ELSEVIER

Tectonophysics 333 (2001) 35–46

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Modelling the seismic velocity structure beneath Indonesia: a comparison with tomography

E. Hafkenscheid*, S.J.H. Buiter, M.J.R. Wortel, W. Spakman, H. Bijwaard

Vening Meinesz Research School of Geodynamics, Utrecht University, Faculty of Earth Sciences, P.O. Box 80021, 3508 TA Utrecht, Netherlands

Received 3 September 1999; revised 10 February 2000

Abstract

Studies of the geodynamic evolution of Southeast Asia have resulted in a number of tectonic reconstructions that exhibit a broad consensus as well as significant differences. In this contribution we apply a method to further test these surface reconstructions, using independent seismic tomography results. Our kinematic modelling procedure comprises the calculation of three-dimensional forward models of the seismic velocity structure beneath Indonesia. From information contained in the tectonic reconstructions, the effect of the proposed surface motions on the thermal structure of the underlying mantle is modelled. This results in a prediction of the present-day temperatures which are converted into seismic (P-wave) velocity anomalies. By comparing the predicted velocity models with recent tomography results of the area, the quality of the tectonic reconstructions can be evaluated. The models presented in this paper are based on the reconstructions of Rangin et al. (Bull. Soc. Géol. France, 8 (1990a) 889; Bull. Soc. Géol. France, 8 (1990b) 907) and Lee and Lawver (Tectonophysics, 251 (1995) 85). In general, we conclude that the calculated positive velocity anomalies beneath the Sunda and Banda arc show strong similarities with the tomography results. The modelled patterns of high velocities beneath southern Sulawesi are not found in the tomographic images. The model predicted from Rangin et al. (1990a,b) does not show the double-sided subduction under the Molucca Sea region that can be seen in the model predicted from Lee and Lawver (1995) and in the tomographic model. Our results indicate the potential of the method for investigating the geodynamic evolution of the Indonesian region.

Keywords: Southeast Asia; tectonic reconstructions; kinematic modelling; upper mantle structure; thermal anomalies; seismic tomography

1. Introduction

Southeast Asia is an actively deforming area located on the junction of the converging Eurasian, Indo-Australian and Philippine Sea plates (Fig. 1). In the last decade, several tectonic reconstructions of the complex Cenozoic development of this region have been proposed, for example by Rangin et al. (1990a), Daly et al. (1991), Lee and Lawver (1995) and Hall (1996). Their descriptions of the tectonic processes are all based on extensive data sets that resulted from geological, paleomagnetic and shallow seismic studies. The very existence of the various reconstructions indicates that the currently incorporated data do not allow definition of one single scenario for the tectonic evolution. Consequently, there are some important — as yet unresolved — differences between the reconstructed surface motions within the Southeast Asian region. In this

* Corresponding author. Fax: +31-30-2535030.
E-mail address: hafkensc@geo.uu.nl (E. Hafkenscheid).

0040-1951/01/$ - see front matter
PII: S0040-1951(00)00265-1

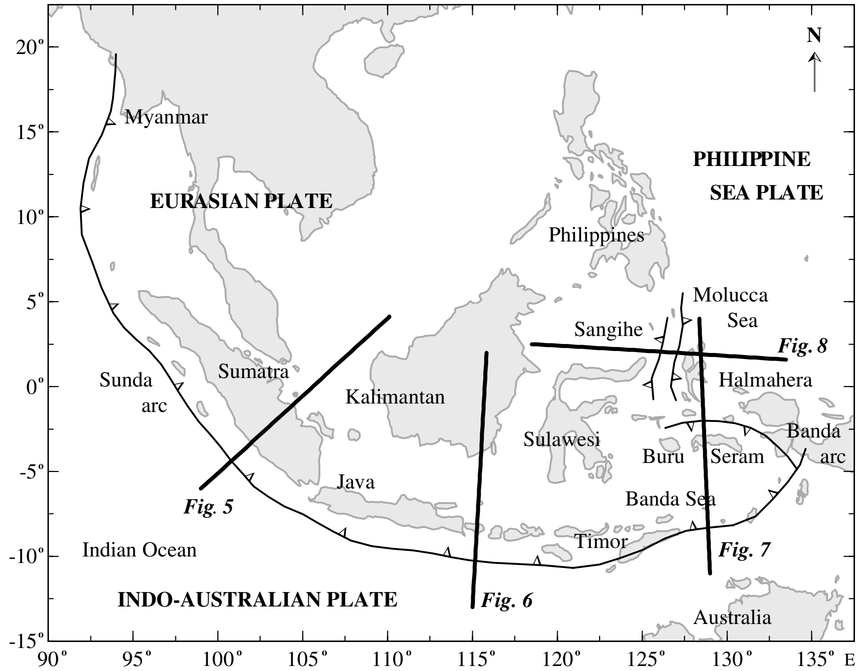

Fig. 1. Location map of the Indonesian region. Barbed lines are the main active trenches from Lee and Lawver (1995). Straight lines indicate the vertical cross-sections that are shown in Figs. 5–8.

study, we investigate whether we can contribute to a better understanding of the geodynamic evolution of the area by incorporating seismic tomography results into the analysis of the tectonic reconstructions.

The method we follow has been applied successfully to the Mediterranean region by De Jonge et al. (1993, 1994). This thermo-kinematic modelling procedure links the surface movements proposed in a tectonic reconstruction to the present seismic P-velocity structure of the underlying lithosphere and mantle. A fundamental assumption in the approach is that horizontal surface motions are always coupled to vertical displacement of material through plate subduction and isostatic compensation of extending lithosphere. Naturally, these processes significantly affect the temperature distribution in the mantle and, therefore, result in a change of the seismic velocity structure. A comparison of the calculated three-dimensional model of velocity anomalies with independently obtained seismic tomography results will enable us to test the proposed tectonic reconstruction. Our approach fully acknowledges the value of the geological and other near-surface data that underlie the tectonic reconstruction and makes use of the fact that the reconstruction intrinsically represents a synthesis of geological and geophysical data on the larger regional scale involved.

