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Key Points:
- Two-dimensional gravity modeling shows a significant high-density structure in the fore-arc region
- Positive buoyancy and weak plate coupling result in serpentinized peridotite exhumed
- Exhumed serpentinized materials in the northern Manila subduction zone are found

Correspondence to:
W.-B. Doo,
wenbindoo@gmail.com

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Exhumation of serpentinized peridotite in the northern Manila subduction zone inferred from forward gravity modeling

Wen-Bin Doo[1], Chung-Liang Lo[2], Hao Kuo-Chen[2], Dennis Brown[3], and Shu-Kun Hsu[1,2]

[1]Center for Environmental Studies, National Central University, Taoyuan, Taiwan, [2]Department of Earth Sciences, National Central University, Taoyuan, Taiwan, [3]Institute of Earth Science "Jaume Almera", CSIC, Barcelona, Spain

Abstract The Taiwan Integrated Geodynamic Research program (TAIGER) collected two wide-angle and reflection seismic transects across the northern Manila subduction zone that provide constraints on the seismic velocity structure of the crust. Two-dimensional gravity modeling along these two transects shows a significant, relatively high density (3.12 and 3.02 g/cm^3) in the fore-arc region, at the interface between the subducting Eurasian Plate and the accretionary prism in front of the Luzon arc on the overriding Philippine Sea Plate. The anomalous density in this zone is higher than that in the fore-arc crust and the accretionary prism but lower than that in mantle. Numerous geophysical and geological data, together with numerical models, have indicated that serpentinization of the fore-arc mantle is both expected and observed. Serpentinization of mantle rocks can dramatically reduce their seismic velocity and therefore their seismic velocity in a density to velocity conversion. Therefore, the source of the high-density material could be serpentinized fore-arc mantle, with serpentinization caused by the dehydration of the subducting Eurasian Plate. We interpret that positive buoyancy combined with weak plate coupling forces in the northern Manila subduction zone is resulting in this serpentinized fore-arc mantle peridotite being exhumed.

1. Introduction

A serpentinized fore-arc mantle wedge is a common feature of many convergent margins worldwide [*Bostock et al.,* 2002; *Hyndman and Peacock*, 2003]. In subduction zones, subducting lithospheric plates induce partial melting in the overlying mantle wedge, causing arc magmatism and resulting in the addition of significant quantities of material to the overlying lithosphere [*Gill*, 1981]. Subducting sediments and altered oceanic crust contain free water in pore spaces and bound water in hydrous minerals that, at depth, can be released into overlying lithosphere causing hydration of the mantle peridotite rocks through the formation of serpentine minerals [*Kirby et al.,* 1996; *Peacock et al.,* 2002]. Furthermore, laboratory measurements of seismic velocities carried out on peridotite rocks show that serpentinization significantly reduces their velocities and densities while increasing Poisson's ratio [*Christensen,* 1966, 2004; *Horen et al.,* 1996]. Recently, *Van Avendonk et al.* [2014] and *Brown et al.* [2015] interpret a high-velocity zone along the arc-continent collision suture in eastern Taiwan to be related to the exhumation of high-pressure rocks and partially serpentinized fore-arc mantle rocks. A key question that remains to be answered is how this zone of exhumation changes southward as the tectonic setting changes from arc-continent collision along eastern Taiwan to intraoceanic subduction in the Manila subduction zone to the south (Figure 1).

In this paper we present the results of gravity modeling along two wide-angle velocity transects (see below) that cross the Manila subduction zone near the transition from the subduction of very thin continental crust to pure intraoceanic subduction with the aim of better constraining the shallow structure and to then investigate the possible presence and nature of a zone of exhumation such as that interpreted farther north.

