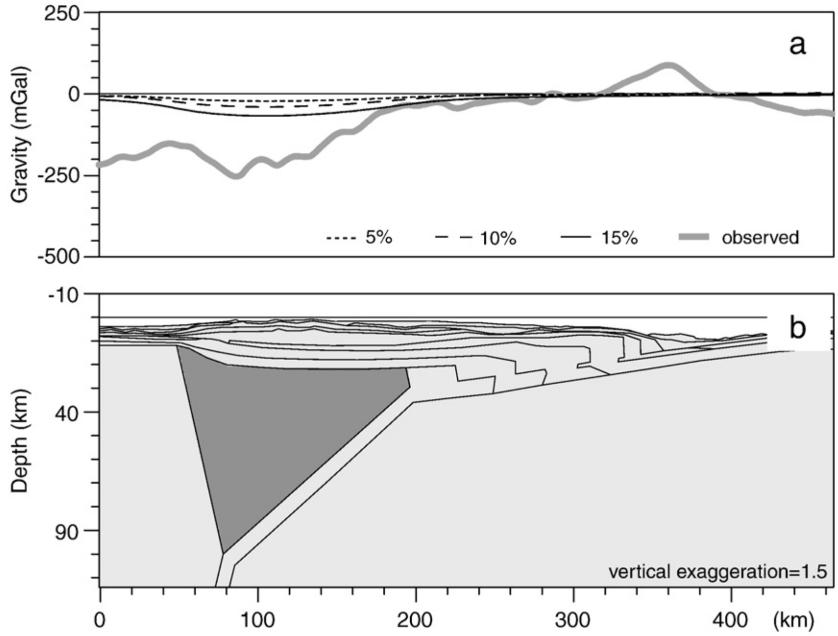


Fig. 11. Simple diagram showing the gravity anomaly caused by partial melting. (a) Gravity anomaly caused by 5 (dotted), 10 (dashed) and 15% (solid) of partial melting within the mantle wedge drawn as shaded area in (b). The thick solid line in (a) represents the observed gravity anomaly that needs to be explained. As shown in (a), partial melting falls very short in explaining the observed gravity anomaly.

Possible explanations for the origin of large, low residual gravity anomaly include: (1) serpentinization of forearc mantle by the dehydration of the downgoing slab; (2) partial melting in the upper mantle above the downgoing slab; (3) difference in the age and thermal structure of the overriding and subducting plates with and without considering compositional stratification between crust and mantle; and (4) anomalous crustal structure beneath the arc and forearc.

Serpentinization reduces the density of the subducting slab and forearc mantle wedge regions (Hyndman and Peacock, 2003). Large amounts of fluid entrapped in the downgoing slab are released into the upper mantle with increasing pressure and temperature. It is thought that most of the water is released beneath the forearc (Peacock, 1990; Schmidt and Poli, 1998). The released fluid generates serpentine and other hydrous minerals from peridotitic upper mantle (Evans, 1977; Kreitler, 1989; Manning, 1995). However, serpentinization generally occurs in a relatively shallow depth, which according to the thermal models of Hyndman and Peacock (2003) is less than about 50 km below the sea level.

Hyndman and Peacock (2003) delineated the zone of hydration within the mantle for various subduction zones in their thermal models. This zone, above which is the most likely location for serpentinization, is found at depth less than 50–60 km below the sea level. Furthermore, in the case of IBM, the zone of mantle hydration is located at less than 150 km from the trench axis. Therefore, in terms of its location, region of possible serpentinization does not match the pattern of the low gravity anomaly in the overriding plate as shown in Figs. 7 and 8. Examination of thermal models for other subduction zones also shows that serpentinization by itself cannot explain the low gravity anomaly in the overriding-plate side of mature subduction system.

Partial melting of the subducting slab may be an important cause of low gravity anomaly under the arc. The release of free water decreases the solidus temperature (Burnham and Davis, 1974) which facilitates the melting. The depth of melting in the subducting plate is generally considered to occur at about 80–150 km below the seafloor (Gill, 1981). However, the distribution and the extent of partial melt within the subduction zone remain controversial.

