Chapter 5

Evolution-related aspects of subduction in the Tethyan region

5.1 Introduction

In the previous chapter, we have analysed the history of subduction within the Tethyan region as deduced from the motions of the African-Arabian and Indian plates relative to Eurasia in the past 200 Ma. From the amount of convergence between the continents we predicted the present thermal volumes associated with the subducted material, and compared these to the seismic anomalous volumes in the tomographic images of the mantle underneath the area. We found that, to first-order, the volumes and distribution of the tomographic anomalies were in agreement with the predicted volumes.

Here we will investigate the Mesozoic-Cenozoic subduction within the Tethyan region in more detail. Whereas we have only used the digitised reconstruction of Norton (1999) to study the Tethyan region as a whole, other plate tectonic reconstructions of the area, e.g. those of Dercourt et al. (1993), Şengör and Natal’in (1996) and Stampfl and Borel (2002, 2004), generally agree on the first-order motions explored so far. However, no overall consensus has been achieved on, for example, the movements of various continental fragments, nor on the spreading and subduction history of the intermediate oceanic basins. Possible back-arc spreading and the subsequent subduction of the lithosphere created may have increased the amount of subducted material, and also lithospheric spreading within the Neo-Tethys during its subduction may have added to the total convergence significantly. Therefore, the total volume of subducted material in the Tethyan region is likely to be larger than calculated from the African-Eurasian convergence alone, and probably different for the various tectonic reconstructions.

Moreover, so far we have only considered the volume of subducted material as a whole, and second-order effects on the subduction processes have not been taken into account. For example, continental collisions may have led to slab break-off, and the subduction of a mid-oceanic ridge system may have created a completely slabless or apparent window in the thermal volumes of the subducted material. To analyse such processes, we will isolate the appropriate
subvolumes, for which the average ages and residence times in the mantle will generally be
different from that of the total volume comprehending these subvolumes. Furthermore, the
possible distribution of the slab volumes in the mantle will be affected by the absolute motion
of the plates since subduction. We expect that incorporation of these various aspects in our
comparison with tomography will enable use to better understand the geodynamic evolution
of the Tethyan region.

5.2 Tectonic evolution

We briefly summarise here the aspects of the tectonic evolution that are expected to have
had major implications for the specific subdivision, location and geometry of the lithosphere
subducted within the Tethyan region. We address other reconstructions than that of Norton
(1999), hereafter referred to as the ExxonMobil reconstruction, where relevant.

Separate Paleo-Tethyan volume

In the Indian region, the Paleo-Tethys closed when the Afghanistan and south Tibet blocks
collided with Eurasia. This happened around Late Triassic (thus before 200 Ma) according to
Stampfli and Borel (2002, 2004), but in other reconstructions, this closure has been proposed
for Late Jurassic - Early Cretaceous times (~140 Ma) instead (ExxonMobil, Dercourt et al.,
1993; Şengör and Natal’ın, 1996). The subducted Paleo-Tethyan lithosphere may be visible
as a separate volume in the tomographic images today.

The approximate direction of subduction is likely to be reflected in the present-day location of
the subducted oceanic lithosphere. Some reconstructions propose the Paleo-Tethyan oceanic
lithosphere to have been subducted northward underneath Eurasia (ExxonMobil, Dercourt
et al., 1993), whereas others have suggested a southward subduction of the Paleo-Tethys
underneath south Tibet and Afghanistan (Şengör and Natal’ın, 1996). In the reconstruction
of Stampfli and Borel (2002, 2004), subduction occurs in a more or less northeast to eastward
direction instead.

Slab volumes after ridge subduction

Because the morphology of the subducted material may have been affected by ridge subduc-
tion, we will investigate three broadly accepted subduction scenarios for the Tethyan litho-
sphere and its spreading ridges.

