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Basin formation by volcanic arc loading

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ABSTRACT

This paper quantifies the flexural subsidence expected from loading by a volcanic arc. The resulting mathematical model shows that the arc width should grow with time and that the subsidence beneath the load can be estimated from the observed arc width at the surface. Application of this model to the Halmahera Arc in Indonesia shows an excellent fit to observations if a broken-plate model of flexure is assumed. The model also gives an excellent fit to data from East Java, also in Indonesia, where it is possible to forward model gravity anomalies. In particular, the depth, location, and width of the depocenter-associated gravity low are accurately reproduced, although the model does require a high density for the volcanic arc (2900 kg m^{-3}). This may indicate additional buried loads due, for example, to magmatic underplating. Our main conclusion is that loads generated by the volcanic arc are sufficient to account for much, if not all, of the subsidence in basins within ~100 km of active volcanoes at subduction plate boundaries, if the plate is broken. The basins will be asymmetrical and, close to the arc, will contain coarse volcaniclastic material, whereas deposits farther away are likely to be volcaniclastic turbidites. The density contrast between arc and underlying crust required to produce the Indonesian arc basins means that they are unlikely to form in young intraoceanic arcs but may be common in older and more mature arcs.

Keywords: volcanic arc, loading, flexural subsidence, Indonesian arcs.

INTRODUCTION

This paper investigates whether the isostatic load of volcanic arcs could be responsible for a significant fraction of the subsidence frequently observed in volcanic arc settings. Arc volcanism occurs in the overriding plate of a subduction system by melting of the mantle wedge owing to introduction of volatiles carried beneath it by the subducting plate. Basins commonly form both trenchward of the arc (the forearc) and behind the arc (the backarc). However, there is no consensus concerning the precise mechanism responsible for basin formation. Dewey (1980) suggested that these basins result from extension caused by rollback of the subduction hinge; i.e., the location of subduction moves progressively away from the overriding plate and so drags the overriding plate with it. Another suggestion is that extensional stresses are set up by secondary mantle currents created by subduction (Toksöz and Bird, 1977). It is also possible that basins result from loading by magmatic underplating, as has been suggested for loading of oceanic lithosphere by volcanic islands (Watts et al., 1985). Another possibility (Bahlburg and Furlong,

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1996; Smith et al., 2002) is that the arc volcanism itself produces significant near-surface loads leading to the formation of flexural basins. This last suggestion is the one pursued in this paper, although we emphasize that basins form in arcs by a number of mechanisms, and we are not proposing that all basins form in this way. The model has particular relevance to basins that form very close to the volcanic arc. The proximal parts of such basins will be characterized by coarse volcanic debris of primary volcanic and sedimentary origin, typically terrestrial to shallow marine, and may include mass-flow deposits of different types.

The idea that the lithosphere flexes in response to volcanic loads is not new, although it has most commonly been applied to loading of oceanic lithosphere by island chains associated with hot-spot volcanism (Watts and Cochran, 1974; Watts et al., 1997). Bahlburg and Furlong (1996) applied a continuous-plate flexure model to subsidence in the Ordovician foreland of northwestern Argentina. Their model used geographically extensive volcanic loads and was able to produce >8 km of subsidence. In a similar study using the same modeling algorithm (attributed to Slingerland et al., 1994), Smith et al. (2002) modeled subsidence of the Abiquiu Embayment in the Rio Grande Rift, southwestern USA. The Rio Grande study also employed a volcanic load that filled most of the resulting basin, but the calculations of Smith et al. (2002) accounted for only 800 m of subsidence in that area. Other authors (e.g., Karner and Watts, 1983; Nunn et al., 1987) applied similar models to continental subsidence resulting from thrust-emplaced loads on an unbroken plate. These studies showed that gravity profiles were consistent with flexural subsidence, although, in most cases, additional subsurface loads were required to explain the observed subsidence.

In this paper we produce a semianalytical model relating the observed surface width of the loading volcanic arc to the resulting subsidence. We also look at the consequences of assuming a broken-plate rather than a continuous-plate model for the underlying lithosphere. Our approach principally differs from that employed by others in that it predicts the volcanic load from first principles, thus providing constraints on loading that are independent of those obtained, for example, from gravity modeling. Such an approach is difficult for geometrically complex thrust-emplaced loads (Nunn et al., 1987) but, as shown here, is relatively straightforward for a volcanic arc load.

EVIDENCE FOR ARC LOADING IN INDONESIA

In many volcanic arcs, thick sequences of sedimentary and volcaniclastic rocks in basins are close to, and on both sides of, the volcanic arc. Much, if not all, of the material in the basins is derived from the arc itself, and much of it is very coarse. In Indonesia (Fig. 1), many basins near modern volcanic arcs have proved rich in hydrocarbons and consequently have been the target of exploration work. The North, Central, and South Sumatra Basins, and the offshore Northwest Java and East Java Basins are examples. However, these basins are typically >100 km from the active volcanic arc and have been described as backarc basins (e.g., Busby and Ingersoll, 1995), although they are not floored by oceanic crust and lack many features of backarc basins (Smyth et al., 2007, this volume). Nor are they retro-arc foreland basins formed in response to thrusting and dynamic subsidence driven by subduction (e.g., DeCelles and Giles, 1996), as pointed out by Moss and McCarthy (1997). The Sunda Shelf basins have many characteristics of rift basins (Cole and Crittenden, 1997; Hall and Morley, 2004). However, the basins we are concerned with are much closer to the arc itself. Seismic lines cross many of these basins, but it is rare for them to approach close to the volcanic arc because the volcanic-rich sequences are normally considered to be relatively unprospective as far as hydrocarbon source rocks are concerned. Also, potential reservoir rocks commonly have problems with loss of porosity and permeability owing to breakdown of unstable grains, and close to the arcs, seismic data are difficult to acquire and interpret. We have studied a number of Indonesian volcanic arcs in the field and have worked on the sequences in basins close to the volcanic arcs. The ages and histories of the basins suggest that their development is related closely to the development of the volcanic arc. We have chosen two different arcs in Indonesia for which the history of the basin and the arc is known, and where volcanic loading is a plausible explanation of at least some of the basin subsidence. These are South Halmahera and East Java (Fig. 1), where the arcs are built on different types of crust.

South Halmahera

Halmahera has a long volcanic arc history extending from the Late Jurassic, almost entirely intraoceanic (Hall et al., 1995). The present arc is in its final stages of activity, as subduction has nearly eliminated the Molucca Sea, and the Sangihe and Halmahera Arcs (Fig. 2), on the west and east sides of the Molucca Sea, are actively colliding. The Molucca Sea plate dips east under Halmahera and west under the Sangihe Arc in an inverted U-shape (McCaffrey et al., 1980). Seismicity shows ~200–300 km of lithosphere subducted beneath Halmahera, whereas the Benioff zone associated with the west-dipping slab can be identified to a depth of at least 600 km beneath the Sangihe Arc.

The modern arc (Figs. 1 and 2) resumed activity in the Quaternary, after a brief decline in volcanic activity, and the axis of the arc moved ~50 km west from its late Miocene to Pliocene position (Hall et al., 1988b, 1995). Both these arcs are built on older volcanic arcs active during Cretaceous and early Cenozoic time. The Quaternary and Neogene Halmahera Arcs have a chemical character typical of intraoceanic arcs (Morris et al., 1983; Forde, 1997). There is no evidence of continental crust beneath them except at the southernmost end of the volcanic arc (Morris et al., 1983), on Bacan and Obi, where movement on strands of the Sorong fault zone brought slivers of the continental crust beneath the arc in the last few million years (Hall et al., 1995; Ali et al., 2001). Mapping of the Halmahera Arc shows that the basement is ophiolitic, formed in an early Mesozoic intraoceanic arc (Hall et al., 1988a; Ballantyne, 1992), overlain by Cretaceous, Eocene,