We apply our procedure to the Indonesian part of the tectonic reconstructions proposed by Rangin et al. (1990a,b) and Lee and Lawver (1995). In the present Indonesian area (Fig. 1), the Indo-Australian plate subducts northward beneath the Indonesian islands along the Sunda arc. Continental collision processes are characteristic of the Banda arc and the Molucca Sea region. The two tectonic reconstructions show important differences in trench migration, rotations of the Indo-Australian and Philippine Sea plates, and the collision of the Eurasian and Australian continental margins (Fig. 2). The calculated models of the seismic P-velocity structure beneath Indonesia are compared with the global seismic velocity model of Bijwaard et al. (1998) which gives detailed tomographic images of the region.

2. The forward modelling procedure

To calculate the present seismic velocity structure from a tectonic reconstruction, we use the numerical modelling procedure developed by De Jonge et al. (1993, 1994) and De Jonge (1995). Three successive stages can be distinguished in this forward approach:

(1) *Quantification of kinematic model.* The time-dependent kinematics of the region are derived from the surface motions proposed in a tectonic reconstruction. Relative convergence between plates is modelled by subduction, for which the velocities are determined from the reconstructed plate rotations and trench migrations. The dip of the subducting slab is held fixed and is estimated from the distribution of recent earthquake hypocentres (ISC data set). Extension of lithosphere is modelled as pure shear deformation (McKenzie, 1978). All motions within the timespan to be tested are translated into a kinematic model for narrow 2D vertical sections perpendicular to the plate boundaries. We note here that the relative convergence velocities between the different fragments are calculated from the information contained in the tectonic reconstructions. The total convergence along a trench segment can, therefore, be directly related to the reconstructions themselves. Our predicted velocity anomalies are influenced by assumptions made in the following modelling steps.

(2) *Calculation of thermal evolution.* Based on the kinematic model, the thermal evolution of each 2D section in the region is calculated. First, the initial temperature distribution needs to be defined. Oceanic lithosphere is approximated by a cooling halfspace with the appropriate lithospheric ages. In continental regions, the crustal thicknesses are used in a steady-state approximation of a typical three-layer model (Chapman, 1986). The mantle temperatures are constrained by an adiabatic thermal gradient with temperature jumps at the 400 and 670 km discontinuities. Next, the thermal evolution within each section is modelled forward in small timesteps, starting from the initial structure. For each timestep, the temperatures are displaced as defined by the kinematic model, and the associated diffusion of heat is calculated (similar to Minear and Toksöz (1970) and Sleep (1973)). Relative to the dominant direction of heat transport in a subduction zone, which is perpendicular to the descending plate, conduction of heat in the direction parallel to the trench is negligible. When the total timespan has been modelled, the differences between the calculated temperatures and the average temperature distribution for the region define the thermal perturbations that are combined into a 3D model.

(3) *Conversion to seismic velocity structure.* The predicted temperature perturbations are converted into seismic P-wave velocity anomalies by using the depth-dependent temperature derivative of the seismic velocity determined by De Jonge (1995). Because the velocity anomalies in the lower lithosphere and upper part of the mantle appear to be primarily controlled by temperature (see for example De Jonge, 1995; Ranalli, 1996; Goes et al., 2000), we believe that our predicted models will yield a reasonable representation of the anomaly distribution. Other contributions to seismic velocities, such as composition and partial melting, are neglected. At crustal depths and in the lower mantle, the effect of temperature may be less dominant, and therefore, we have to analyse the models with caution.

For further details and values of the standard modelling parameters, we refer to De Jonge et al. (1993, 1994) and De Jonge (1995).

3. Tectonic reconstructions

Rangin et al. (1990a) and Lee and Lawver (1995) have presented their reconstructions in a sequence of tectonic maps of the Southeast Asian region for the past 43 and 60 Myr, respectively. In this section, we give a short outline of the differences between the two reconstructions within the Indonesian region. For a more detailed description, we refer to the original publications.

In both reconstructions, the present-day Sunda arc (Fig. 1) was the western part of an ancient subduction zone that once curved around the Eurasian plate from west of the Andaman Sea to northeast of Sulawesi (Fig. 2). Indian Ocean lithosphere has subducted northward along this trench system during the total reconstructed timespans. A similar history, as well as indications for earlier subduction, has also been proposed by others, e.g. Audley-Charles et al. (1988), Daly et al. (1991) and Hall (1996). In the two reconstructions, the location and horizontal extent

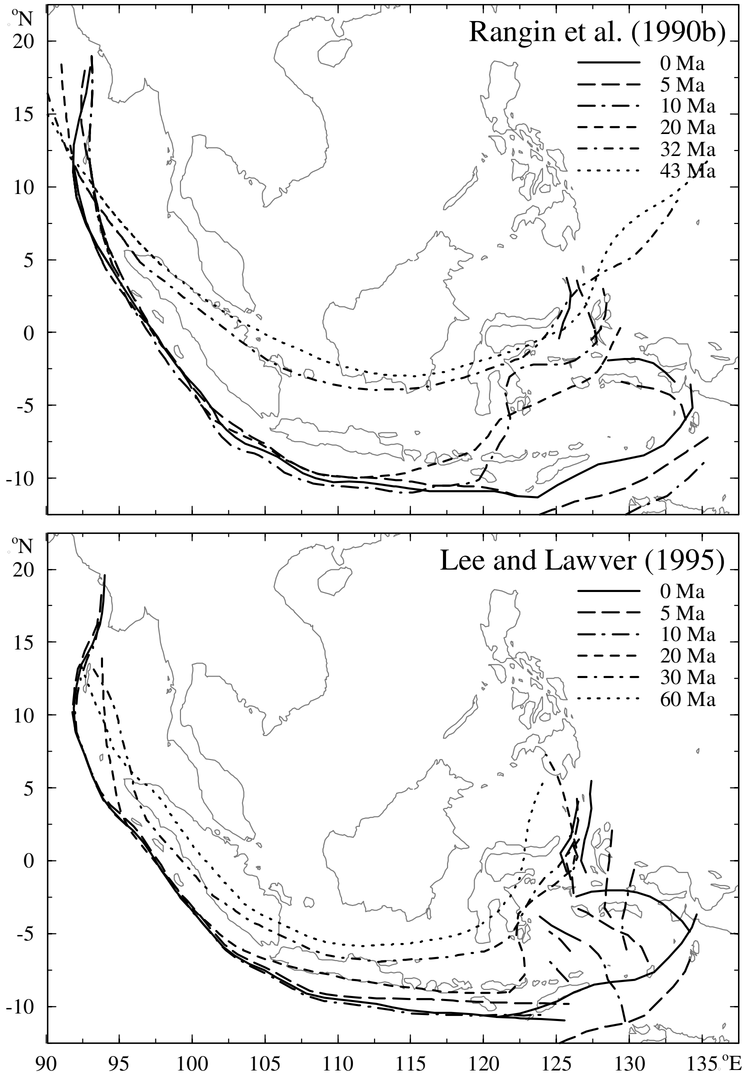

Fig. 2. Stages in the evolution of the active Indonesian trench system according to the reconstruction of Rangin et al. (1990a,b) (top) and the reconstruction of Lee and Lawver (1995) (bottom). Present coastlines are given for reference only.