The two end-member spreading scenarios for the oceanic lithosphere discussed in the pre-
vious chapter (p. 87) are considered for all three subduction scenarios: Spreading scenario
A in which all oceanic spreading systems are assumed to remain active until the ridges are
subducted, and spreading scenario B in which spreading within the oceanic basins stops at
the very moment the plates start subducting. We aim at testing the tectonic reconstructions
underlying the various scenarios as they are, i.e. without an a-priori judgement of their quality.

Subduction scenario I  Subduction scenario I (Fig. 5.1, upper panel) is the most simple,
straightforward scenario, e.g. proposed by ExxonMobil and by Şengör and Natal’ın (1996)
for the subduction of the Neo-Tethys in the Indian region. This is basically the scenario we have discussed in Chapter 4. In this scenario, all displacement between the converging African/Arabian/Indian and Eurasian continents, as well as the possible additional spreading in between them, is accommodated along the same trench system at the Eurasian margin. For such a scenario we would expect all Neo-Tethyan slab material to be subducted relatively close to the present Zagros/Indus-Tsangpo Sutures, even when ridge subduction has affected the morphology of the material.

**Subduction scenario II** Subduction scenario II (Fig. 5.1, middle panel) is often proposed for the Arabian region (e.g. Dercourt et al., 1993; Şengör and Natal' in, 1996) to explain the \( \sim 80 \) Ma emplacement time of the Oman ophiolites on the Arabian continental margin. In this scenario, the ridge of the Neo-Tethys resided very close to the Arabian continent. Subsequently, during a short period of intra-oceanic subduction, the spreading ridge was obducted onto Arabia. Because the distance between the ridge and the Arabian continent is proposed to have been small, the amount of lithosphere subducted at this location will be small as well. Basically the entire Neo-Tethyan lithosphere is assumed to be subducted underneath the Eurasian margin, as in scenario I.

**Subduction scenario III** Subduction scenario III (Fig. 5.1, lower panel) is proposed by Stampfli and Borel (2002, 2004) for both the Arabian and Indian region. This scenario assumes an early (\( \sim 140-120 \) Ma) subduction of the Neo-Tethyan ridge to have triggered the opening of two distinct back-arc basins within the Eurasian margin: The Semail Ocean in the Middle East and the Spongtag Ocean in the Indian region. In the Arabian region, the Neo-Tethys had disappeared completely with the obduction of the Semail spreading ridge onto the Arabian peninsula at \( \sim 80 \) Ma, after which the Semail Ocean subducted northward underneath Eurasia again. The exact closure times of the Neo-Tethys and Spongtag Oceans in the Indian region are not so clear, but are probably around 65 and 50 Ma, respectively. Because spreading within the back-arc oceans occured at the direct expense of the Neo-Tethys, this will have added certainly to the amount of subduction as calculated from the converging continents alone. Furthermore, we expect two or three separate slab volumes for this scenario, namely 1) a Neo-Tethyan slab part subducted beneath the Eurasian margin, 2) the remaining Neo-Tethyan slab subducted near the Arabian and Indian continental margins, and 3) the slab of the back-arc ocean subducted underneath Eurasia again.

**Slab break-off after Cenozoic continental collisions** There is general agreement that the continental part of Greater India collided with the Eurasian continent in Early Eocene times, and the collision of Arabia with Eurasia took place in the Early Miocene. We will here use the accretion times of ExxonMobil, namely \( \sim 48 \) Ma and \( \sim 22 \) Ma, respectively. We will investigate whether these continental collisions have caused the subducting slabs to break-off and, if so, at what time. If slab detachment occurred, the present-day depth and location of the slab material in the lower mantle must be in accordance with the time of break-off. Also the volumes, both of the slab broken off and the lithosphere still attached to the surface, may help us at this point.
Figure 5.1: Three subduction scenarios for the Neo-Tethys: **Subduction scenario I**: All Neo-Tethyan subduction is accommodated along one single trench system at the Eurasian margin. **Subduction scenario II**: The Neo-Tethyan ridge is emplaced onto the Arabian/Indian margin, whereas basically all Neo-Tethyan lithosphere is subducted along the same Eurasian trench system. **Subduction scenario III**: Neo-Tethyan ridge subduction underneath Eurasia is followed by the opening of a Semail/Spongtang back-arc basin. After this oceanic basin has completely overridden the Neo-Tethys, and its ridge is obducted onto the Arabian/Indian margin, its lithosphere is subducted below Eurasia. **Key**: A/I = Arabian/Indian continent, EU = Eurasian continent, N-T = Neo-Tethys Ocean, S/S = Semail/Spongtang Ocean, and obd = ridge obduction.
5.3 Absolute motion

