Topography and gravity across subduction zones

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Abstract. Topographic and Free-air gravimetric profiles across subduction zones show two distinct signatures. Average low topography (-1250 m) and pronounced gravimetric anomalies characterize west-directed subduction zones. Average elevated topography (1200 m) and smoother gravimetric waves are peculiar to east- or northeast-directed subduction zones. These differences are particularly evident along the Pacific margins, but they persist also along the other subduction zones of the world in the Atlantic, Mediterranean, Himalayas and Indonesia regions. Therefore topography and gravimetry confirm the existence of two separate classes of subduction zones which appear to be independent of the age and nature of the subducting slab. It is suggested that these differences might be linked to the 'westward' drift of the lithosphere relative to the underlying upper mantle.

Introduction

The topographic expression of subduction zones in the Pacific is impressively different comparing the western and eastern sides of the ocean. High elevation occurs in the hangingwall of the Andean subduction whereas average elevation below the sea-level characterizes the hangingwall of the Marianas and similar subduction zones. In the Pacific, the subduction zones directed to the west are steep (up to 90°) and deep (down to 670 km) with respect to those directed to the east which are in the average shallower and less inclined [Isacks and Barazangi, 1977; Lundgren and Giardini, 1994]. Doglioni [1993] described the geological signatures associated with this asymmetry and proposed an undulate flow of plate motion on the Earth’s surface. Along this flow the asymmetry of the western and eastern Pacific subduction zones persist as a function of the geographic polarity of the other subduction zones of the world, even in complicated areas such as the Mediterranean or Indonesia. The east- or northeast-directed subduction zones are characterized by orogens with high structural elevation, double vergence, basement rocks deeply involved by deformation, and two foredeeps with low subsidence rates. The west-directed subduction zones are instead associated with low structural elevation, single eastward vergence of the accretionary prism, mainly sedimentary cover involved, one foredeep with high subsidence rates, and a back-arc basin to the west.

We aim to better quantify some aspects of these global signatures in terms of topography [e.g. Talwani, 1970] and gravimetry, and we present representative profiles of the main subduction zones of the Earth. We used the data base from the Global Relief Data of the National Geophysical Data Center (Boulder, CO, USA) and performed a first selection of 22 topographic and Free-air gravimetric sections across the most typical subduction zones of the world (Figure 1). Since gravimetric data are satellite-based, it is not necessary to apply any correction (e.g. Bouguer); topographic effects are already filtered out. The topographic sections were positioned along transsects that represent the mean elevation of the subduction systems, with variations along strike in the order of about 10-15%. These subductions are clearly divided into two classes. The first, which we named W-class, and the second, named E-class. W-class subductions (Figure 1) are directed W (e.g., Marianas, Barbados, Apennines, Randa) or W-NW (Alentijans) while E-class subductions (Figure 1) are directed E (Oregon, Peru, Chile), NE (e.g. Dinarides, Cyprus, Zagros, New Hbrides) or NNE (e.g., Himalayas, Sumatra). W-class subductions are characterized by steep subduction angles (up to 90°), while E-class subductions are associated with rather low angles (less than 40°). The topographic and gravimetric signature of two profiles is affected by the signature of both types of subductions (W-class Apennines and E-class Dinarides-Hellenides; and W-class Banda and E-class New Guinea); therefore we did not include them in the stack and average profiles (Figures 2, 3 and 4). We present the two sections separately as Figure 5. The topographic and gravimetric profiles relative to the remaining 20 sections comprises 9 subductions of the W-

Table 1. List of the sections across subduction zones used for the average profiles. a) subduction; b) and c) section extremities (lat. and long.); d) age of subducting plate (Ma); e) convergence rate (cm/yr); f) gravity minimum in correspondence of trench (mgal); g) gravity maximum in correspondence of the arc (mgal); h) gravity difference between f) and g); i) minimum elevation at the trench (m); j) minimum elevation at the arc (m); k) elevation difference between i) and j).