of the ancient arc systems differ. Compared to the evolution described by Lee and Lawver (1995), Rangin et al. (1990a) placed the earlier stages of the arc in a more northerly position, while the arc extended further to the northeast (Fig. 2). Rangin et al. (1990a) have used constant rotation poles for the lower Indo-Australian plate motions which differ from the variable poles of Lee and Lawver (1995).

During the Paleogene, the Indonesian trench system migrated southwards in both reconstructions (Fig. 2). In early Neogene, the eastern part of the trench was pushed north(west)ward again due to the collision with the first fragments of the Australian continental margin. As a result, the southeast arm of present-day Sulawesi accreted with the — Eurasian — north and west arms, and large parts of the trench became inactive (Fig. 2). Today, active subduction only takes place beneath the Sangihe islands (see also Fig. 1). According to Lee and Lawver (1995), the first continent–continent collision started at 20 Ma and the larger part of the eastern trench became inactive before 14 Ma. Rangin et al. (1990a) placed these events about 5 Myr later (15 and 10 Ma, respectively). Nowadays, the Molucca Sea plate subducts westward beneath the Sangihe islands as well as eastward beneath Halmahera (Fig. 1). Lee and Lawver (1995) proposed that the eastward subduction has been active since 10 Ma, whereas Rangin et al. (1990a) indicated eastward subduction since 6 Ma. In the latter reconstruction, the Halmahera trench has recently collided with the Sangihe trench (see Fig. 2).

The highly curved Banda arc is apparently continuous with the present-day Sunda arc (Fig. 1). The cause of the extreme curvature of the Banda arc is still a point of discussion. It has been suggested that the arc was constructed from two separate trench systems (e.g. McCaffrey, 1988; Daly et al., 1991; Hall, 1996), or that the arc has been one continuous trench system that was bent into its present configuration (e.g. Katili 1975; Milsom et al. 1996). Rangin et al. (1990a,b) proposed an evolution of the Banda arc in which the southern trench (along Timor) and the northern trench (along the Buru-Seram islands) of the system lay separately in their present-day relative configuration. Lithospheric material subducted southward along the Buru-Seram part of the trench in the past 8 Myr. Northward subduction of a marginal basin south of Timor was proposed since 20 Ma. Lee and Lawver (1995) also reconstructed the Banda arc from two separate trench systems, but they took into account a counterclockwise rotation (~90°) of Buru-Seram in the past 18 Myr through which the underlying lithosphere was subducted southward beneath the islands. Only a short timespan of 4 Myr of northward subduction was proposed to have taken place beneath Timor.

4. Modelling results

We predict models of the seismic velocity distribution beneath Indonesia from both the reconstruction of Rangin et al. (1990a,b) and the reconstruction of Lee and Lawver (1995). The calculations for the 3D models are made within vertical 2D sections spaced at 50–100 km intervals, depending on the complexity of the trench structure. In this paper, we will refer to the modelling results for the above two reconstructions as the R-model and LL-model which represent evolutions of the past 40 and 60 Myr, respectively.

The predicted structures are compared with the global tomographic BSE-model of Bijwaard et al. (1998). The horizontal resolution of the BSE-model is good in the Indonesian region, where it gradually decreases from below 100 km in the subduction zone regions of the upper mantle to 250 km in the lower mantle. Vertical resolution can be poorer in the shallow parts of subduction zones when rays are travelling predominantly down dip, but is usually better than 200 km. We will restrict our analysis to the large-scale features in the model.

Generally we find that the amplitudes of imaged seismic velocities are smaller than those computed from forward modelling. The underestimation of the tomographic amplitudes can be inferred from tests with synthetic velocity models (Bijwaard et al. 1998) and is due to a combination of model parameterisation, regularisation, and incomplete convergence in the tomographic inversion. Therefore, the shown amplitude range of the imaged velocity anomalies will be different from the range of the predicted anomalies.

4.1. General structure

Figs. 3–8 show horizontal and vertical slices down to a 1500-km depth through the R-, LL- and BSE-models (see also Fig. 1 for locations of the cross-sections). To allow for the identification of an approximate relationship between depth range and time window on the tectonic evolution, we indicate in Figs. 3 and 4 the average time (in Myr) it took for the predicted slabs to subduct down to the depth of 200 and 500 km, respectively. We find that for the reconstructions used, the subduction-related high-velocity anomalies in the upper 500 km are an expression of the modelled geodynamic evolution during the last 8 Myr (east of Java) to 40 Myr (under Myanmar (Burma)). With a minor exception for the southern Sulawesi region, a similar conclusion (about 10–40 Myr) holds for the entire upper mantle, i.e. down to 670 km depth. High-velocity anomalies associated with earlier episodes — depending on the subregion — in the regional evolution are likely to be found in the lower mantle.