Still, one can make some quantitative assessments on the contribution of partial melting on the gravity anomaly. The change in density of upper mantle rocks such as peridotite resulting from solid–liquid transition is unclear, but is not thought to be much different from other rock types. In the case of granitic magma, this transition is considered to cause about 10% reduction in density (Philpotts, 1990). Assuming 10% reduction in density, we calculated the resulting gravity anomaly for various degrees of partial melting (Fig. 11). The region affected by partial melting is unclear. In this study, the whole region of the mantle wedge under the crust was taken as the zone of partial melting, although in reality the zone might be smaller. So in effect, our estimate can be considered as the upper bound value. As shown in Fig. 11, the gravitational effect of partial melting is low, generally less than 50 mGal or so. Hence, we argue that partial melting alone cannot explain the large low gravity anomaly seen over the mature subduction zones.

Next, we consider gravitational effect due to difference in the ages of two converging plates, and the effect that it has on the density of the plates as a result of temperature. This effect was studied recently by Marotta et al. (2006, 2007). They examined two cases, one where there is no compositional difference between crust and mantle and one where there is. The results were drastically different. In the case without compositional difference, the thermal contraction produces a gravity high over the subduction zone, whereas the case with compositional difference resulted in a negative gravity anomaly. The sinking of lighter crustal material appears to be an important source of negative anomaly in the subduction zone.

A careful examination of Marotta et al. (2006) reveals that the gravity anomaly resulting from compositional difference, although significant (~100 mGal), lies within 100 km from the trench axis. Thus it alone cannot explain the broad negative gravity anomaly that we observed in the overriding plate of the mature subduction zones. Like other sources, it may, however, explain some part of the total anomaly.

Fig. 10. (a–d) Maps of free-air gravity anomaly derived from satellite altimeters (FAA) for Izu–Bonin, Mariana, Tonga and Kermadec trenches considered as mature subduction zones (see Fig. 1 for locations). (e–h) Maps of isostatic residual gravity anomaly (IRGA). The contour intervals are 40 mGal.

In the case of Marotta et al. (2006), there was little no age difference between the two abutting intra-oceanic plates. In order to study a more realistic case of the western Pacific, it is important to consider gravity anomaly resulting from thermal structure of two plates with large age difference. We examine two cases, one where the two plates are abutting each other, representing a stage just prior to convergence (Fig. 12a–b), and the other where there is a down-dipping slab (Fig. 12c–d). The former case is shown as a reference where young (20 Myr old) and old (150 Myr old) plates are abutting across a plate boundary such as a fracture zone. In the latter case, we use a simple 2-D steady-state thermal model that appeared in van Keken (2003) to calculate gravitational effect. The model is meant to represent a case like the initiation of the Izu–Bonin subduction zone where 20-Myr-old plate was underthrusted by a 150-Myr-old plate. The thermal expansion coefficient of 3.0×10^{-5} K^{-1} is used.

One needs to understand that the thermal model is oversimplified in a sense that it does not consider dynamic topography of the seafloor as a result of subduction and does not take into account of the situations like partial melting. For the moment, such simplification does not matter as we are interested in gross variations in gravity anomaly that occurs at 150–200 km or so from the trench axis. Dynamic topography produces a large variation in the seafloor topography (King and Hager, 1994), but the effect of seafloor topography was already removed in our estimation of SBGA. Thus we do not need to consider in our comparisons.

The resulting gravity anomalies predicted by the two cases differ significantly around the plate boundary (Fig. 12). In the case where two plates are simply adjoining (Fig. 12b), gravity anomaly varies monotonously across the plate boundary (Fig. 12a). However, in the case where the slab is being underthrusted (Fig. 12d), the resulting gravity anomaly shows a huge increase around the trench (Fig. 12c). The latter result is the same as that of Marotta et al. (2006).