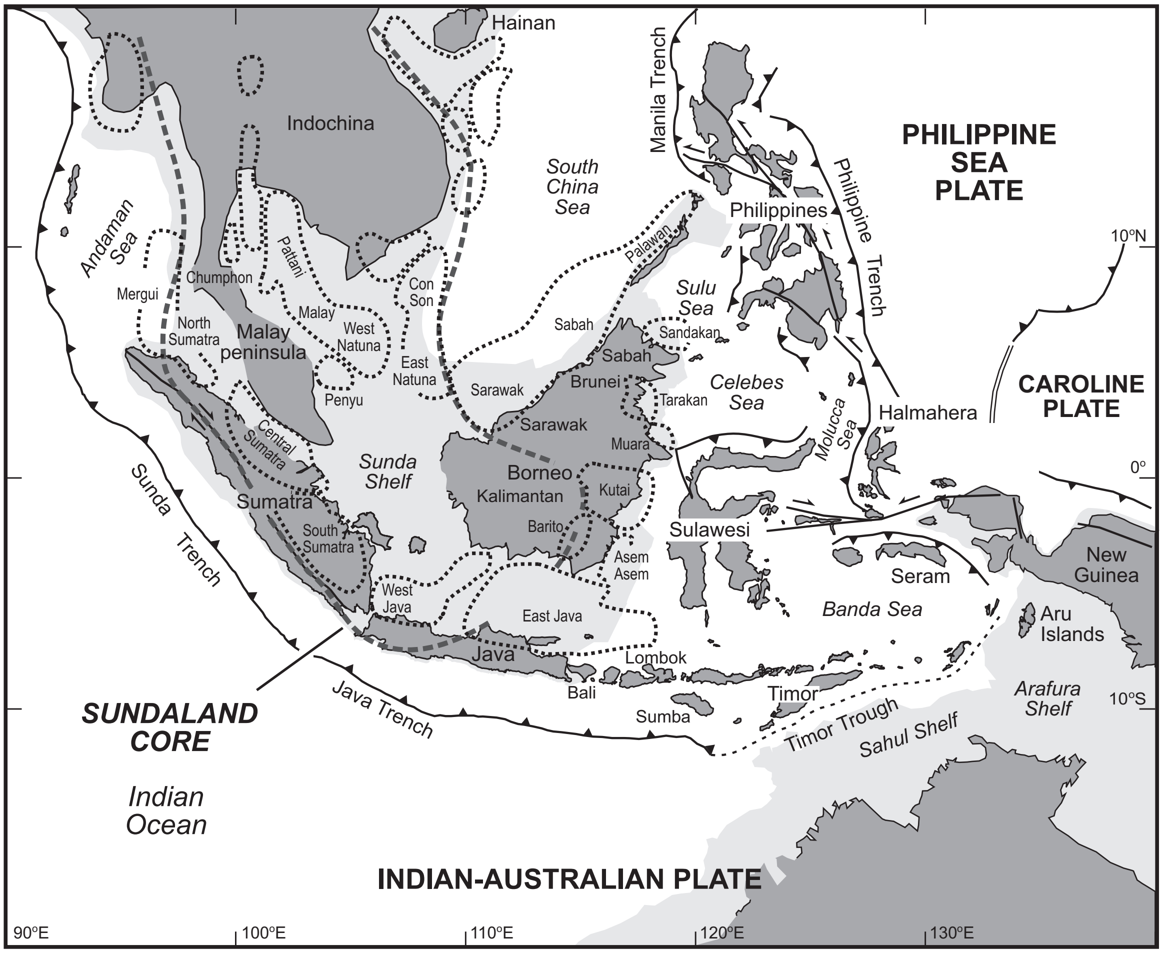

Figure 1. Major basins of the southern Sundaland margin and location of the Halmahera and Java Arcs.

and Oligocene arc volcanic rocks. Shallow Miocene marine carbonates unconformably overlie all the older rocks.

The Neogene Halmahera Arc became active at ca. 11 Ma at its southern end on Obi (Hall et al., 1995). In SW Halmahera, volcanic activity began a little later as magmatism propagated north. Basins formed on each side of the arc. In South Halmahera, activity in the volcanic arc, and subsidence on each side of the arc, began in the late Miocene at ca. 8 Ma. To the west, turbidites and debris flows were deposited in the forearc, and to the east (Fig. 2), a marine basin developed in Weda Bay (Hall, 1987; Hall et al., 1988b; Nichols and Hall, 1991).

On the western side of the SW arm of Halmahera (Fig. 2) there was subsidence and deposition of at least 1000 m of submarine slope deposits in the forearc (Nichols and Hall, 1991). In the forearc, subsidence significantly exceeded the supply of material. In contrast, on the backarc side, sediment supply broadly kept pace with subsidence. On land in the SW arm of Halmahera there are between 2800 and 3800 m of sedimentary rocks in the basin east of the arc (Nichols and Hall, 1991). They were deposited close to the arc in shallow water and rest unconformably on pre-Miocene volcanic rocks or locally on shallow-water lower to middle Miocene limestones. The sequence fines up from fan-delta conglomerates into sandstones, mudstones, and limestones. Shallow marine deposition continued into the Pliocene. The depth of water at the time of deposition of the upper part of the sequence is uncertain but was no more than a few hundred meters.

The Miocene–Pliocene sequence interpreted from the seismic sections (Fig. 3) across Weda Bay varies in thickness. It rests unconformably on a karstified limestone surface and is up to 2000 m thick in local depocenters but is typically ~1000 m thick. Hence the basin was markedly asymmetric, with the greatest thickness of sediment adjacent to the Halmahera Arc on the western side of the basin. The local depocenters offshore, and the fan deltas onshore, are thickest close to interpreted volcanic centers. There is little evidence of faulting associated with basin formation on seismic lines (Fig. 3), and there is no indication of rifting. The lower-middle Miocene limestones represent an approximate sea-level datum and probably covered the whole area; close to the arc they were removed by erosion before deposition of the basin sequence. The Halmahera Basin was actively

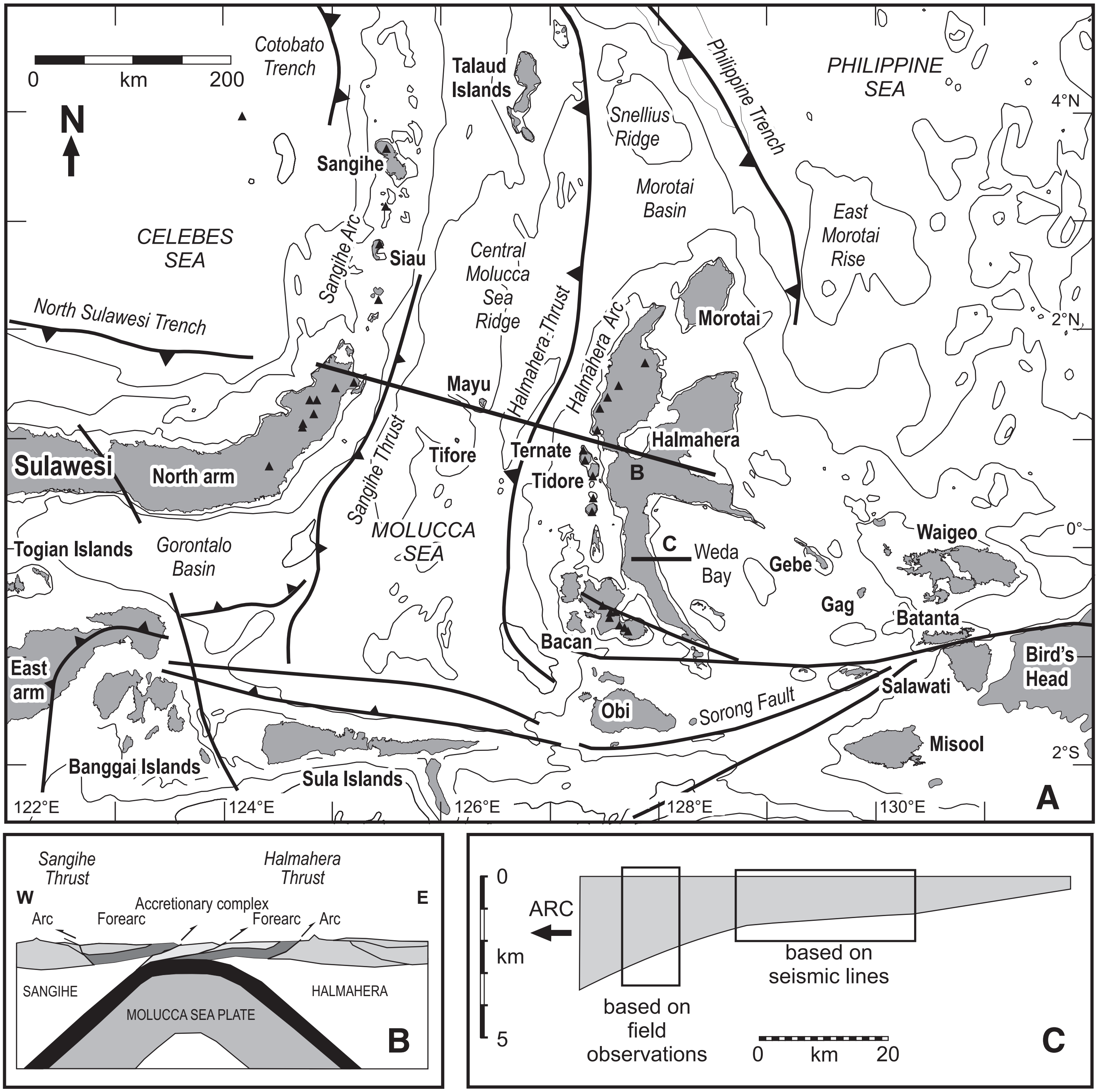

Figure 2. (A) Location and major tectonic features of the Molucca Sea region. Small, black-filled triangles are modern volcanoes. Bathymetric contours are at 200, 2000, 4000, and 6000 m. Large barbed lines are subduction zones, and small barbed lines are thrusts. (B) Cross section across the Halmahera and Sangihe Arcs on section line B. Thrusts on each side of the Molucca Sea are directed outward toward the adjacent arcs, although the subducting Molucca Sea plate dips east beneath Halmahera and west below the Sangihe Arc. (C) Inset is the restored cross section of the Miocene–Pliocene Weda Bay Basin of SW Halmahera on section line C, flattened to the Pliocene unconformity, showing estimated thickness of the section.