2. Tectonic Background

Taiwan is characterized by an active arc-continent collision orogeny that involves two subduction systems: the Ryukyu and the Manila subduction zones to the east and south, respectively (Figure 1). The Taiwan orogen is forming as the result of the collision of the Luzon arc on the Philippine Sea Plate (PSP) with the Eurasian Plate (EUP) with a convergence velocity of ~ 8.2 cm/yr along a direction of N310° [*Seno et al.,* 1993; *Yu et al.,* 1997].

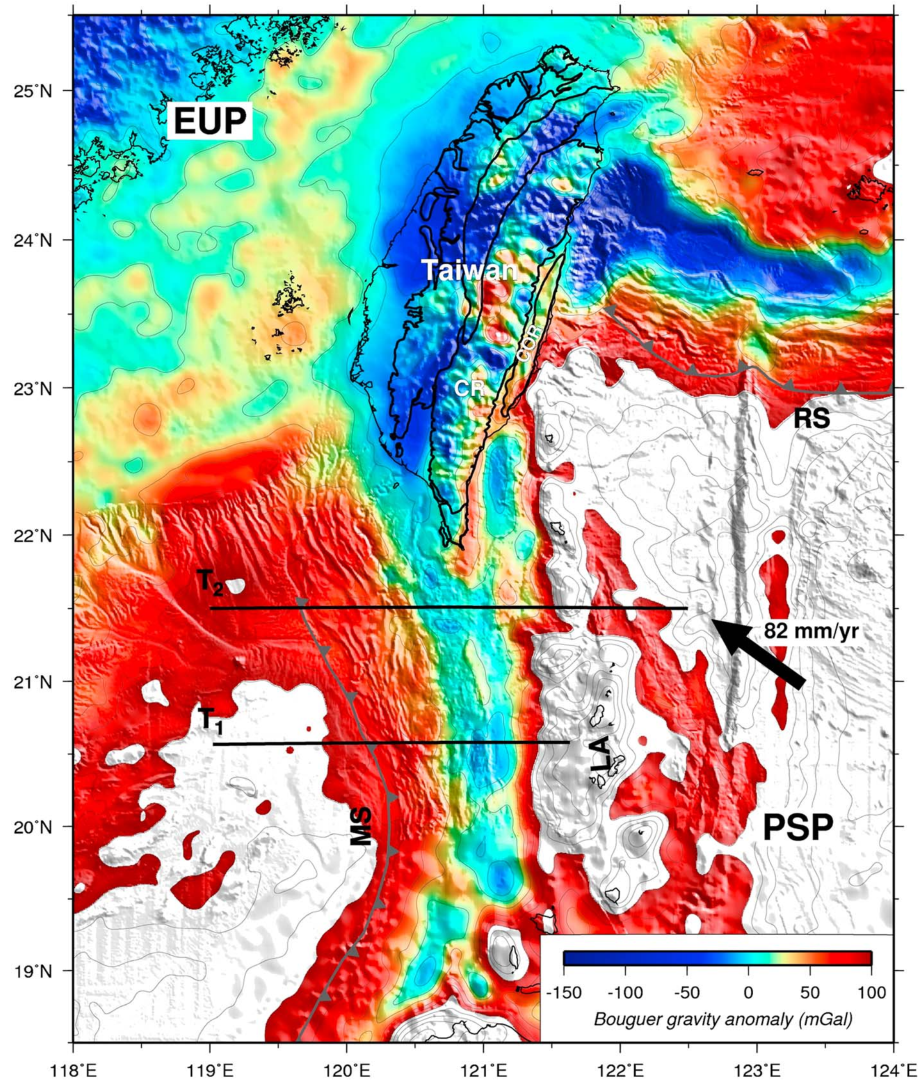

Figure 1. Bouguer gravity anomaly [*Hsu et al.,* 1998] in the Taiwan region. Gravity anomaly contours of 20 mGal interval are plotted. White color indicates that the Bouguer anomalies are larger than 100 mGal. The black arrow indicates the relative plate motion. The locations of 2-D gravity modeling transects shown in Figures 2 and 3 are indicated by thick black lines labeled T_1 and T_2. CR, Central Range; COR, Coastal Range; EUP, Eurasia Plate; LA, Luzon arc; MS, Manila subduction zone; RS, Ryukyu subduction zone; and PSP, Philippine Sea Plate.