If we ignore the gravity anomalies around the plate boundary for a moment due to reasons mentioned above and compare the values at the distal ends of our models, the age difference between young and old plates results in about 100 mGal difference (Fig. 12c–d). This predicted value (100 mGal) is half or less of what is observed (200–250 mGal) in SBGA of mature subduction zones, and therefore age difference alone cannot explain the low gravity anomaly of mature subduction zones. Also it is worth noting that we do not see a large

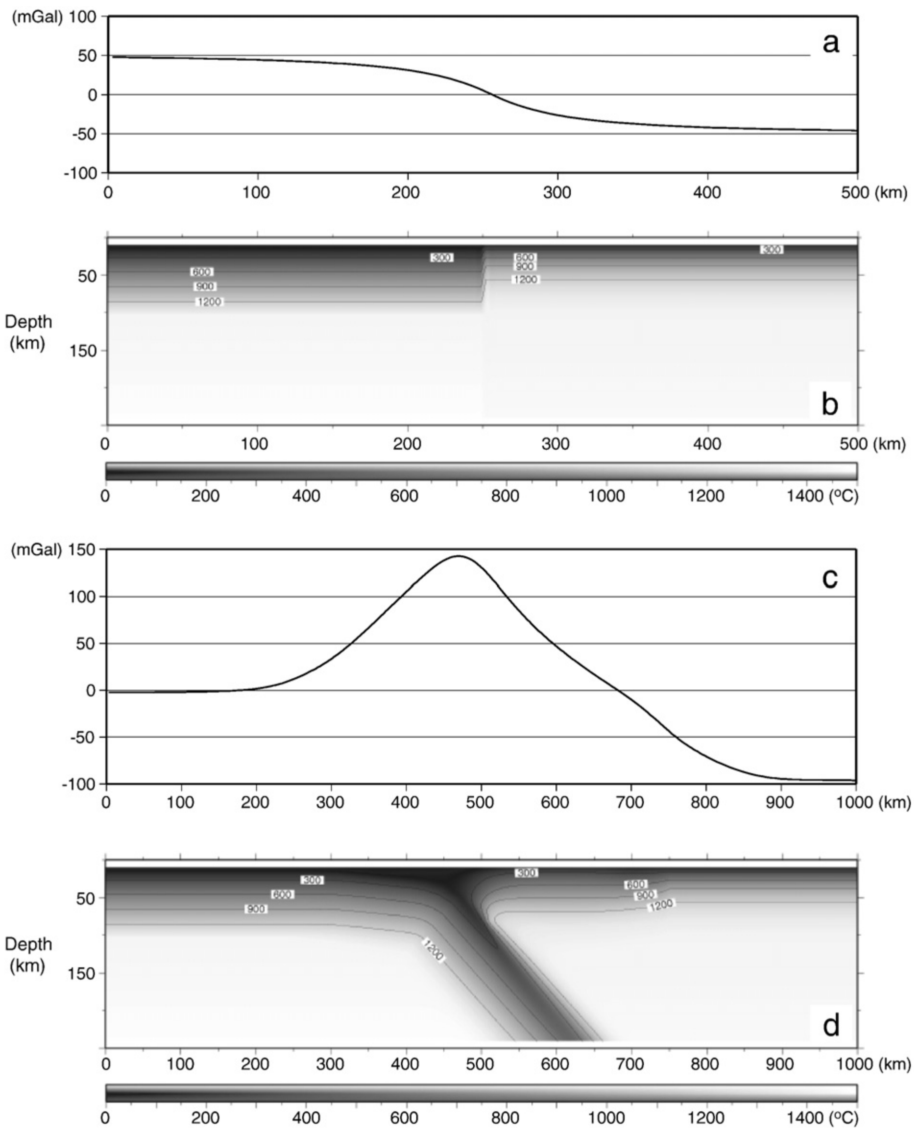


Fig. 12. (a) Calculated gravity anomaly caused by two different age plates abutting each other. (b) Cross section showing the density variation of thermal structure. The slab ages of 20 and 150 Ma are assumed in young and old plates, respectively. (c) Calculated gravity anomaly caused by overriding and downgoing plates in well-developed subduction zone. (d) A simple 2-D steady-state thermal model from van Keken (2003). This model is assumes that the ages of overriding and downgoing slabs are 20 and 150-Myr-old, respectively and subducting speed is 56 mm/yr.

difference in SBGA between two abutting plates at initial stage of subduction (Fig. 12a–b), which seems to suggest that the immature subduction zones that are considered here do not have much age difference between the overriding and subducting plates.