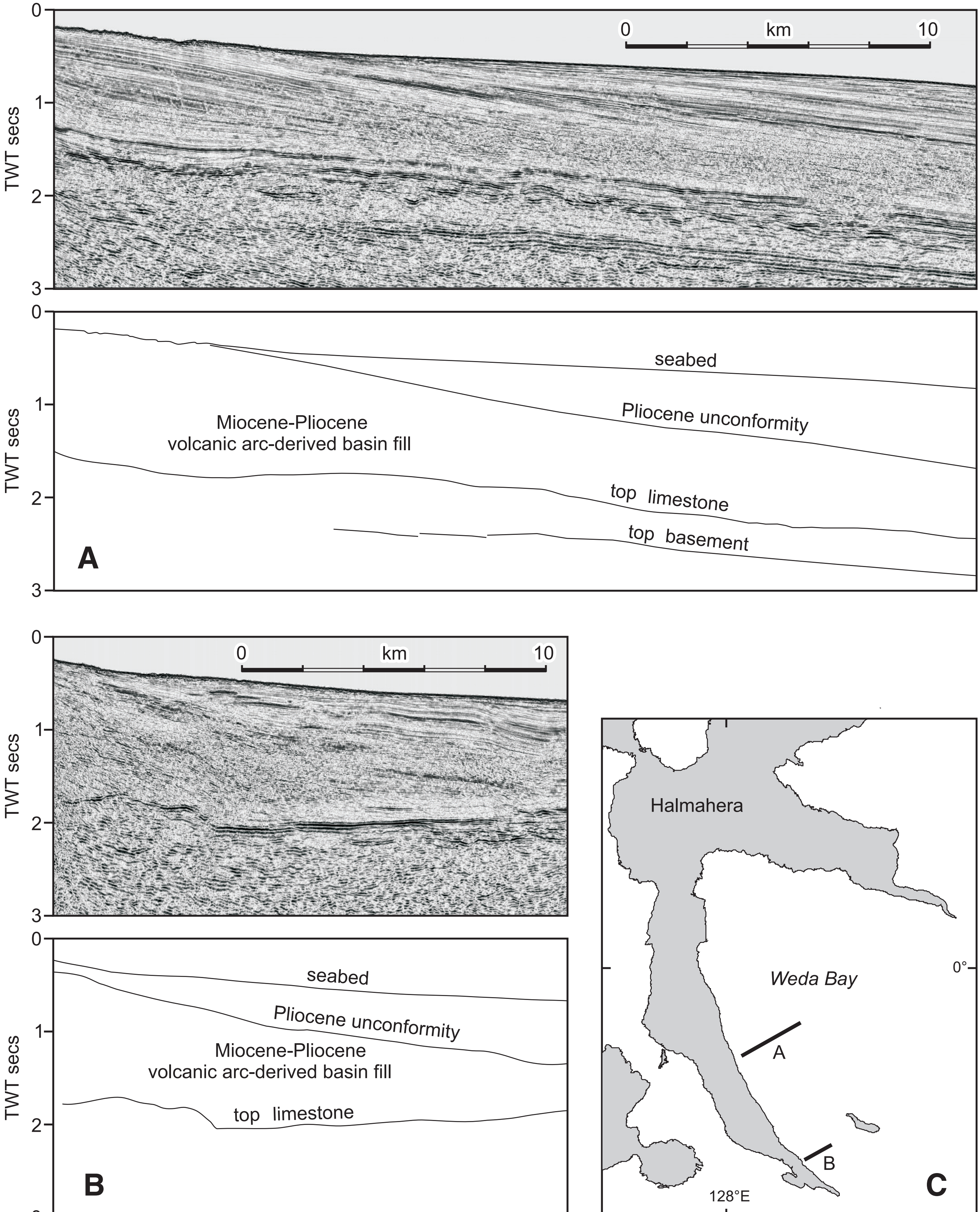

Figure 3. Uninterpreted seismic lines and interpreted sections across parts of the sedimentary sequences deposited at the western edge of Weda Bay, Halmahera. Locations of lines A and B are shown on inset map C. There is little evidence of faulting on the sections and no indication of a rift character to the basin. The Miocene–Pliocene arc-derived sequence is deposited on top of middle Miocene shallow marine limestones and is terminated by an intra-Pliocene unconformity. The sequence thickens toward the Miocene–Pliocene volcanic arc. TWT—two-way traveltime.

subsiding from the late Miocene until the middle to late Pliocene, an interval of ~5 m.y. Based on field measurement of sections and biostratigraphic dating, Nichols and Hall (1991) estimated that during deposition of this interval the western side of the basin, adjacent to the arc, subsided at least 2.8 km, representing an average subsidence rate of at least 47 cm/1000 yr. Subsidence rates for the eastern part of the basin, ~100 km from the arc, were between 17 and 34 cm/1000 yr.

At ca. 3 Ma, sedimentary rocks of this basin were thrust west over the Neogene arc, and later there was thrusting of the forearc from the west. The Quaternary Halmahera Arc is built unconformably upon all these rocks. The thrusting is a result of collision of the Sangihe and Halmahera Arcs. In Weda Bay there has been recent subsidence, and its deepest parts are almost 2000 m below sea level. Part of this subsidence is probably due to thrust loading to the west, but part may result from movements along splays of the Sorong Fault that appear to control the form of the present-day depocenter (Nichols and Hall, 1991).

East Java

East Java (Fig. 4) is situated on the continental margin of Sundaland. There has been subduction to the south of Java, along the Java Trench, since the early Cenozoic (Hall, 2002). The basement of most of East Java has previously been interpreted as arc and ophiolitic material accreted to the continental margin in the Late Cretaceous, but our work (Smyth et al., this volume) has shown that there is old continental crust beneath the Southern Mountains of East Java. Our work in East Java also suggests that the present northward subduction of Indian-Australian lithosphere began in the middle Eocene. The oldest Cenozoic rocks resting on older basement are terrestrial conglomerates without volcanic material, but a short distance above these rocks volcanic debris appears in middle Eocene sediments and increases in abundance upsection (Smyth, 2005).

There is a record of two volcanic arcs (Fig. 4) in East Java (Smyth et al., this volume). An early Cenozoic arc formed in the