In eastern Taiwan, the full thickness of the Eurasian continental margin is involved in the collision, whereas farther south the margin thins and eventually the tectonic setting becomes one of intraoceanic subduction along the Manila subduction zone [*Kao et al.,* 2000] (Figure 1). Therefore, the deep structural features in this area are of key importance for understanding the transition from subduction to collision. With this in mind, the aim of the TAIGER marine experiment that was carried out in 2009 was to characterize differences in structure and physical properties (e.g., seismic velocities) along the subduction zone as it evolves from intraoceanic subduction to arc-continent collision [*McIntosh et al.,* 2013]. Of interest to this paper, two transects (T_1 and T_2) were acquired using ocean-bottom seismometers (OBS) and coincident multichannel reflection seismic (MCS) data (MGL0905_23, 25) in the Bashi Strait between Taiwan and Luzon (Figure 1). These data provide constraints on the geometry of the crust [*Eakin et al.,* 2014], but because of resolution problems, they provide clear images of only the accretionary prism but not the deeper structure along the subduction interface. They do, however, provide an opportunity to further examine the lithospheric structure by high-resolution forward modeling of the gravity data in the area.

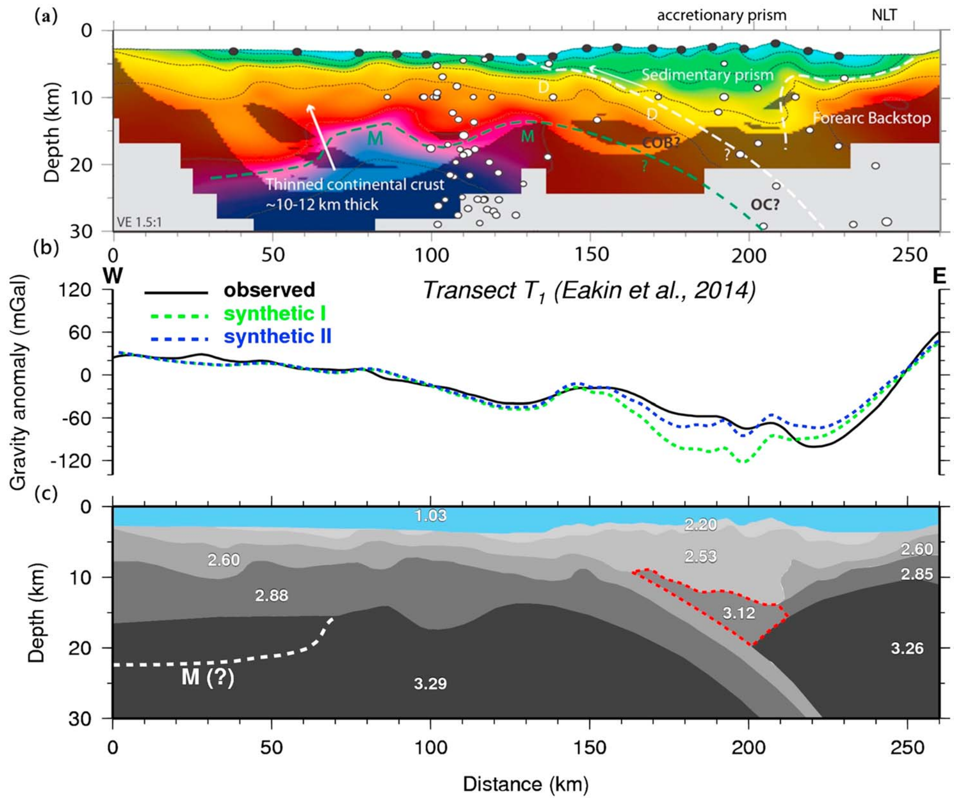

Figure 2. Two-dimensional gravity modeling of the transect T_1 perpendicular to the Manila subduction zone. The profile location is shown in Figure 1. (a) Velocity structures along the profile [from *Eakin et al.,* 2014]. The basal detachment between the accretionary prism and subducting thinned continental crust is labeled D, and the base of the crust is labeled M. COB, continent-ocean boundary; NLT, northern Luzon trough; and OC, oceanic crust. (b) Observed and synthetic gravity anomalies, and (c) gravity modeling result in which the white dashed line indicates the Moho depth identified by *Eakin et al.* [2014].

3. Gravity and Seismic Velocity Data South of Taiwan