Whereas the predicted division of the volumes associated with the subducted lithosphere will depend on the assumed subduction scenario, the actual distribution of the slab material is a function of the absolute motion of the plates since the time of subduction. By plate motion in an absolute reference frame we generally mean the motion relative to the underlying mantle.

In a hotspot reference frame, it is assumed that the distance between a group of individual hotspots remains nearly constant over long periods of time such that the hotspot tracks give us the direction of absolute plate motion (e.g. Morgan, 1971; Gordon and Jurdy, 1986; O’Connor and le Roex, 1992; Müller et al., 1993). There is increasing evidence, however, that hotspots are not very stable with respect to one another, and therefore to the lower mantle (e.g. Tarduno and Gee, 1995; Norton, 2000; Torsvik et al., 2002; O’Neill et al., 2003).

To account for the present uncertainties in defining absolute plate motion, we will here consider the geographical locations of the Arabian/Indian and Eurasian continental margins in three different reference frames: One in which the Eurasian craton is held fixed (EU), a fixed hotspot reference frame based on Duncan and Richards (1991) for the past 30 Ma and Müller et al. (1993) prior to that time (HS), and the hotspot reference frame of O’Neill et al. (2003) based on the motion of hotspots in the Indian Ocean (MHS). In Figures 5.2-5.4, the positions of the continental blocks that formed the margins considered are shown at a few relevant times since 120 Ma (EU, HS) and 65 Ma (MHS) until 20 Ma.

As can be seen in Figures 5.2 and 5.3, the locations of the Arabian/Indian and Eurasian continental margins plotted in the EU frame significantly differ from those given in the HS frame: Around 80 Ma, the positions in the HS frame are ~4-5° south of those plotted with Eurasia fixed. As the HS frame is uncertain prior to 84 Ma, the remarkably northern location of the Eurasian margin at 120 Ma (lowerright panel Fig. 5.3) may not be correct. The actual position of Eurasia around 120 Ma was suggested to have been much further south than in the HS frame, and to have remained stationary until 90 Ma, by Torsvik et al. (2002). In the MHS frame, India is placed much further north and west than in fixed hotspot models as HS. During the past 65 Myr, the locations of the Arabian/Indian and Eurasian continental margins in this MHS frame have similar or even higher latitudes than those in a EU frame (Fig. 5.4 vs. 5.2). Moreover, the continents are positioned much further west in the MHS frame than in both the HS and EU frame. The large westward shift was needed to fit the moving hotspots, but could not be independently constrained and was suggested by the authors not to be as robust as the northward shift.

In the following, we want to compare the positions of the various tomographic anomalies with the past locations of the trench systems. We have therefore also plotted in Figures 5.2-5.4 the tomographic anomalous bodies associated with subducted Tethyan lithosphere from Figures 4.5 and 4.6 (pp. 74 and 75). The lowermost mantle anomalies underneath the Tethyan region (~1100-2560 km) are likely to be associated with Mesozoic subduction, whereas the Cenozoic evolution will probably be reflected in the more shallow anomalies (~660-1100 km). The upper mantle anomalies of Figure 4.4 (p. 73) can be primarily associated with the most recent phases of subduction only.
Figure 5.2: Geographical locations of the continental blocks that form the Eurasian and Arabian/Indian margins from ExxonMobil with Eurasia fixed, shown together with the tomographic anomalous bodies associated with Tethyan subducted lithosphere in this study. Present coastlines and political borders are given for reference only. **Top panel:** Positions at 20 and 40 Ma with tomographic anomalies between 660-1100 km depth; **Middle panel:** Positions at 50 and 65 Ma with anomalies between 660-1100 km depth; **Lower panel:** Positions at 80 and 120 Ma with anomalies between 1100-2600 km depth. For clarity, only the southernmost fragments on the Eurasian margin are shown (cf. Figs. 2.2 and 2.7-2.8, pp. 17-29).