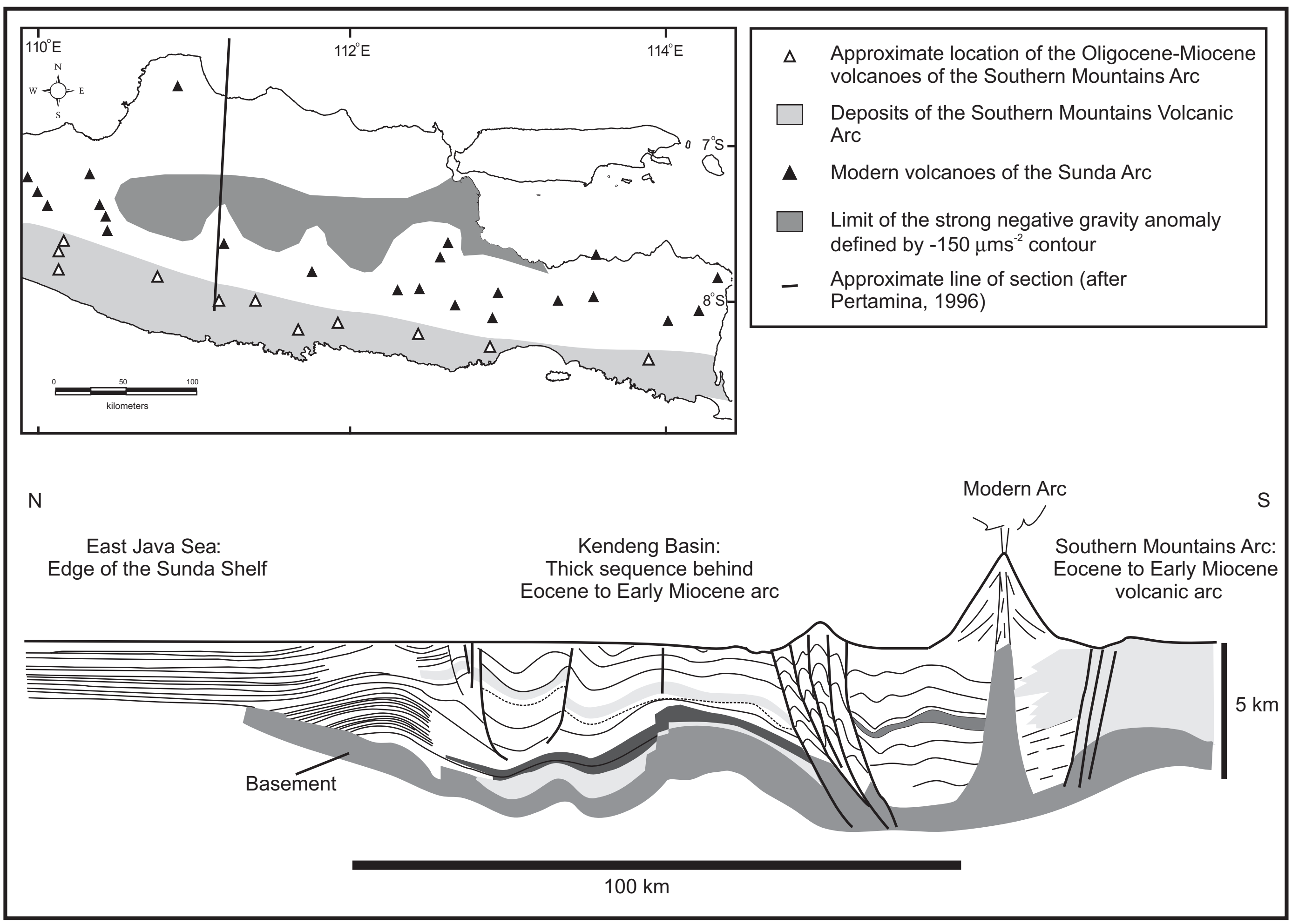

Figure 4. Location of the Eocene to early Miocene volcanic arc in the Southern Mountains of East Java, the Kendeng Basin, and the modern arc. Inferred volcanic centers of the Southern Mountains Arc are shown with open triangles, and active volcanoes are shown with solid triangles. A cross section of the Kendeng Basin along the line indicated is based on Pertamina (1996). The Kendeng Basin sequence is interpreted to thicken toward the Southern Mountains volcanic arc.

Southern Mountains and was active from the middle Eocene to the early Miocene (ca. 42–18 Ma). It erupted material ranging in composition from andesite to rhyolite (Smyth, 2005). The arc formed a chain of volcanic islands during the early Cenozoic that were initially similar in character to volcanoes of the present-day Izu-Bonin-Mariana Arc and the Aleutian Islands, except that behind the arc was a broadly shallow marine shelf and no deep oceanic backarc basin. The volcanoes were terrestrial, but some of their products were deposited close to the arc in a marine setting, and they formed separate small islands. The Oligocene volcanic centers are well preserved and have a spacing similar to volcanoes of the modern arc on Java (Smyth et al., this volume). They are predominantly andesitic and have been described as the "Old Andesites" (van Bemmelen, 1949). However, the volcanoes erupted considerable volumes of more siliceous material in explosive Plinian eruptions, and this material was dispersed widely as ash. The volume of siliceous material has been overlooked in descriptions of volcanic activity on Java. More details of the stratigraphy are given in Smyth et al. (this volume).

Immediately behind, and to the north of, the Southern Mountains Arc is the deep Kendeng Basin (Fig. 4). The basin is long (at least 400 km) and narrow (100–120 km) and trends east-west, parallel to the Southern Mountains Arc. The basin is characterized by a strong negative Bouguer gravity anomaly (Fig. 5), which exceeds −580 μms^{-2}, and extends from west to east. The basin formed during the middle Eocene (Untung and Sato, 1978). The Kendeng Basin succession is not well exposed but contains much volcanic debris carried north from the arc. The oldest rocks are not seen in situ but are sampled by mud volcanoes currently erupting through the basin sequence. They are terrestrial and shallow marine rocks similar to those deposited close to the arc during the Eocene (de Genevraye and Samuel, 1972). The Kendeng Basin succession records a deepening of the basin with time, and during the Oligocene thick sequences of volcaniclastic turbidites and pelagic mudstones were deposited, suggesting that subsidence exceeded the supply of material. Seismic lines across the northern parts of the depocenter show that the Kendeng Basin sequence thickens toward the Southern Mountains Arc and is ~3 km thick in the north (Fig. 4; Pertamina,

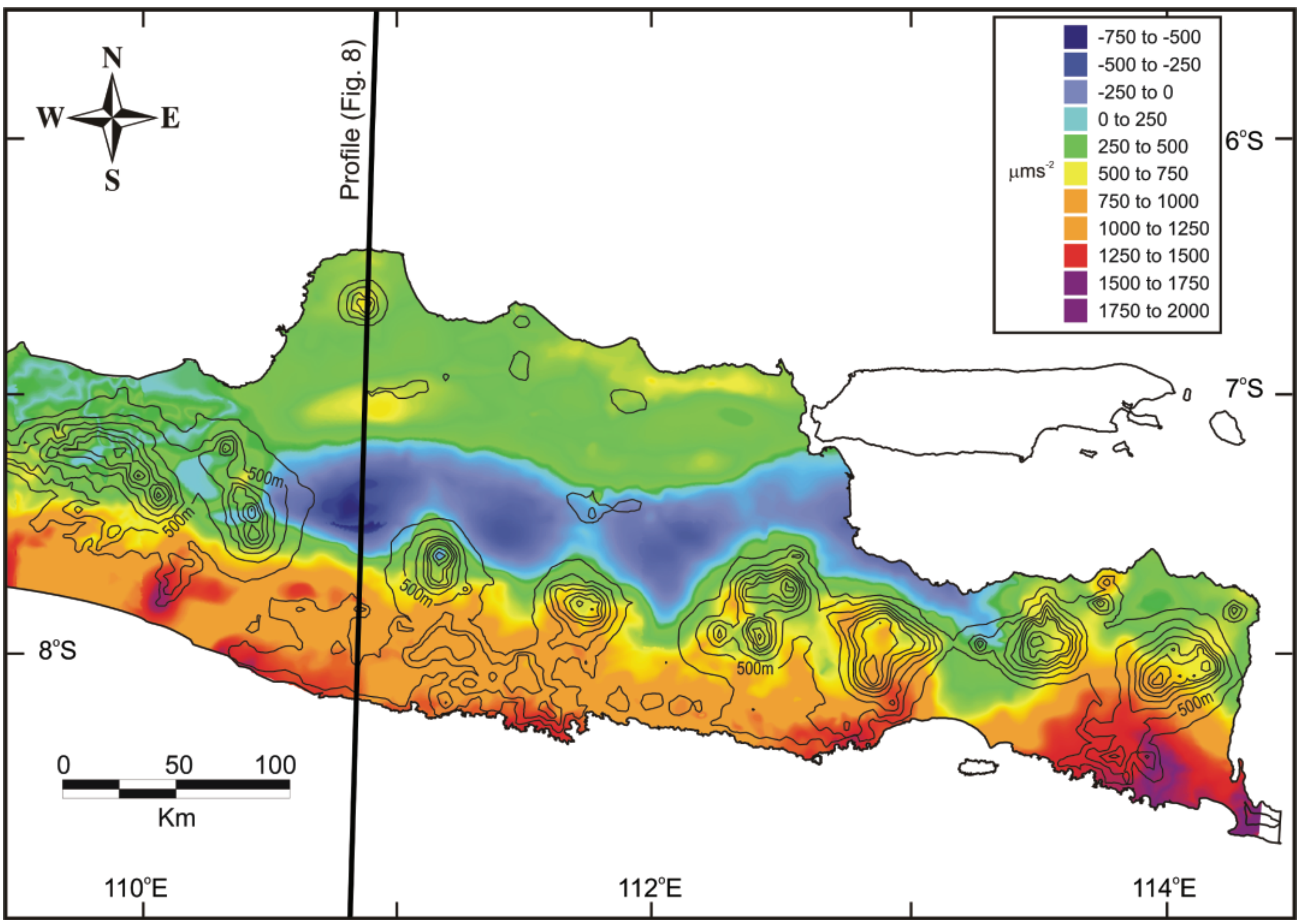

Figure 5. Bouguer gravity anomaly map of East Java and location of the modeled profile discussed in the text.