The regional Bouguer anomaly map [*Hsu et al.,* 1998] shows a relative high associated with the Central and Coastal ranges of Taiwan (south of 24°N) that, southward, becomes a patchy relative low along the eastern part of the accretionary prism that flanks the Luzon fore arc (Figure 1). In the Central and Coastal ranges, this high has been interpreted to indicate the presence of high-density rocks in the subsurface [*Hsu et al.,* 1998]. Several tomography studies [*Lin et al.,* 1998; *Kuo-Chen et al.,* 2012; *Van Avendonk et al.,* 2014; *Huang et al.,* 2014] have also pointed out the high-velocity zone roughly located in the same area. In southernmost Taiwan, *McIntosh et al.* [2005, 2013] and *Cheng* [2009] found prominent high-velocity zones beneath the offshore area and the Central Range. Farther south, between Taiwan and Luzon, *Chi et al.* [2003] used MCS and gravity data to study the deeper structural geometry of the Manila accretionary prism. In that work, they found a free-air gravity anomaly high in the rear of the accretionary prism at 20.9°N. The authors interpreted this high-density material to be derived from the fore-arc. However, the depth resolution is limited to above 8 km. *Eakin et al.* [2014] presented two *P* wave velocity transects in which they suggested that hyperextended continental crust of the rifted Eurasian margin is being subducted and underplated to the accretionary prism at its base and along the subduction channel. Due to poor resolution in the deeper parts of the accretionary prism, they could not interpret the structure of this part of the subduction channel and fore-arc mantle. They do, however, interpret a relative rise in seismic velocities along the subduction channel to be related to low-grade metamorphic rocks that are being exhumed by continued convergence and buoyancy.

4. Gravity Modeling

Gravity modeling was carried out by first converting the *P* wave velocity models of *Eakin et al.* [2014] for transects T_1 and T_2 (Figures 2a and 3a) using the *P* wave to density relationship of *Brocher* [2005]. In the