Finally, lateral variations in the density interface such as the crust–mantle boundary can be important sources of gravity anomalies. The crust–mantle boundary lies less than 15 km below the sea surface and represents a contrast in density of at least 0.3 g/cm^3. Therefore, a small change in the depth of crust–mantle boundary or crust thickness will significantly affect the gravity anomaly. One place where a large deviation in the crustal thickness from that expected due to isostatic equilibrium alone may occur is below the magmatic arc. Beneath the arc, dynamic forces such as positive buoyancy resulting from mantle upwelling may act as well. Also there maybe lateral forces acting on the arc. Like contributions due to partial melting discussed earlier, it is difficult to assess the effect of crustal thickness variations under the arc because there are few observational constraints. However, a small deviation in the crust–mantle boundary will be an important source of gravity anomaly compared to other sources.

It was found that, when we compared the gravity anomaly resulting from the P-wave velocity structure of Suyehiro et al. (1996) against the observed, there were some discrepancies (Fig. 4a). The mismatch may not be surprising because the results of Suyehiro et al. (1996) are limited to a depth less than 25 km. Furthermore, the slab is absent (Fig. 4b). In Fig. 13c, we artificially incorporate a downgoing slab to the model of Suyehiro et al. (1996) using the earthquake catalog of Engdahl et al. (1998) as an angle and depth of the downgoing slab. Again the densities of the mantle and slab are in question. We use 3.37 g/cm^3 for the mantle (Afonso et al., 2007) and apply different values for the slab from 3.42 to 3.50 g/cm^3. The resulting gravity anomaly compared against the observed is shown in Fig. 13. We are not suggesting that one of the density values for the slab is correct but instead trying to show that a range of gravity anomalies is possible depending on the density structure.

As mentioned, conversion of P-wave velocity to density may pose as an important source of error in our gravity analysis. Unfortunately, there have been few studies on this matter except for several empirical measurements. This is especially true for cases involving region less than 100 km deep below the seafloor which is the section sensitive to gravity anomaly. Variations in P-wave velocity can result from changes in melt content, rock anisotropy, temperature, rock type and other factors. However, in this study, we did not consider these effects, keeping in mind that gravity anomaly resulting from mistakes in density would have applied to all subduction zones that we considered.

In this study, we were only able to compare two extreme end-members of ATS. In order to provide a more complete picture of subduction evolution, it is important to have ATS that represent intermediate stages of development. The Philippine trench and Puerto Rico trench were suggested as examples representing the intermediate stages of subduction evolution spectrum. Unfortunately, much of the arcs in these trenches are exposed well above the sea surface, and therefore there are no free air-gravity anomaly data. Collection of gravity data over these terrestrial regions requires a lot of time and resources, and as a result the data are scarce. All seven ATS that we examined lie below the sea surface, which makes them possible to compare using satellite altimetry information. Examination and comparison of the gravity anomaly across the intermediate-stage subduction zone remains to be done by combining marine and terrestrial gravity data.

Finally, according to our study, gravity anomaly can be effective means of constraining the structure of ATS, especially within 100 km or so below the sea surface. Unfortunately, the analysis of gravity data has inherent ambiguity, but this can be to certain extent circumvented by complementary geological information. As more information on deep crustal structure becomes available, a significant improvement could be made in the analysis and interpretation of marine gravity anomaly data.