1996). Untung and Sato (1978) suggested that the deeper parts of the basin contain ~6 km of section. Gravity calculations suggest there may be as much as 10 km of sediment in its thickest parts. The increase in thickness of the sequence toward the arc and the importance of volcanic debris suggest that most of the Kendeng Basin fill was derived from the arc. Because the Kendeng Basin is so poorly exposed, and there are no seismic lines crossing the entire basin, it is impossible to assess the role of faulting in the basin's development. South- and north-dipping thrusts shown on interpreted sections across the basin (Pertamina, 1996) could be reactivated normal faults.

To the north of the Kendeng Basin was a carbonate and clastic shelf during the early Cenozoic. This was the edge of the Sundaland continent. During the Eocene to early Miocene there were elongate emergent ridges, trending roughly NE-SW and oblique to the arc, separated by depressions. These ridges contain terrestrial clastic sediments and coals at their base, thought to be Eocene, overlain by shallow marine Eocene to Miocene clastic sediments and platform carbonates. There are no reports of volcanic material in the shelf sequences, although reported clay layers may be fine-grained volcanogenic air-fall tuff deposited far from the arc. At the shelf edge there is volcanic material, including clays, zircons, and volcanic quartz (Smyth, 2005). The basin edge at the southern edge of the shelf is partly exposed in a fold-thrust belt where there was 10–30 km of shortening, suggested to have occurred during the Pliocene (de Genevraye and Samuel, 1972) or late Miocene.

The Southern Mountains Arc extends to the south coast of Java, and there has been almost no hydrocarbon exploration offshore directly south of the coast, so little is known about this region. Marine geophysical studies show ~1 km of sedimentary cover of unknown age on basement in small forearc basins (Kopp et al., 2006).

The Southern Mountains Arc has been elevated and tilted since the early Miocene and now dips uniformly to the south at ~30° (Smyth, 2005). On land the arc is ~40 km wide. Arc activity ceased in the early Miocene, followed by a period of little or no volcanic activity (Smyth et al., this volume). Volcanic arc activity resumed in the late Miocene ~50 km north of the Southern Mountains Arc, and the modern volcanoes are built on the Kendeng Basin (Smyth et al., this volume). The products of the late Miocene to Holocene arc are more basic than the older arc and are predominantly basaltic andesites to andesites (e.g., Soeria-Atmadja et al., 1994; van Bemmelen, 1949).

Causes of Basin Formation

In South Halmahera and East Java there is association between volcanic arc activity and basin formation. Both areas were emergent or close to sea level at the time of basin initiation. Subsidence began as the volcanic arc became active. Both basins have asymmetrical profiles, with the greatest thickness of material close to the volcanic arc. Clastic input came from the volcanic arc, and both basins are dominated by volcanic debris. In Halmahera, local depocenters contain sequences that are thickest close to inferred volcanic centers. Some crustal extension is likely in both volcanic arcs and is probably required in order to allow magma to reach the surface. However, in Halmahera there is little evidence for extensional faulting in the basin sequences, and no significant faulting is seen on seismic lines. In neither basin is there evidence for a typical rift character, nor is there evidence for significant crustal extension. In neither region are there oceanic backarc basins. There is no evidence for thrusting before or during sedimentation. Thrusting, unrelated to arc development, occurred in both areas after the basins formed and filled. In Halmahera, arc-arc collision caused thrusting, first from the backarc side and then from the forearc side, directed toward the volcanic arc. In East Java there was mainly northward-thrusting of the Kendeng Basin at its northern edge some time after volcanic arc activity ceased. All these observations suggest that volcanic activity contributed in some way to basin formation, possibly through loading by the volcanic arc itself or possibly by weakening of the plate, or by a combination of both.

MATHEMATICAL MODEL

In this section we develop a simple analytical model for describing how load-generated subsidence is controlled by an accumulating volcanic arc. The aim is to produce the simplest possible model capable of testing whether the observed subsidence is compatible with the likely size of load. The primary assumptions of our model are that subsidence is caused by a volcanic arc–generated line load and that the subsidence directly under the load is proportional to the size of the load, i.e.,

$$s = kV, \tag{1}$$

where s is subsidence, k is a constant, and V is the load (Fig. 6). For flexure of a uniform, unbroken beam, k is given by (Turcotte and Schubert, 2002, equations 3.127, 3.131, and 3.135)

$$k = \pi/(2x_b\Delta\rho_1 g), \tag{2}$$

where x_b is the flexural-bulge to arc-center distance, $\Delta\rho_1$ is the density contrast between the basin fill and the asthenosphere, and g is the acceleration from gravity. For a broken plate the equivalent formula is (Turcotte and Schubert, 2002, equations 3.127, 3.141, and 3.144)

$$k = 3\pi/(4x_b\Delta\rho_1 g). \tag{3}$$

The resulting basin is assumed to be filled by sediments up to a horizontal surface and also filled by the volcanic arc but with a triangular (in cross section) subaerial load caused by the current volcanic edifice itself. The load therefore consists of two components, a load resulting from the density excess of the buried volcanic arc plus a load resulting from the subaerial volcanic edifice. Hence

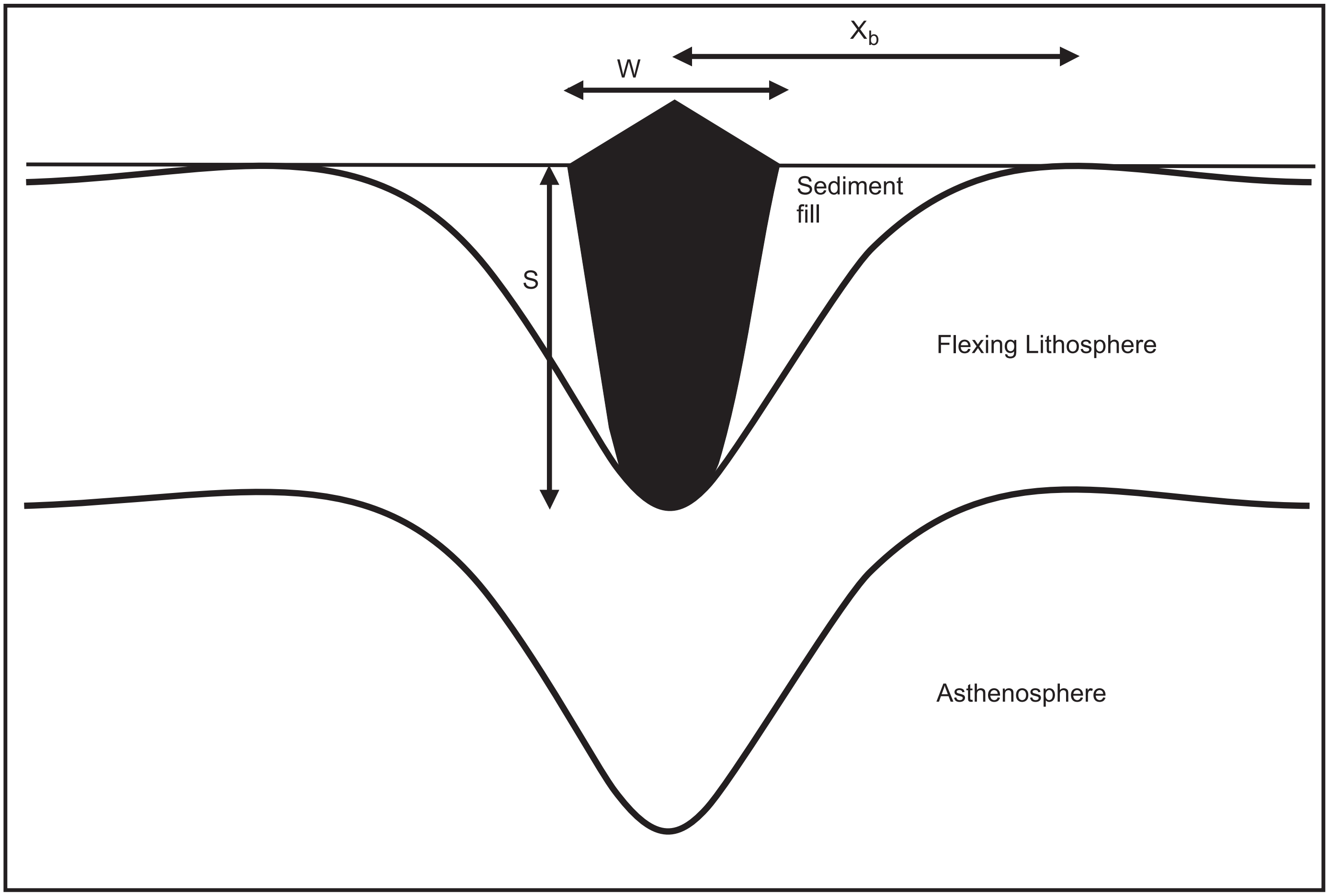

Figure 6. Schematic diagram showing concept of basin formation by volcanic arc loading. W—arc width; x_b—flexural bulge to arc-center distance; s—subsidence.

$$V = \left\{ \Delta\rho_2 \int_0^s w ds' + \rho\beta w^2 \right\} g, \tag{4}$$

where $\Delta\rho_2$ is the density excess of the volcanic arc over the remaining basin fill, *w(s)* is the arc width as a function of subsidence, ρ is the volcanic arc density, and β is given by

$$\beta = 0.5 \tan(\theta) = h/W, \tag{5}$$

where θ is the volcano slope, *h* is the final volcano height, and *W* the final arc width. Note that equation 4 implies that there was no significant deformation of the volcanic arc during basin subsidence.