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<th>a</th>
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<td>W-ALPS</td>
<td>46.4°N - 16.4°N</td>
<td>46.4°N - 16.4°N</td>
<td>17</td>
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<td>41.5°N - 36.8°N</td>
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<td>-91</td>
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<td>310</td>
<td>319</td>
<td>17</td>
<td>-91</td>
<td>165</td>
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<td>54.1°N - 68.6°N</td>
<td>17</td>
<td>-36</td>
<td>61</td>
<td>127</td>
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<td>275</td>
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<td>0.4°S - 10.9°S</td>
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<td>-106</td>
<td>93</td>
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<td>-37</td>
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<td>32</td>
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<td>-56</td>
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<td>54</td>
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class and 11 of the E-class. In Table 1 are listed the coordinates and the main variables of the profiles.

**Data Discussion**

Regarding topography, the W-class (Figure 2a and b) is characterized by a narrow arc-chain in the hangingwall of the subduction (about 200-300 km in section), that rises to 2000-3000 m over the mean plate height. The subducting plate is typically only 1000-2000 m lower than the overriding one. If the subducting plate is oceanic, there is always a pronounced trench, whereas for continental plates, the trench may be filled (e.g., Carpathians) or unfilled (Banda) by sediments. The associated volcanic arc is typically well defined. Conversely the E-class is marked by a massive hangingwall chain (even 1000-2000 km in section) that rises to 4000-6000 m over the mean plate height (Figure 2c and d). This, in turn, is on average 2000-3000 m higher than that of the subducting plate. The trench is much less prominent or sometimes completely absent also in case of subducting oceanic plates.

W-class subductions are characterized by strong negative Free-air gravimetric anomalies with an asymmetric shape (150-200 mgal) along the trench (Figure 3a and b), by a prominent positive signature (over 100 mgal) corresponding to the arc-chain, and similar gravimetric values on both plates immediately off the trench-arc system. Conversely E-class subductions are characterized by less pronounced negative gravimetric anomalies (about 100 mgal or less) with a strong asymmetric shape relative to the trench (Figure 3c and d), less pronounced positive anomalies (less than 100 mgal) corresponding to the orogen, and higher gravimetric values (20-40 mgal) on the overriding plate immediately off the back-thrust belt with respect to those observed on the subducting plate immediately before the plate.
bulge. In case of subducting continental plates there seems to be a large compensation.

Some of the subduction zones do not present all the peculiarities of the W- or E-class. However none of them differs by more than a couple of characteristics from the standard of its assigned class. In the case of the New Hebrides, for example, the backthrust belt is not as massive as the typical E-class chain probably because the subduction is at a very early stage. The Ryukyu back-arc basin is at a much higher elevation than the fore-arc because of the great quantity of sediments from the Asiatic rivers. For the same reason gravimetric anomalies are much less pronounced.

Average W- and E-class topographic and gravimetric profiles are shown in Figure 4. They are obtained by stacking the profiles after multiple cross-correlation where the dominant terms of the spectrum are the gross features (e.g. arc, trench). It is interesting to note that this operation has the effect of filtering out local topographic and gravimetric effects leaving only the long wave-length signals. These in turn yield the same trend both for topographic and gravimetric profiles, supporting the hypothesis that a significant portion of the zero-order effects are linked to the shallower topographic features. Maximum average values of elevations of belts in the hangingwall plate of the W-class are about 1250 m below sea level, whereas this value is about 1200 m above sea level for the E-class. Regarding gravity, both classes exhibit asymmetric profiles (Figure 3). However the W-class has the same dip on the limbs of the negative anomaly (Figure 3a and b), whereas the anomaly of the E-class shows a steeper limb toward the hangingwall plate (Figure 3c and d). Moreover the minimum of the E-class is wider and not nearly as peaked in the W-class. Another important feature is the positive values (about 30 mgal) of the overriding plate in E-class subductions. Figure 4 (a-c) shows that the minimum of the free-air anomaly of the W-class does not correspond to the topographic minimum as it does for the E-class (Figure 4 b-d), but it is rather shifted toward the chain.

The elevated topography along east- or northeast-directed subduction zones is consistent with the high uplift rates associated with this type of orogens (e.g. Cordillera, Himalayas), in contrast with the low-lying accretory prisms associated with west-directed subduction zones, which are very often below sea-level despite high convergence rates (e.g., Marianas). Japan topography could recall E-class subduction. Even if it is clear that the most relevant system during the Neogene has been the west-directed subduction zone, seismicity, morphology and low dip of the slab might indicate that the system has began to invert to an east-directed subduction zone which will ultimately close the Japanese back-arc basin. It is noteworthy however that the gravity profile of Japan follows the W-class.