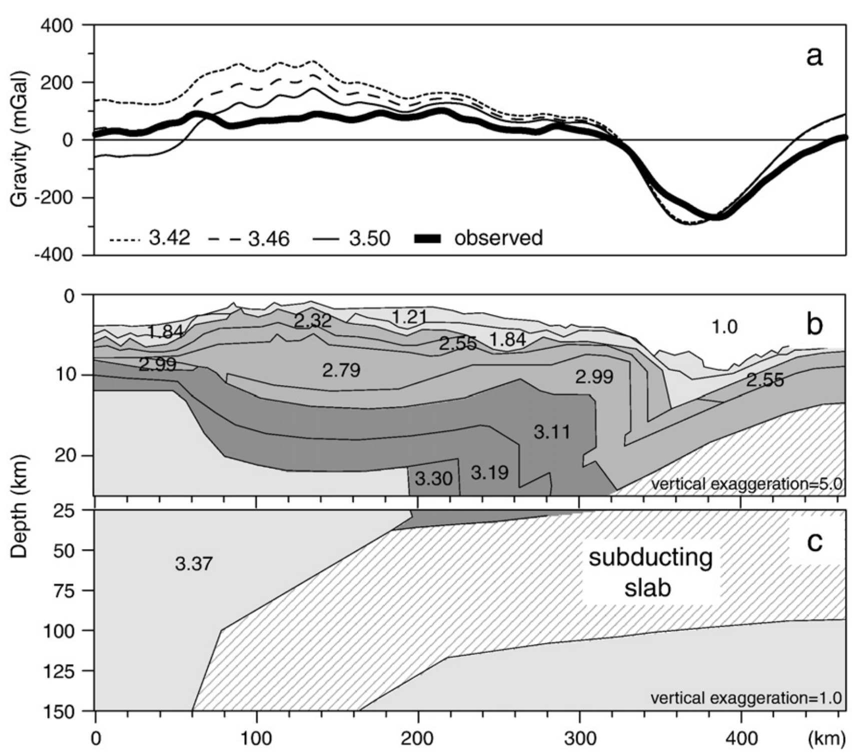


Fig. 13. (a) The comparison of calculated and observed gravity anomalies along the same trackline in Fig. 4. The thick solid line represents the observed value. The thin lines are calculated assuming different slab densities from 3.42 to 3.50 g/cm^3. Density structure of the crust and mantle for upper 25 km (b), same as Fig. 4b, and upper 150 km (c). Dip angle of subducting slab is assumed to be ~30° based on earthquake catalog of Engdahl et al. (1998).

7. Conclusions

Satellite-derived gravity data were used to compare the deep crust and upper mantle regions of mature and immature intra-oceanic subduction zones. Comparison with shipboard gravity data showed that satellite-derived gravity is sufficiently accurate in our regions for examining features that are approximately >10–20 km long.

Substantial difference was found between the gravity anomalies of mature and immature subduction zones. Mature subduction zones show a broad negative gravity anomaly of 200–250 mGal in the overriding plate, whereas immature subduction zones do not. Our study suggests that evolution of subduction zone involves widening of low-gravity-anomaly zone in the overriding plate side. However, the rate at which the widening occurs remains unclear due to lack of cases and gravity data representing intermediate stage of subduction zones.

We evaluate four possible causes of low gravity anomaly in the overriding plate of mature subduction zones. These include (1) serpentinization in the upper mantle beneath the forearc, (2) presence of partial melt in the mantle wedge caused by release of volatiles from the slab, frictional heating and distributed by mantle circulation, (3) difference in the density structure between the overriding and subducting plates resulting from age and thermal structure, and (4) anomalous thickness of the arc crust. Although the gravity anomaly can have stemmed from a combination of above causes, we assess the effectiveness of the individual causes for the moment.

Serpentinization alone does not appear to be the primary source because its location does not match with the pattern of low gravity anomaly in the overriding plate. Furthermore, the gravity anomaly is too widespread to be explained by serpentinization. Our simple calculation shows that the presence of the partial melting in the mantle wedge, despite uncertainty in its degree and extent, cannot be a major source of gravity anomaly as it accounts for less than 50 mGal. The difference of density structure by lithospheric aging is important in two converging plates but it alone cannot explain the total amplitude of the low gravity anomaly. While the sinking of lighter crustal material into the mantle produces a negative gravity anomaly of 100 mGal or so, the location of this anomaly does not match the observed whose center lies at 150–200 km from the trench axis of the overriding plate. In this study, we explored (that is, 20-Myr-old plate abutting 150-Myr-old plate), the difference in thermal structure explains less than half of the total anomaly. The density contrast between crust and mantle is large compared to other sources, and thus the change in the crust–mantle boundary can be effective means of gravitational change. Unfortunately, there is very little information such as deep seismic data to explore the variations in crustal thickness beneath the arc.

In spite of this shortcoming, the analysis of marine gravity data is an important tool for understanding the shallow mantle structure of subduction zones. Also, with greater acquisition of deep seismic data and better knowledge of seismic velocity versus density relationship, a substantial improvement may be made in using gravity data to constrain the evolution of intra-oceanic subduction systems.

Acknowledgements

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