Given a well-constrained cross-sectional geometry, equations 1 through 4 alone would be sufficient to test the concept that basins can be formed by flexural loading resulting from a volcanic arc. In practice the required information (e.g., detailed geometry of the arc deposits beneath the present-day volcanic edifice) is unlikely to be available, and so a theoretical model for arc width as a function of subsidence is required.

Combining equations 1 and 4, differentiating with respect to *s,* and using the boundary condition that $w(0) = 0$ produces,

$$1 = Aw + 2Bww', \tag{6}$$

where the prime indicates differentiation and

$$A = \mathrm{kg}\Delta\rho_2, \tag{7}$$

$$B = \mathrm{kg}\beta\rho, \tag{8}$$

with *k* given by equation 2 or 3. The solution to ordinary differential equation 6 is (Appendix)

$$w = (1/A)\, f(A^2 s/B), \tag{9}$$

where *f(x)* is the function shown in Figure 7A. Hence, the width of the arc increases rapidly in the early stages of subsidence (i.e.,

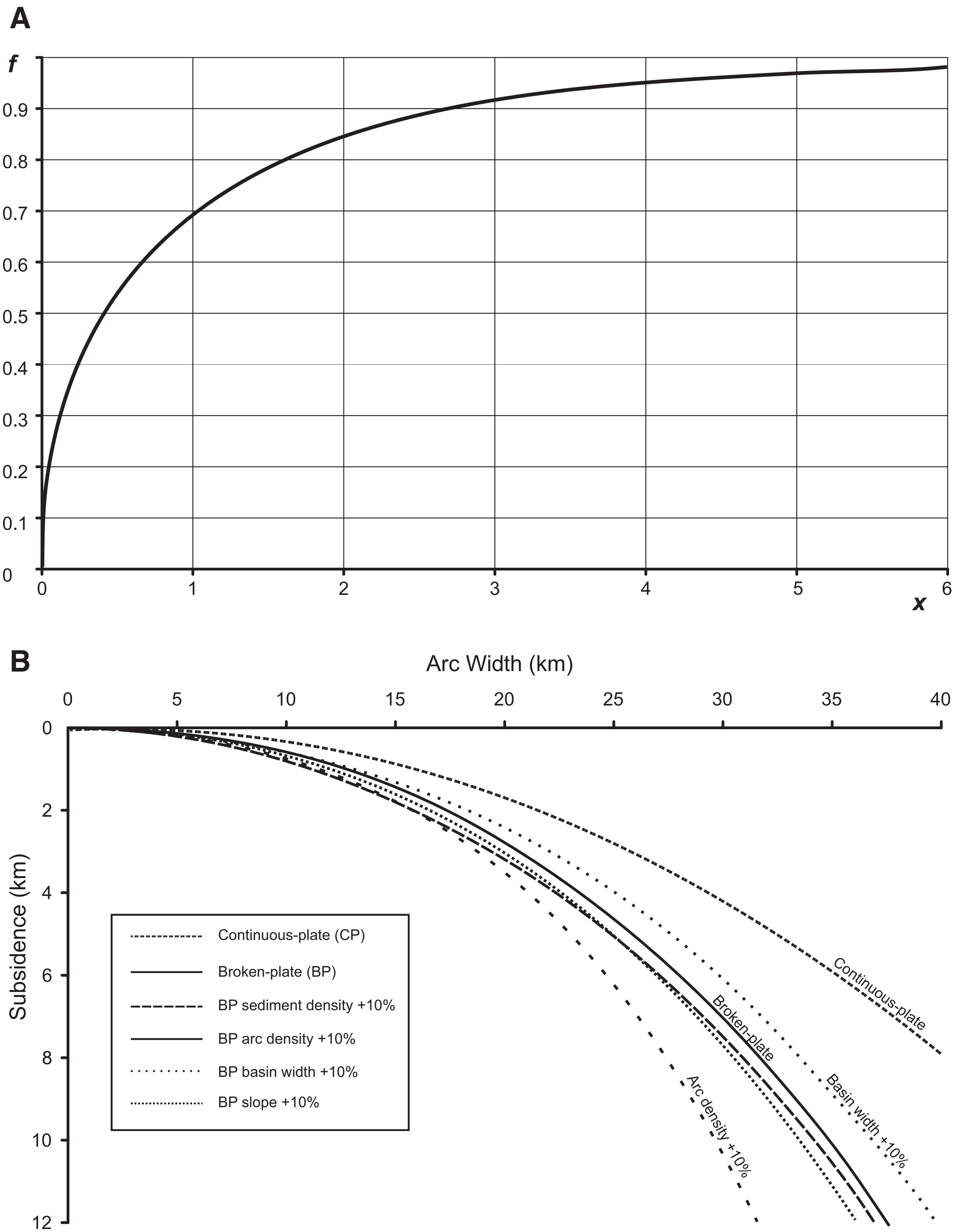

Figure 7. (A) Loading function derived in Appendix. Arc width increases with subsidence along a suitably scaled version of this curve. (B) Sensitivity analysis. The highest dashed line shows the result for the continuous-plate model, equation 9, and the average values from Table 1. The solid line shows the result for the broken-plate model, equation 9, and the average values from Table 1. The other curves show the result of increasing each parameter by 10% using the broken-plate model.

when A^2s/B is small) and asymptotically approaches a maximum width of $1/A$ as subsidence becomes large. Figure 7B illustrates the effect of arc width on basin subsidence predicted from equation 9. The "standard" simulation uses the average values of the parameters given in Table 1 and assumes a broken-plate model (i.e., it uses equation 3 rather than equation 2). This simulation shows that highly significant subsidence can be obtained from reasonable parameter values given sensible widths for a volcanic arc.

Figure 7B also shows the sensitivity to parameter uncertainties. Each of the curves is obtained by increasing a single parameter 10% above its standard value. The result of using a continuous rather than a broken plate is also shown. Figure 7B demonstrates that the most important factor is whether or not the plate can be considered broken. Other factors have relatively minor influences, although uncertainties in the arc density are, perhaps, the most significant factor. However, it should be noted that a 10% uncertainty in arc density is unlikely, whereas a 10% uncertainty in volcanic slope or in basin width is realistic.

In the following section, observations on the geometry and gravity profiles from two Indonesian arcs are used to test the model developed in this section.

APPLICATION TO INDONESIAN ARCS

The modern Halmahera volcanoes have elevations up to 1730 m and diameters at sea level of their base of between 10 and 25 km, typically ~20 km for those on land. Most of the active volcanoes with smaller diameters are offshore volcanic islands (Makian, Tidore, and Ternate) rising from sea-floor depths of several hundred meters, and therefore their diameter at the base is not known. A diameter of 20 km for all the volcanoes at their base is reasonable. The volcanoes of the Quaternary arc have been active for no more than 2 m.y. and probably less. The dimensions of the Neogene volcanic centers are not known precisely, partly because of the nature of the exposure in rainforest terrain, and partly because they are overthrust by backarc and forearc basin rocks. The distribution of their products identified during mapping of the islands at 1:250,000 scale suggests that they were larger than the Quaternary volcanoes, consistent with their longer period of activity from 8 to 3 Ma. A width of the arc of 20 km is therefore a reasonable value. Like the Neogene arc, the exact width of the Halmahera backarc basin is uncertain. Its eastern edge is in Weda Bay at water depths of 2 km, and detailed seismic lines cover only the western side of the offshore basin. Although the backarc basin has been thrust westward, the very coarse character of the Neogene fan-delta deposits suggests they were deposited within a few kilometers of the arc. The seismic lines show that the basin deposits thin eastward, away from the arc, and suggest that the basin width was between 60 and 80 km. The estimated thickness of the sequence close to the Neogene arc is between 2800 and 3800 m (Nichols and Hall, 1991) and up to 2 km offshore farther from the arc.