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Figure 5.3: Geographical locations of the Eurasian and Arabian/Indian continental margins as in Figure 5.2, but now plotted in the hotspot reference frame of Duncan and Richards (1991) at 20 Ma and of Müller et al. (1993) prior to that time. Note that the positions at 120 Ma are uncertain.
Section 5.3

Figure 5.4: Geographical locations of the Eurasian and Arabian/Indian continental margins as in Figure 5.2, but now plotted in the moving hotspot reference frame of O’Neill et al. (2003) for the past 65 Ma.
Bulk volumes for various subduction scenarios

5.4 Bulk volumes for various subduction scenarios

Subduction scenario I

In the previous chapter, the thermal volume of the subducted material - approximately following subduction scenario I - has been predicted for an average lithospheric age upon subduction based on the plate reconstruction of ExxonMobil. The resulting ratios of tomographic and predicted volumes are summarised in the left columns of Table 5.1, p. 114. For the Tethyan region as a whole, as well as for the Aegean/Arabian and Indian region separately, the predicted volumes are found to be significantly larger than the tomographic volumes when no slab deformation is assumed (T/P-ratios < 1). If lithospheric thickening by a factor of 2 or 3 is taken into account, considered to be necessary for the large Tethyan slabs, the resulting thermal volumes associated with the subducted material decrease: The thermal volumes predicted for spreading scenario B are approximately similar to the tomographic volumes (T/P-ratios ≈1). For spreading scenario A the volumes (T/P-ratios > 1) leave room for an additional subducted volume of ~0.2-0.3 times the tomographic volume, i.e. about 1-2·10⁹ km³, depending on the amount of thickening.

Subduction scenario II

The variation of the age of the lithosphere in subduction scenario II is relatively simple (see Fig. 5.5). As in subduction scenario I, the age of the Tethyan lithosphere was 70 Ma at initiation of subduction underneath Eurasia. In spreading scenario A, its ridge stopped spreading upon obduction onto the Arabian continental margin at 80 Ma. Therefore, the last remnants of lithosphere to be subducted around 20 Ma along the Eurasian trench system were aged 60 Ma, and the 200-Ma average was 65 Ma. In spreading scenario B, the ridge stopped spreading when subduction of the Neo-Tethys commenced at 200 Ma. Subsequently, the fossil ridge was aged 120 Ma when obducting onto the Arabian margin, and the last remnants of Neo-Tethyan lithosphere had an age of 180 Ma upon subduction underneath Eurasia at 20 Ma. In this scenario, the average age of the subducting lithosphere was 125 Ma. Analogously, it can be derived that the 200-Ma average age of the small lithospheric surface to be subducted underneath the obducting Neo-Tethyan ridge was 95-155 Ma. However, because the distance between the ridge and the Arabian continent must have been small (Dercourt et al., 1993; Şengör and Natal'in, 1996), we will not consider this slablet separately. All Mesozoic-Cenozoic convergence, as well as the possible additional convergence in spreading scenario A, is assumed to be accommodated underneath Eurasia. As in subduction scenario I, the 200-Ma average age of the Tethyan lithosphere upon subduction is 65-125 Ma. The thermal volumes predicted for subduction scenarios I and II will therefore be equal, as well.