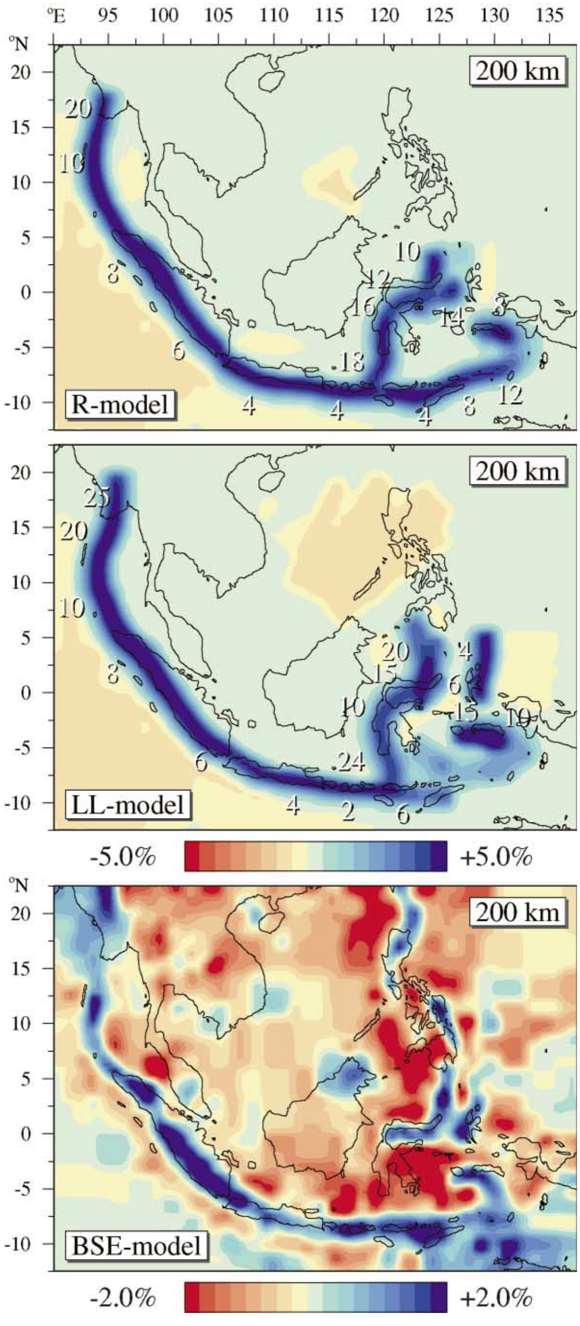

Fig. 3. P-velocity anomaly structure at 200 km depth. From the top downward: The R-model (based on Rangin et al., 1990a,b), LL-model (based on Lee and Lawver, 1995) and tomographic BSE-model (Bijwaard et al., 1998). Numbers give an indication of the average time (Myr) it has taken for the predicted slab remnants to subduct down to the shown depth.

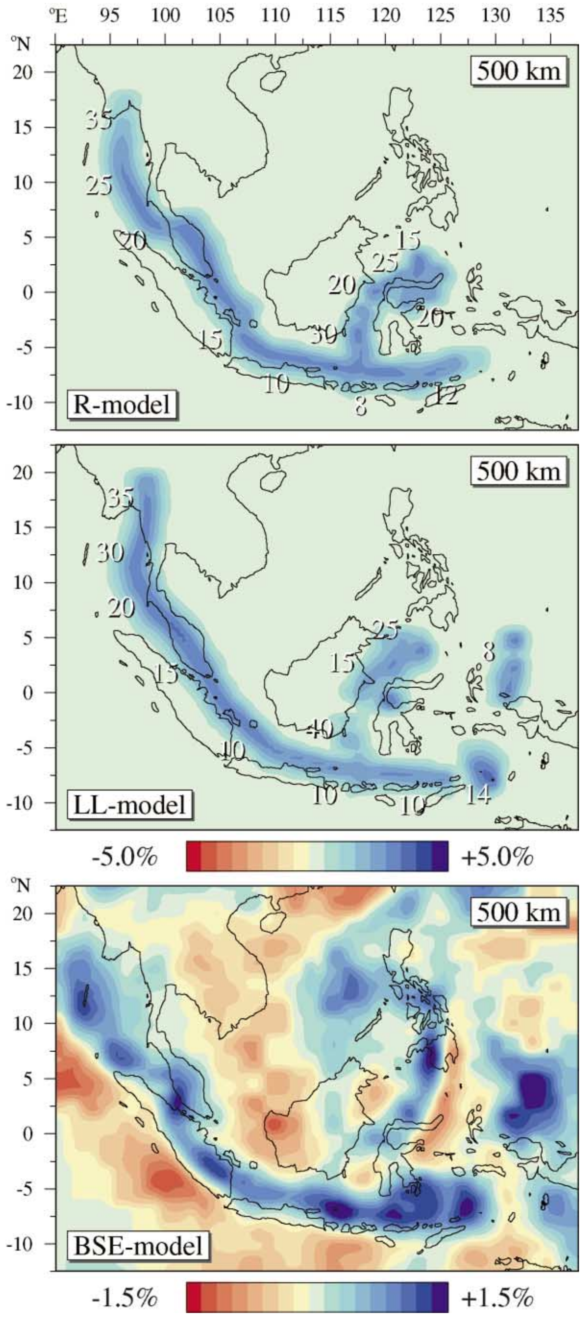

Fig. 4. P-velocity anomaly structure at 500 km depth of the R-model (upper), LL-model (middle) and tomographic BSE-model (lower panel). Numbers as in Fig. 3.