In addition to this information, the mathematical model requires densities for the basin fill, mantle, and volcanic arc. Based upon Hamilton (1979), we assume a basin-fill density of 2300 ± 100 kg/m^3, a mantle density of 3400 kg/m^3, and a volcanic arc density of 2700 kg/m^3. These densities, together with the observed basin width of 70 ± 10 km, subsidence of 3300 ± 500 m, and $\beta = 0.07 \pm 0.02$ (i.e., volcano slopes of 8 ± 2°), give a predicted arc width of 23 ± 5 km for a broken-plate model, in good agreement with the observed volcano diameters. The continuous plate model predicts an arc width of 28 ± 7 km. Hence, the observed subsidence and arc width are compatible with basin formation by arc loading and suggest that a broken-plate model fits the data better than a continuous-plate model of lithospheric flexure. The parameters used, and the results obtained, for the Halmahera example are summarized in Table 1.

In our second test case we do not, unfortunately, have good constraints upon basin subsidence, but, on the other hand, we do have a gravity profile that can be directly compared with a simulated profile based upon our mathematical model of arc-loaded flexure.

In East Java the volcanoes are much larger than those on Halmahera. Several of the present-day volcanoes have elevations >3000 m, and all except two of East Java's modern volcanoes are between 1600 and 3300 m high. The volcanoes typically have diameters of 50–55 km at their base. The modern arc began activity ~10–12 m.y. ago. As in Halmahera, the size of the volcanic centers of the Southern Mountains Arc is more difficult to assess. They have a similar distribution and spacing to the modern volcanoes. Several of the centers can be mapped up to 40 km north of the coast, and the present steep coastline is not the southern limit of the volcanoes. Thus, an arc width of 50 km, similar to the diameter of the modern volcanoes, is reasonable and consistent with an interval of arc activity of ~23 m.y. The basin width can be determined with greater certainty; it is between 100 and 120 km from the arc margin to the shelf edge, and there is estimated to have been 10–30 km of shortening on thrusts at the shelf edge.

TABLE 1. PARAMETERS USED IN THE FLEXURAL MODEL FOR HALMAHERA

Parameter	Minimum	Maximum	Comments
Basin fill density (kg/m^3)	2400	2200	Minimum density gives maximum arc width
Volcanic arc density (kg/m^3)	2700	2700	Andesite
Mantle density (kg/m^3)	3400	3400	Standard
Basin width (km)	60	80	Gives estimated elastic thickness of 4.5–7.1 km
Subsidence (m)	3250	3350	See text
Slope (°)	10	6	Minimum slope gives maximum arc width
Arc width (km)	10	25	Observed
Arc width (km)	17	28	Predicted broken-plate model
Arc width (km)	21	34	Predicted continuous-plate model

Independent estimates of basin thickness are unavailable for this area, but gravity data (see Fig. 3) can be used to test the model.

The Bouguer anomaly data along an East Java profile is shown in Figure 8. Figure 9 shows the same data after a regional trend was removed owing to the gravity signature of a subducting lithospheric plate deep beneath Java. The gravity modeling was performed by an add-on to our main arc-load modeling program, which simply summed contributions from a large number of small, rectangular, constant-density slabs using well-known expressions (e.g., see Telford et al., 1990). The small density contrast between the mantle lithosphere and the asthenosphere was ignored, and a single density was assumed for the entire mantle. A forward model of gravity over an arc-loaded, flexing, broken elastic lithosphere is also shown in Figure 9. Flexure and gravity model parameters are given in Table 2. Note that $\beta = 0.05$ implies a modern volcano height of 2500 m and a slope of 6°. Using the parameters listed in Table 2, the mathematical model predicts a subsidence of 6.9 km beneath the arc.

The key features of Figure 9 are the gravity low owing to the basin depocenter, but also the gravity high at the south end

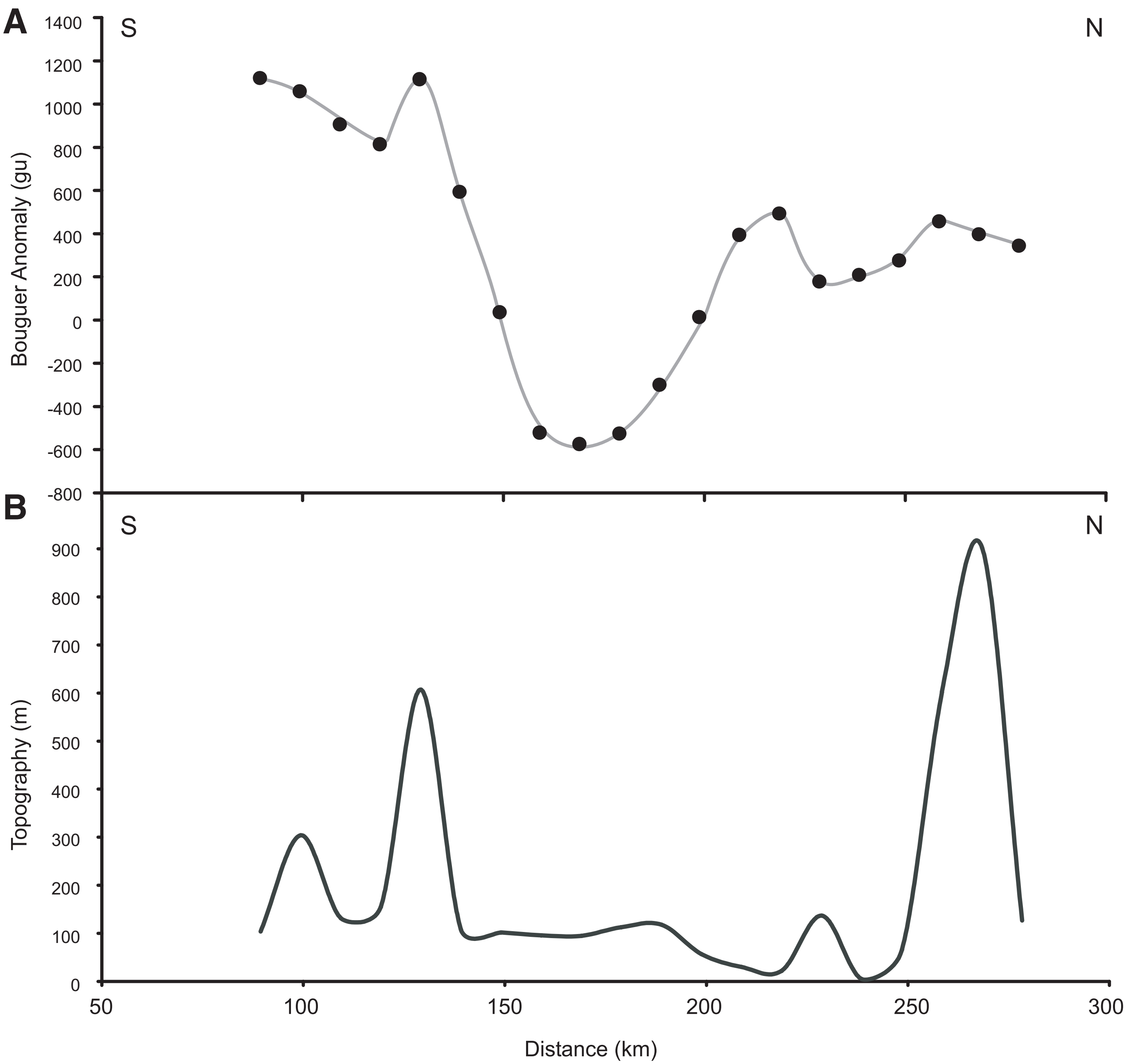

Figure 8. Bouguer anomaly (A) and topographic profile (B) for East Java for the line shown in Figure 5.