Geodynamic Implications and Conclusions

Differences in subduction styles have been explained as due to variations in age and thickness of the oceanic lithosphere and convergence rates [e.g., Jarrard, 1986; Royden, 1993]. However, there are cases where the same plate is subducting with a different style and angle depending only on the orientation (W or E-NE). One example is the Adriatic microplate (Figure 5A). The western margin of this plate is continental in the central northern Adriatic sea and oceanic in the Ionian sea to the south and it is sinking toward the west almost vertically beneath the Apenninic arc [Mongelli et al., 1975; Selvaggi and Chiariabba, 1995]. The eastern margin of the same plate which is still continental in the Adriatic sea offshore former Yugoslavia and Albania, and oce-
nic to the south in the Ionian sea, offshore Greece, is instead sinking at low angle beneath the Dinarides and Hellenides [Papazachos & Comninakis, 1977; Christova and Nikolova, 1993; Pirimollo & Morelli, 1996]. Therefore the same plate with along-strike lithospheric variations is subducting along the western and eastern Adriatic and Ionian seas, and it determines orogens that fall into the W-class and E-class independently from the nature and age of the downgoing lithosphere. For a geodynamic discussion about the E-class nature of the Hellenic-Aegean system, see Doglioni [1995]. Another case of comparison among the two classes are the Banda and western New Guinea subduction zones (Figure 5B). There the thinned northern Australia continental lithosphere subducts both toward the west underneath the Banda arc and toward the northeast beneath New Guinea. Topography, gravimetry and all the other geologic and geophysical parameters of the two subductions fall respectively into the W-class and E-class even in the presence of the same continental lithosphere. This suggests that the nature and age of the downgoing lithosphere is not the primary factor in determining the characteristics of the W- and E-classes. Even more striking is the example of the Kermadec-Macquarie subduction; to the north the Pacific plate subducts westward at a high angle, with low elevation of the hangingwall plate and a deep trench. As we move south where the subduction flips from west directed to northeast-directed, there is immediate high elevation of the hangingwall plate (New Zealand) and the trenches are shallower, despite the upper plate is either continental or oceanic. However in this case the New Zealand-Macquarie subduction has the Tasmanian sea oceanic lithosphere in the footwall which is younger than the Pacific lithosphere of the Kermadec subduction, but still all the parameters fall into the W-class for Kermadec and E-class for New Zealand subduction zones. On the other hand, along the Sandwich subduction zone the uniformly Atlantic and Antarctic oceanic lithospheres show age variations (5-120 Ma), but the subduction system maintains the characteristics of the W-class. These examples suggest that the geographic polarity of the subduction more than any other parameter constrains the different character observed in the two classes. This poses the question whether subduction can be influenced by the relative ‘westward’ drift of the lithosphere with respect to the upper mantle postulated by several authors [Le Pichon, 1968; Ricard et al., 1991; O’Connell et al. 1991]. The polarization imposed by the ‘westward’ drift would be able to differentiate the opposite behaviour of the decollement planes along the W-directed and E- or NE-directed subduction zones and to determine the differences on the orogenetic belts [Doglioni, 1993] which may be analyzed also in terms of the ratio between convergence rate and retreat rate of the subduction hinge [Waschbusch and Beaumont, 1996]. The cross-sections of the subductions examined here parallel the undulated flow of plate motion proposed by Doglioni [1993]. One could argue that the two classes of subduction zones and related orogenes are simply sensible to the thickness and composition of the hangingwall and footwall plates. It has been interpreted that the characteristics of the W-class are defined by the intratropics nature of the subduction zones, but we have also shown cases of continental subduction (e.g. Carpathians and Banda arcs). Moreover, at the early stages, the subductions pertaining to the W-class in the Pacific were in a continent-ocean condition without generation of elevated orogens. However the observations suggest that the two classes persist independent of the age and nature of the involved lithospheres, and that they are primarily constrained by the geographic polarity (Figure 5).

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References


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