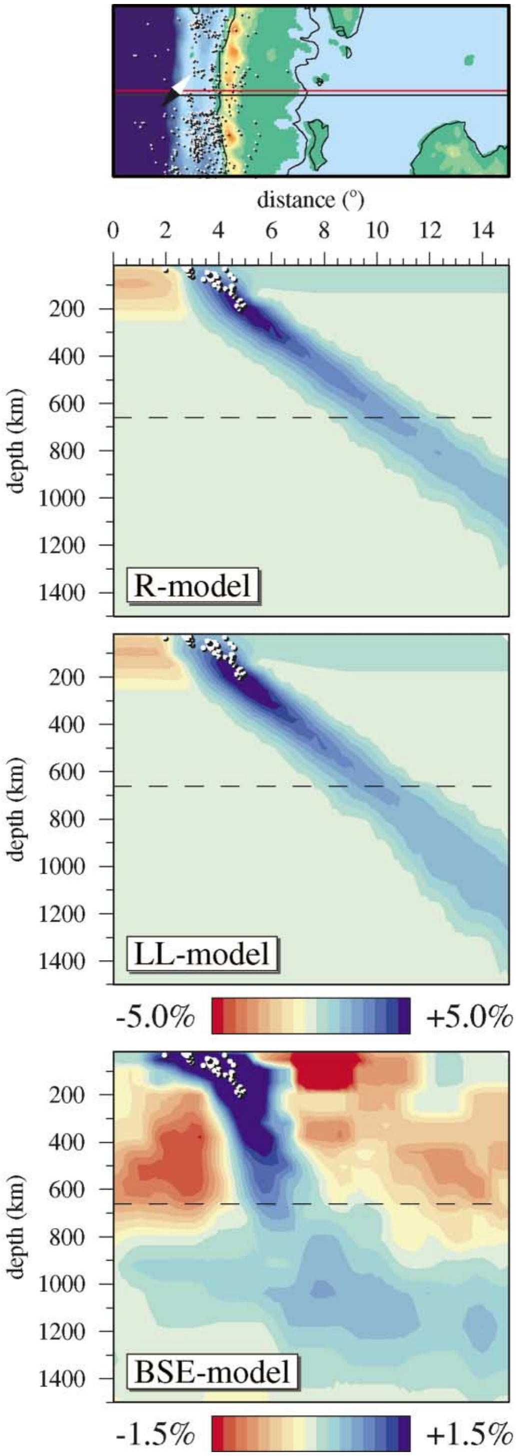

Fig. 5. Vertical sections down to 1500 km depth across Sumatra through the P-velocity anomalies of the R-model (upper), LL-model (middle) and tomographic BSE-model (lower panel). The location of the section is indicated in the small map on top and in Fig. 1. The dots represent earthquake hypocentres.

While our predicted slabs subduct at fixed dips, in some regions (for example beneath the Sunda arc, see Figs. 5 and 6) the tomographic anomalies lose their plate-like geometry in the lower mantle (see Bijwaard et al. (1998) for a discussion). This indicates that our current approach is not yet appropriate for a comparison between the models at lower mantle levels. In this paper, we will therefore concentrate on the upper mantle structure and only give an indication of possible similarities and dissimilarities between the lower mantle anomalies. Below, we will focus on sections through the Sunda arc, Banda arc, Molucca Sea and Sulawesi region (see Fig. 1 for locations).

4.2. Sunda arc

The reconstructions proposed by Rangin et al. (1990a,b) and Lee and Lawver (1995) differ in the migration of the Sunda arc as well as in the rotation of the subducting Indo-Australian plate (Section 3). Nevertheless, we find that the amounts of Cenozoic convergence along the trench are comparable. During the total modelled timespan of 40 Myr (in the R-model) and 60 Myr (in the LL-model) lithosphere of up to 2500 km and 3000 km length, respectively, has descended into the mantle underneath Sumatra and about 500 km more beneath Java. Near Myanmar (Burma), about 700 km of convergence is predicted for the reconstruction of Lee and Lawver (1995) and an average 500 km of convergence for the reconstruction of Rangin et al. (1990a,b). The lithospheric subduction has resulted in a comparable positive velocity pattern beneath the present-day Sunda arc (Figs. 3–6). The predicted distributions show strong similarities with the tomographic images. In this case, the comparison between the predicted models and the tomography model lends support to both reconstructions. Because the eastern part of the Paleogenic Indonesian trench system (mentioned above, in Section 3) is totally disconnected from the present-day Sunda arc, we prefer to discuss the results of

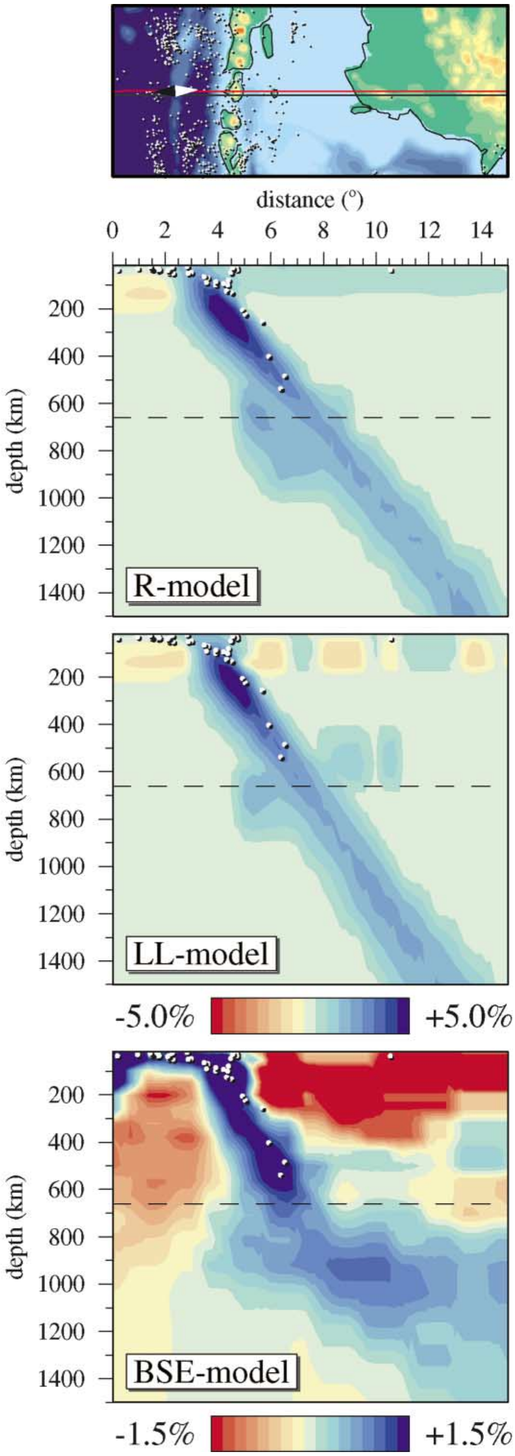

Fig. 6. Vertical sections across Java through the R-model (upper), LL-model (middle) and tomographic BSE-model (lower panel). See Fig. 1 for location of the section.