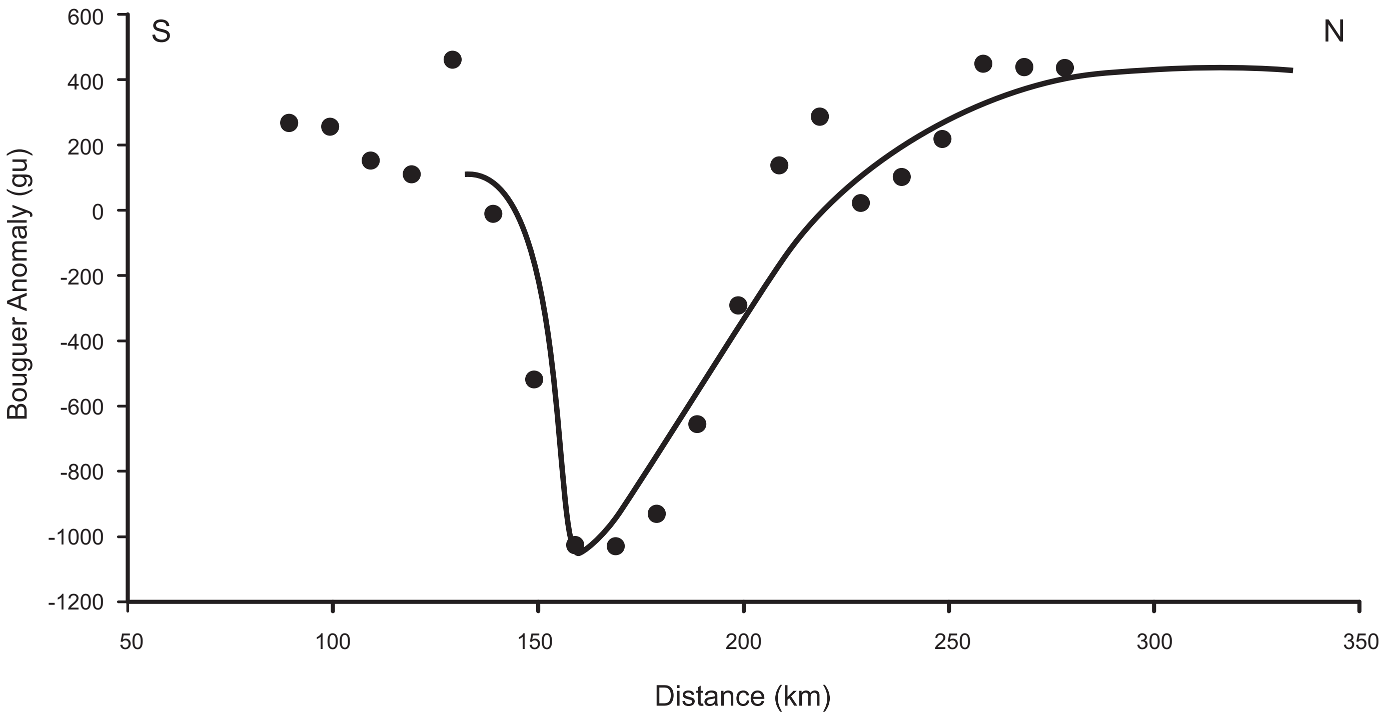

Figure 9. Bouguer anomaly from Figure 8 after removal of regional trend. The solid line is the predicted gravity anomaly based on a filled basin produced by subsidence caused by volcanic arc loading of a broken elastic plate.

TABLE 2. PARAMETERS USED IN THE GRAVITY AND FLEXURAL MODELING OF THE EAST JAVA BASIN

Parameters	Units
Basin fill density (kg/m^3)	2200
Volcanic arc density (kg/m^3)	2900
Crustal density (kg/m^3)	2700
Crustal thickness (kg/m^3)	40
Mantle density (kg/m^3)	3400
Basin width (km)	150
Arc width (km)	50
Slope (°)	6
Subsidence predicted (m)	6900

of the profile between 50 and 150 km, which is due to the positive effect of the volcanic arc itself. The remaining discrepancies between modeled and observed gravity profiles occur at distinct topographic highs and would be removed by suitable topographic corrections. The basin-fill density is at the low end of figures given by Hamilton (1979). The crustal thickness of 40 km is possibly too high, although Hamilton (1979) shows a speculative thickness beneath the Java magmatic arc of >30 km, and the value is well within the plausible range for a mature arc built on continental crust (e.g., Kay and Mpodozis, 2001). However, the arc density has been set rather high, and this may reflect the need for further loads to produce the observed gravity high near the arc.

DISCUSSION

The key prediction of the mathematical model of basin formation by volcanic arc loading, as presented here, is that there is a simple relationship between arc width at the surface and the amount of subsidence. This model is strongly supported by analysis of the Halmahera Arc, whose width agrees closely with that predicted by our model from the observed subsidence. Our model is further supported by the strong similarity between the observed Bouguer anomaly on East Java to that predicted by a model of basin subsidence above a broken plate. The gravity profiles agree closely in both the depth and width of the anomaly produced by the basin.

For Halmahera, the subsidence observed can be accounted for entirely by arc loading if a broken-plate model is assumed. This is consistent with weakening of the arc crust by magmatic heating. For East Java, the modeling suggests that an additional load is required to produce the observed subsidence. One obvious contributor could be crustal extension, and we cannot rule out extensional faulting, as the Kendeng Basin is poorly exposed and there are no seismic lines crossing the basin. However, the large volumes of highly acidic volcanic products that erupted in East Java in the Southern Mountains Arc suggest significant differentiation of arc magmas before eruption, which should have produced large volumes of basic cumulates (S. Sparks, 2005, personal commun.). The relatively high density used in the model would be consistent with large volumes of dense cumulates at deep crustal levels. Magmatic underplating by such cumulates would have provided an additional load as in volcanic islands (Watts et al., 1985).

Probably the biggest uncertainty in the modeling and interpretation is the density contrast between crust and arc. Little is known about the crustal structure and thickness of any Indonesian arc. The model assumes a normal continental crust for the arc basement with a load similar in composition to andesites. This is reasonable in East Java, where the basement is continental crust and preserved volcanic centers are predominantly andesites. It is also likely, based on observations of the character of small areas of exposed basement and oil-company drilling of the basement, that accreted arc and ophiolitic material includes serpentinites, which would lower the average crustal density. For Halmahera, Milsom et al. (1996) concluded that the crust was at least 20 km thick and had a bulk density approaching that of continental rather than oceanic crust. Local gravity highs are associated with Paleogene arc volcanic rocks rather than the ophiolites, and nowhere do the ophiolites have the high gravity fields associated with classic ophiolites. Although much of Halmahera is underlain by ophiolitic rocks, significant serpentinization of the ultramafic parts could account for the low crustal density. The products of the modern arc (Morris et al., 1983) and the Neogene arc (Forde, 1997; Macpherson et al., 2003) are almost entirely basaltic andesites and andesites.

CONCLUSIONS

The role of volcanoes in the development of basins in arc regions has generally been ignored, overlooked, or not considered important. This is possibly because most studies have been concerned with larger true backarc basins and forearc basins both of which are formed much farther from the arc. However, in several Indonesian arcs there are thick sequences of sedimentary and volcaniclastic rocks in deep basins very close to the arc. The mathematical modeling shows that volcanic loading can make a contribution to basin subsidence in these settings, and may be the primary cause. Volcanic loading can account for basins close to the arc but is not relevant to basins >~100 km from the arc. The basins produced by arc loading are asymmetrical, and basin sequences are thickest close to the arc. These are likely to be dominated by very coarse, terrestrial and shallow marine, primary volcanic and volcaniclastic rocks that may include a variety of mass-flow deposits. Locally and intermittently the supply of material from the arc may exceed subsidence, and there may be rapid vertical and lateral variations in grain size and changes from shallow marine to terrestrial deposits. Farther from the arc, subsidence typically exceeds supply, and the more proximal deposits pass laterally into deeper water sedimentary deposits such as turbidites. The distribution and character of the material, particularly close to the arc, has some similarities to rocks described by Draut and Clift (2006) from the Jurassic Talkeetna Formation of Alaska. However, in the Alaskan Jurassic arc and in the modern Mariana and Tonga Arcs, accommodation space is not likely to have been created by volcanic loading but had already existed. This is because in young intraoceanic settings the volcanoes rise from great depths above the ocean floor. In young intraoceanic arcs there is also likely to be little density difference between the arc volcanoes and the underlying crust, and therefore the volcanoes do not act as a load. In continental margin arcs such as Java, and long-lived intraoceanic arcs such as Halmahera, there is a larger density contrast between the deeper crust and the eruptive products of the arc. In these cases the volcanoes act as a significant load and produce flexural basins close to the arc. The absence of deep basins in arcs in some parts of Indonesia and elsewhere in the world may be due to the small density contrast between volcanoes and the underlying crust in those regions.

APPENDIX

Equation 6 is

$$1 = Aw + 2Bww'. \tag{A1}$$

Changing the variable to

$$x = A^2s/B \tag{A2}$$

and scaling using

$$f = Aw \tag{A3}$$

then gives

$$1 = f + 2ff', \tag{A4}$$

where f' now indicates differentiation with respect to x. Equation A4 is a nonlinear ordinary differential equation (ode), which does not have an analytical solution in terms of elementary functions. However, at small values of f the second term on the right side dominates, so that $1 \sim 2ff'$ with a solution of $f = x^{0.5}$. At large values of f the first term dominates, and the solution asymptotically approaches $f = 1$. The function f can be estimated using finite differencing with

$$f \sim (f_i + f_{i+1})/2 \tag{A5}$$

and

$$f' \sim (f_{i+1} - f_i)/\Delta x, \tag{A6}$$

which, after substitution into (A4), yields

$$f_{i+1} = \frac{-\Delta x}{4} + \sqrt{\left(\frac{\Delta x}{4}\right)^2 + f_i^2 - \frac{\Delta x}{2} f_i + \Delta x}\ , \tag{A7}$$

which, together with the boundary condition that $f_0 = 0$, allows the function in Figure 2 to be calculated. The resultant function has the required properties that $f \sim x^{0.5}$ for small x and $f \sim 1$ for large x.

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