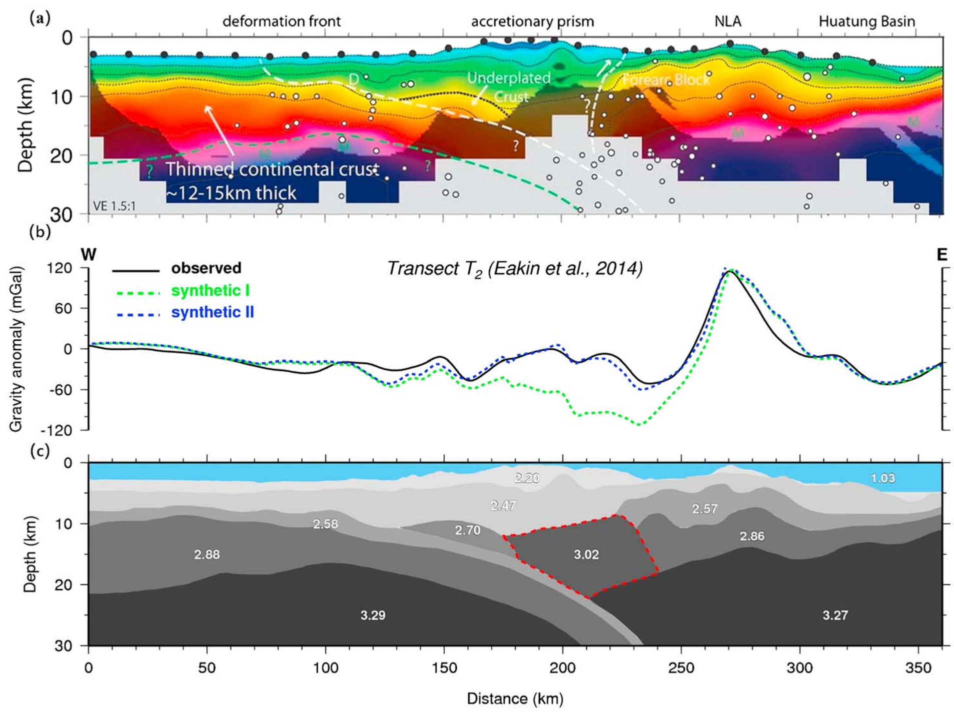

Figure 3. Two-dimensional gravity modeling of the transect T_2 perpendicular to the Manila subduction zone. The profile location is shown in Figure 1. (a) Velocity structures along the profile [from *Eakin et al.,* 2014]. NLA, Northern Luzon arc. (b) Observed and synthetic gravity anomalies and (c) gravity modeling result.

deeper part of the fore-arc area, where the resolution of the MCS and OBS data is poor, we have extended the velocity contours to be the layer boundaries and then adjusted the densities and layer geometries until the synthetic anomaly was fitted to the measured gravity anomaly (Figures 2 and 3). Although the gravity modeling is nonunique, the constraints placed on the crustal structure by the velocity models, and hence the layer geometries and densities of the gravity model, reduce this problem, while at the same time providing possible solutions for the deeper fore-arc area that is poorly resolved by the MCS and OBS data.

Overall, our density models coincide very well with the velocity models of *Eakin et al.* [2014], although in order to fit the observed regional long-wavelength gravity anomaly, the Moho depth in transect T_1 should be revised as shown in Figure 2. Of interest to this paper, in the area along the subduction channel where *Eakin et al.* [2014] could not resolve the structure, we find that, in both transects, rocks with a high density (3.12 and 3.02 g/cm^3) are needed in order to fit the short wavelength gravity anomaly above the accretionary prism (blue dashed line shown in Figures 2 and 3). If we assign a density of 2.75 g/cm^3 (normal crustal density) for the block, the maximum misfit between synthetic (green dashed line shown in Figures 2 and 3) and observed gravity anomalies can reach 40 and 80 mGal in transects T_1 and T_2, respectively. These rocks must have densities that are higher than that for the average continental crust that is subducting and lower than that for the average mantle peridotite beneath the Luzon arc. The high density, combined with the location of this body above the subducting continental crust and beneath the accretionary prism, leads us to interpret it as comprising serpentinized mantle rocks.

5. Discussion and Conclusions

It is well known that there is a significant reduction in the seismic velocities (both *P* and *S* waves) and density of peridotite with an increase in the modal abundance of serpentine [*Christensen,* 1966, 2004; *Horen et al.,* 1996; *Hyndman and Peacock*, 2003]. Furthermore, there is widespread geophysical evidence for serpentinized fore-arc mantle in a number of subduction zones including those in Alaska, the Aleutian Islands, Chile, Cascadia, Izu-Bonin-Mariana, and central Japan [*Kamiya and Kobayashi*, 2000; *Bostock et al.,* 2002; *Carlson and Miller*, 2003; *Hacker et al.,* 2003; *Alt and Shanks*, 2006]. In these active tectonic settings, low-velocity