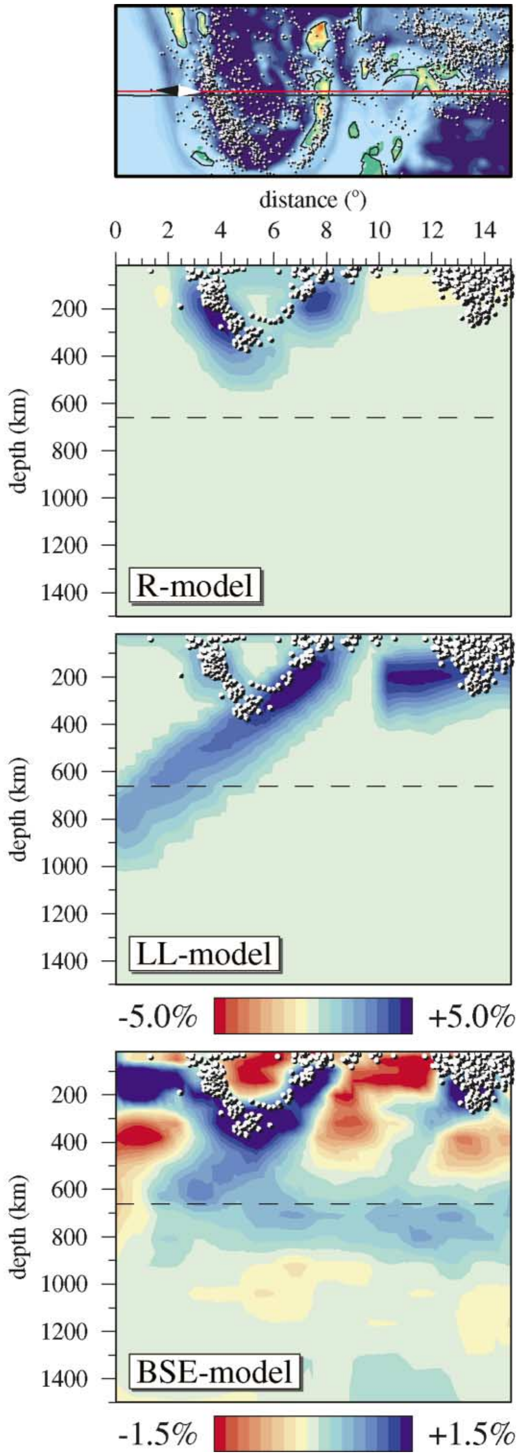

Fig. 7. Vertical sections across the Banda arc through the R-model (upper), LL-model (middle) and tomographic BSE-model (lower panel). The shallow high-velocity structure on the north side (right) of the LL-model subducted along the Halmahera trench system. See Fig. 1 for location of the section.

this area in the section about the Sulawesi and Molucca Sea region.

According to Bijwaard et al. (1998) and Van der Voo et al. (1999), part of the lower mantle anomalies beneath the western Sunda arc of the BSE-model (Fig. 5) may represent lithospheric material of the Mesozoic Tethys Ocean. Since the continental margins of Greater India and Eurasia started to collide around 60 Ma, followed by a continent–continent collision after 45 Ma (e.g. Audley-Charles et al. 1988; Lee and Lawver 1995; Van der Voo et al. 1999), most of the Tethys Ocean must have been subducted before the start of both reconstructions. The upper mantle anomalies of the BSE-model indicate a subduction of about 900 km of lithosphere. If the lower mantle anomalies do represent the remnants of the Tethys Ocean, then these upper mantle anomalies may be the result of processes of the past 45–60 Myr. Continuity between the upper mantle anomalies and the lower mantle reservoir is not very clear. The calculated convergence along this part of the trench (2500 km in the R-model to 3000 km in the LL-model) far exceeds the 900 km of tomographic upper mantle anomalies. This may indicate that for the modelled timespan, part of the subducted material did indeed accumulate into the lower mantle reservoirs or that the total amount of convergence that was predicted by the tectonic reconstructions is too large. Beneath Myanmar, the slab length that is predicted in the LL-model is larger than the maximum of 500 km that can be estimated from the tomography.

The positive velocity anomalies in the BSE-model (Fig. 6) merge into another huge high-velocity pattern, situated at 800–1400 km depth beneath Java and Kalimantan up to southern Philippines. From the total volume of this SW–NE-oriented anomaly we arrive at an estimate of ancient convergence of up to 4500 km in approximately NW direction. The Indian Ocean lithospheric material subducted along the Java trench (Fig. 6) may have fed this huge eastern reservoir, and probably still does. The upper mantle slab of 900 km length in the BSE-model increases the total

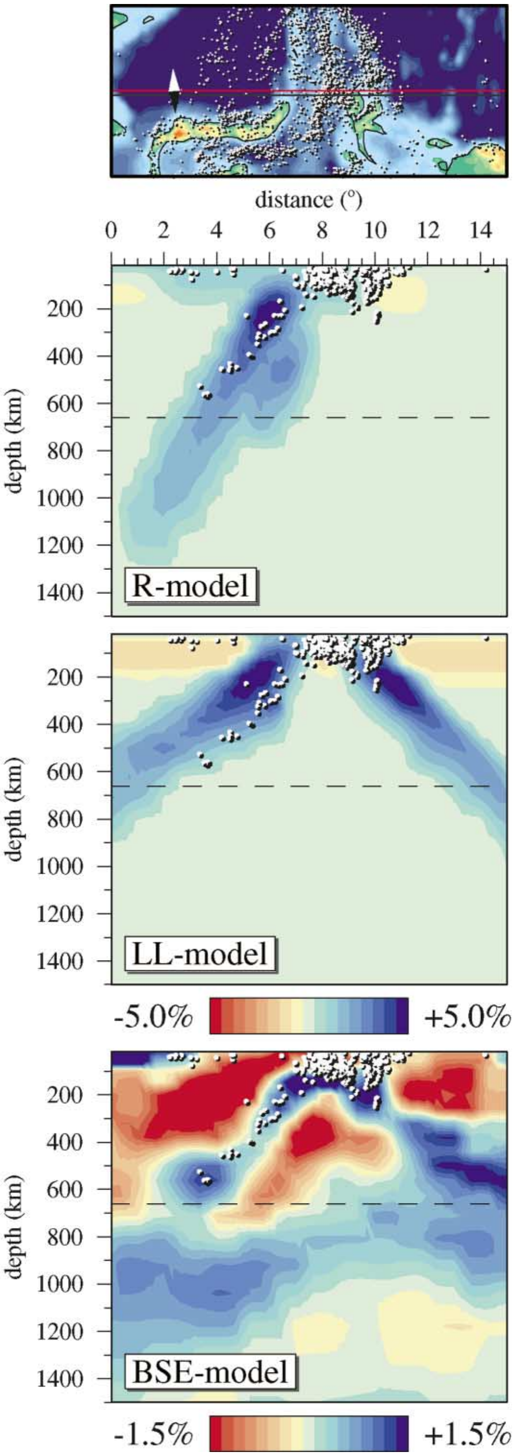

Fig. 8. Vertical sections across the Molucca Sea through the R-model (upper), LL-model (middle) and tomographic BSE-model (lower panel). In the R- and LL-model, material that subducted along the Sulawesi trench system can be seen on the west side of the section (left). See Fig. 1 for location of the section.

convergence along this part of the trench to 5400 km. This is much longer than the 3000–3500 km length of our calculated models and suggests an actual subduction of more material, probably prior to the modelled timespans.

4.3. Banda arc

In the R-model, lithospheric material of about 250 km length subducted northward along the Timor trench, and some 150 km subducted southward along the Buru-Seram trench (Fig. 2). The counterclockwise rotation of Buru-Seram, proposed in the Lee and Lawver (1995) reconstruction, has resulted in a southward subduction of over 700 km of lithosphere under Seram which is significantly more than calculated for the R-model. Beneath Timor, the short timespan (4 Myr) of subduction has resulted in only 50–100 km of convergence. Because all reconstructed processes of subduction along the Banda arc take place within the modelled timespans, the comparison with the tomography results should be very meaningful.

Highly curved velocity anomalies can be seen clearly around the Banda Sea in the tomographic BSE-model (Figs. 3 and 4). Both the R-model and the LL-model show a similar u-shape geometry of subducted material, predicted from the two separate north and south trenches. The vertical cross-section of Fig. 7 cuts both the north- and southward subducted material beneath the Banda arc. Across the arc, the positive velocity anomalies in the BSE-model represent a subduction of approximately 300 km beneath Timor and nearly 800 km under Buru-Seram. In view of the tomographic anomalies, the subduction beneath Timor is underestimated in the LL-model, where the small amount of convergence beneath Timor has resulted in only minimal anomalies.

Although it is difficult to draw conclusions from the anomalies alone, the R-model seems to give a better estimate of the convergence along the trench. This would favour the suggestion for a longer duration of subduction beneath the southern Banda arc (e.g. Richardson and Blundell, 1996). Beneath the Buru-Seram islands, the predicted subducted material in the R-model is clearly less than the 800 km length that can be inferred from the tomographic slab remnants. In Fig. 7, the LL-model seems to overestimate this amount.

4.4. Molucca Sea and Sulawesi region

The patterns of positive velocity anomalies in the upper mantle beneath Sulawesi that can be seen in our forward models (Figs. 3 and 4) result from the northward subduction of the oceanic lithosphere ahead of the Australian continent and the eventual collision with its margins (Section 3). Under the region between Sulawesi and the Sunda arc, both the R-model and the LL-model show N–S oriented material that subducted along presently inactive trenches, so the anomalies represent relatively old material. In the Molucca region, the Molucca Sea plate has subducted westward beneath the Sangihe islands and eastward beneath Halmahera. Along the Sangihe trench, both predicted mantle models reflect a total subduction of approximately 1000 km (R-model) to over 1500 km (LL-model) of lithospheric material. In the LL-model, the large anomalies beneath Halmahera represent a convergence of more than 900 km in 10 Myr of subduction with high convergence velocities. In the R-model, modest subduction beneath the Halmahera islands (6 Myr with an average convergence velocity of only 1.5 cm/yr) has resulted in minimal anomalies.

The BSE-model clearly shows a high velocity pattern associated with the double-sided subduction of the Molucca Sea plate (Figs. 3 and 8). The locations of the two trench systems are very close to each other and the plate seems to be subducted completely. Both slabs seem to connect up to larger positive velocity reservoirs in the mantle (Fig. 8). The Sangihe slab is continuous with the SW–NE oriented lower mantle reservoir (see the previous section) for which a 4500 km of convergence in approximately NW direction was derived above. Including the anomalies in this reservoir, the BSE slab remnants beneath the Sangihe islands represent a total length of about 5500 km. The positive velocity reservoir beneath the Halmahera subduction zone can be interpreted as an accumulation of about 3500 km of lithosphere subducted earlier along the Halmahera trench system.

The geometry of the subduction zones shown in the LL-model is similar to the BSE-model, although the modelled locations of the two trenches may be too far apart. The lack of a significant slab beneath Halmahera in the R-model is in clear contradiction with the tomography results. In the BSE-model, the total amount of subducted material beneath the Sangihe islands is significantly more than predicted from the reconstructions. In addition, the amounts under the Halmahera trenches exceed the predicted lengths. The results indicate that higher convergence velocities must have occurred during the reconstructed timespan of subduction, or that there has been subduction prior to the modelled period.

In contrast to the calculated models, the N–S pattern of positive velocity anomalies between Sulawesi and the Sunda arc can not be seen in the BSE-model (Figs. 3 and 4). The only structure that could be identified as a continuity between the material subducted along the Sunda arc and the E–W-oriented pattern beneath Sulawesi (Rangin et al., 1999) is the SW–NE-oriented lower mantle reservoir below Kalimantan (discussed previously). This would indeed imply a former connection of the trenches. In that case, however, the eastern part of the ancient arc system must have been in a more westward position (i.e. at lower longitudes) than proposed in both tectonic reconstructions.

5. Conclusions

We have presented models of the seismic P-velocity structure beneath Indonesia calculated from the tectonic reconstructions of Rangin et al. (1990a,b) and Lee and Lawver (1995). The models have been compared to the tomographic BSE-model of Bijwaard et al. (1998). This comparison provides a tool for defining the merits and shortcomings of the different scenarios for the Cenozoic evolution that are proposed in the two reconstructions.

We conclude that both the R-model and LL-model predict positive velocity anomalies — associated with subducted material — in upper mantle regions that are characterised by high velocities in the BSE-model as well. The calculated upper mantle anomalies reflect the tectonic evolution of the past 10 to 40 Myr (depending on the subregion).

From both reconstructions, a similar pattern of subducted material is predicted beneath the Sunda arc. Along the southern part of this trench, the length of subducted material is much less than the length inferred from the upper and lower mantle anomalies of the tomography. The results suggest that more material must have subducted along the trench system than was calculated, probably prior to the reconstructed timespan. The anomalies under Myanmar (Burma) that can be seen in the tomographic images indicate a convergence of at most 500 km which is less than the 700 km predicted in the LL-model.