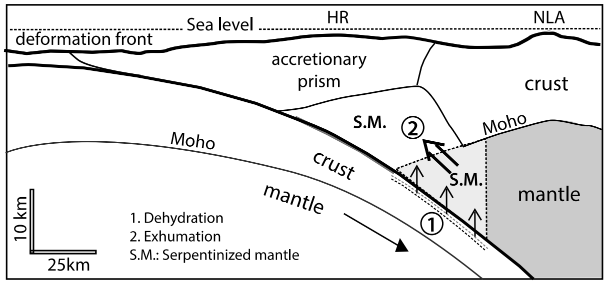

Figure 4. Schematic diagrams illustrating the evolution model of the exhumed serpentinized mantle materials. HR, Hengchun ridge and NLA, Northern Luzon arc.

and low-density anomalies are often interpreted to be associated with the degree of serpentinization of the fore-arc mantle. For example, *Zhao et al.* [2001] and *Hyndman and Peacock* [2003] suggest that as little as a 5% decrease in seismic velocity in a fore-arc region can be explained by 15–20% serpentinization of the upper mantle, and that this reduction in velocity is concomitant with a reduction in density. Although the *P* wave model from *Eakin et al.* [2014] does not provide any constraint on the velocity of mantle, based on the gravity modeling of the unserpentinized and serpentinized Luzon fore-arc mantle, we can calculate a density reduction of the serpentinized Luzon fore-arc mantle in transects T_1 and T_2 to be 4.3% and 7.6%, respectively. With the density to *P* wave relationship of *Brocher* [2005], thus, we can then use the velocity reduction expected for serpentinized peridotite [e.g., *Christensen*, 1966] to speculate that the degree of serpentinization in these transects could be 13–17% and 23–30%, respectively. These values are in keeping with those of *Cheng et al.* [2012] who use Poisson's ratio to estimate the percentage of serpentine in fore-arc mantle in the southeastern Taiwan. Farther north, where arc-continent collision is in progress, a tectonic mélange in eastern Taiwan contains a variety of exhumed rocks including serpentinized mantle [e.g., *Liou*, 1981], providing clear evidence that this process was active in the Manila subduction zone. *Van Avendonk et al.* [2014] and *Brown et al.* [2015] have also interpreted the presence of serpentinized mantle rocks beneath eastern Taiwan to explain an observed high-velocity zone in this area. The density of 3.10 g/cm^3 that *Van Avendonk et al.* [2014] calculate for this high-velocity zone is in keeping with that obtained from our gravity modeling result.

Geological studies combined with numerical modeling have shown that serpentinization of the fore-arc mantle region plays an important role in the exhumation of high-pressure terranes along subduction zones [e.g., *Gerya et al.*, 2002; *Gerya*, 2011; *Hacker and Gerya*, 2013; *Erdman and Lee*, 2014]. While various mechanisms have been proposed for how exhumation proceeds [*Hacker and Gerya*, 2013], the buoyancy of the serpentinized mantle in the channel flow model is important. Furthermore, *Hyndman and Peacock* [2003] have proposed that the serpentinization of the mantle wedge seaward of the arc will decrease the coupling between the subducting plate and mantle wedge, and that the weak rheology and positive buoyancy of the serpentinized mantle will act to isolate hydrated fore-arc from the mantle wedge flow system. Using an estimation of the buoyancy of mantle lithosphere, *Lo et al.* [2015] suggest that coupling in the northern Manila subduction zone is weak. We suggest, therefore, that positive buoyancy of the serpentinized mantle rocks modeled here, together with weak coupling along the subduction interface, is resulting in the exhumation of these rocks along the subduction channel via the process of channel flow (Figure 4). With an increasing thickness of the continental crust entering the subduction zone farther north, these rocks appear to become intermixed with variably metamorphosed rocks derived from the fore arc and the continental margin to form the high-pressure terrane that crops out in eastern Taiwan and possibly the high-velocity zone that extends from beneath it to deep into the subduction zone [*Brown et al.*, 2015].

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