Along the Banda arc, the curved geometry of anomalies in the predicted models is in agreement with the tomography results. This indicates that the tomographic Banda anomaly can be explained by subduction along the two separate trench systems that are proposed in both reconstructions. Beneath the southside of the arc, the 250 km of subduction proposed for the R-model results in positive velocity anomalies that are comparable to the tomography, whereas the length for the LL-model is underestimated. Under the northside, the R-model predicts less subduction than the 800 km inferred from the tomographic images. The counterclockwise rotation of Buru-Seram as proposed for the LL-model results in a better estimate of the convergence along this trench.

The positive velocity anomalies between the Sunda arc and Sulawesi that were modelled from the reconstructions cannot be found in the tomographic images. The double-sided subduction of the Molucca Sea plate of the LL-model is in agreement with the tomography. In the R-model, the length of subducted material beneath the Halmahera islands (<100 km) clearly is too small, but also the 500 km of the LL-model is an underestimation. The large anomalies within the tomographic mantle model suggest that nearly 6500–8000 km lithospheric material may have subducted along the double trench system, either during or prior to the proposed subduction processes.

Our forward approach is limited by its kinematic properties, implying that dynamically related features like trench migration, convergence velocity, age and slab geometry are all predescribed. Strike-slip faulting and oblique subduction (or extension) cannot be modelled properly owing to our 2D calculations. Furthermore, the conversion into seismic P-velocity anomalies is simplified. In spite of these limitations, our results show that the method enables us to evaluate the qualities of the proposed tectonic reconstructions. Therefore, we expect that continued application and further development of our approach will significantly contribute to resolving major issues in the complex evolution of Southeast Asia.

Acknowledgements

We are grateful to Marc de Jonge for the use of his modelling procedure. We thank Frédéric Masson, Serge Lallemand and an anonymous reviewer for their constructive comments on the manuscript. S.J.H. Buiter and H. Bijwaard were financially supported by the Geoscience Foundation (ALW) of the Netherlands Organization for Scientific Research (NWO). This work was conducted under the programme of the Vening Meinesz Research School of Geodynamics (VMSG) and the Netherlands Research Centre for Integrated Solid Earth Sciences (ISES).

References

Audley-Charles, M.G., Ballantyne, P.D., Hall, R., 1988. Mesozoic–Cenozoic rift–drift sequence of Asian fragments from Gondwanaland. Tectonophysics 155, 317–330.

Bijwaard, H., Spakman, W., Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography. J. Geophys. Res. 103, 30 055–30 076.

Chapman, D.S., 1986. Thermal gradients in the continental crust. In: Dawson, J.B., Carswell, D.A., Hall, J., Wedepohl, K.H. (Eds.), The Nature of the Lower Continental Crust. Geol. Soc. Spec. Publ. 24, 63–70.

Daly, M.C., Cooper, M.A., Wilson, I., 1991. Cenozoic plate tectonics and basin evolution in Indonesia. Mar. Pet. Geol. 8, 2–21.

De Jonge, M.R., 1995. Geodynamic evolution and mantle structure. PhD thesis. Utrecht University, the Netherlands.

De Jonge, M.R., Wortel, M.J.R., Spakman, W., 1993. From tectonic reconstruction to upper mantle model: an application to the Alpine-Mediterranean region. Tectonophysics 223, 53–65.

De Jonge, M.R., Wortel, M.J.R., Spakman, W., 1994. Regional scale tectonic evolution and the seismic velocity structure of the lithosphere and upper mantle: the Mediterranean region. J. Geophys. Res. 99, 12 091–12 108.

Goes, S., Govers, R., Vacher, P., 2000. Shallow mantle temperatures under Europe from P and S wave tomography. J. Geophys. Res. 105, 11 153–11 169.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., Blundell, D. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 153–184.

Katili, J.A., 1975. Volcanism and plate tectonics in the Indonesian island arcs. Tectonophysics 26, 165–188.

Lee, T.-Y., Lawver, L.A., 1995. Cenozoic plate reconstruction of Southeast Asia. Tectonophysics 251, 85–138.

McCaffrey, R., 1988. Active tectonics of the eastern Sunda and Banda Arcs. J. Geophys. Res. 93, 15 163–15 182.

McKenzie, D.P., 1978. Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett. 40, 25–32.

Milsom, J., Kaye S., Sardjono, 1996. Extension, collision and curvature in the eastern Banda arc. In: Hall, R., Blundell, D. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 85–94.

Minear, J.W., Toksöz, M.N., 1970. Thermal regime of a downgoing slab and new global tectonics. J. Geophys. Res. 8, 1397–1419.

Ranalli, G., 1996. Seismic tomography and mineral physics. In: Boschi, E., et al. (Eds.), Seismic modelling of the Earth structure. Instituto Nazionale di Geofisica, Bologna, Italy, pp. 443–459.

Rangin, C., Jolivet, L., Pubellier, M., et al., 1990a. A simple model for the tectonic evolution of southeast Asia and Indonesian region for the past 43 m.y. Bull. Soc. Géol. France 8, 889–905.

Rangin, C., Pubellier, M., Azéma, J., Briais, A., Chotin, P., Fontaine, H., Huchon, P., Jolivet, L., Maury, R., Muller, C., Rampnoux, J.P., Stephan, J.F., Tournon, J., Cottereau, N., Dercourt, J., Ricou, L.E., 1990b. The quest for Tethys in the western Pacific: 8 paleogeodynamic maps for Cenozoic time. Bull. Soc. Géol. France 8, 907–913.

Rangin, C., Spakman, W., Pubellier, M., Bijwaard, H., 1999. Tomographic and geological constraints on subduction along the eastern Sundaland continental margin (South–East Asia). Bull. Soc. Géol. France 170, 775–788.

Richardson, A.N., Blundell, D.J., 1996. Continental collision in the Banda arc. In: Hall, R., Blundell, D. (Eds.), Tectonic Evolution of Southeast Asia, Geol. Soc. Spec. Publ. 106, 47–60.

Sleep, N.H., 1973. Teleseismic P-wave transmission through slabs. Bull. Seismol. Soc. Am. 63, 1349–1373.

Van der Voo, R., Spakman, W., Bijwaard, H., 1999. Tethyan subducted slabs under India. Earth Planet. Sci. Lett. 171, 7–20.