Subduction scenario III

For subduction scenario III, we consider here an alternative scenario for the variation of the lithospheric age upon subduction based on the reconstruction of Stampfli and Borel (2002, 2004) (see Figs. 2.3-2.6, pp. 22-25) as shown in Figure 5.5. Although the reconstructed isochrons of Stampfli and Borel (2002, 2004) would allow for a more detailed assessment of this variation in the future, we here use similar approaches for all three subduction scenarios.
Section 5.4

**Figure 5.5:** The variation of the age of the Tethyan lithosphere upon subduction for two end-member spreading scenarios (p. 87) and three different subduction scenarios (p. 106). The encircled numbers approximate the average ages of the separate oceanic domains. *Aegean/Arabian region* (top panel): Subduction scenario I (black lines) and II (light grey) that consider subduction of the Neo-Tethys only (200-Ma average age, based on ExxonMobil, is 65-125 Ma). Subduction scenario III (dark grey) includes the existence of a separate Semail Ocean as well (average age, based on Stampfli and Borel (2002, 2004), is 65-85 Ma). *Indian region* (bottom panel): Subduction scenario I (black lines) considers subduction of the Paleo-Tethys before 140 Ma and the Neo-Tethys thereafter (average age is 60-80 Ma). Subduction scenario III (grey lines), based on Stampfli and Borel (2002, 2004), assumes subduction of the Neo-Tethys since 200 Ma (average age is 70-110 Ma). See text for more detailed explanation.
In the Aegean/Arabian region, the age of the oceanic lithosphere was 70 Ma at initiation of subduction at 200 Ma, and active spreading within the Neo-Tethys must have stopped with the subduction of its ridge around 140 Ma at the latest. Triggered by the ridge subduction, the Semail back-arc ocean started spreading at direct expense of the Neo-Tethys. At 80 Ma, the Neo-Tethys closed completely with the obduction of the Semail spreading ridge onto the Arabian peninsula. Thereafter, the Semail Ocean subducted northward underneath Eurasia until it had disappeared around 20 Ma. For spreading scenario A, the Neo-Tethys lithospheric age upon subduction linearly decreased to 0 Ma when the ridge subducted at 140 Ma, and linearly increased again until the oldest parts of the Neo-Tethys were 190 Ma when subducted at 80 Ma. At that time, the Semail Ocean started to subduct with its oldest lithosphere aged 60 Ma. With cessation of spreading at 80 Ma, the youngest parts of the Semail oceanic lithosphere were still only 60 Ma when subducting at 20 Ma. In this spreading scenario, the 200-Ma average age of the subducting lithosphere was 65 Ma. For spreading scenario B, the age of the fossil ridge was already 60 Ma when it subducted, and the average age of the oceanic lithosphere was 85 Ma.

In the Indian region, the Neo-Tethys started spreading around 270 Ma as in the Aegean/Arabian region. Furthermore, the Paleo-Tethys already disappeared around 200 Ma, and the Neo-Tethyan ridge subducted around 120 Ma. In spreading scenario A, the age of the subducting oceanic lithosphere varied from 70 Ma at initiation of subduction at 200 Ma, to 0 Ma when the ridge subducted at 120 Ma, and to a final 220 Ma at 50 Ma. The average age of the subducted oceanic lithosphere was 70 Ma in this scenario. In spreading scenario B, the age of the fossil ridge was 80 Ma when it subducted, and the 200-Ma average was 110 Ma. In the reconstruction of Stampfli and Borel (2002, 2004), the Spongtag back-arc Ocean is proposed to have started spreading after subduction of the Neo-Tethyan ridge at 120 Ma (e.g. Fig. 2.6, p. 25). Because the eventual closure time of this basin is not very clear and its size relatively small, we will not use it for predicting the 200-Ma average age of the Tethyan oceanic lithosphere here, and have not incorporated it in Figure 5.5 either. However, the Spongtag back-arc Ocean will be discussed in Section 5.6, where - assuming subduction of the basin between 65 and 50 Ma (Stampfli and Borel, 2004) - the average age of the oceanic lithosphere upon subduction will be taken as 65 Ma.

Based on the plate reconstruction of Stampfli and Borel (2002, 2004), we propose a 200-Ma average for the age of the subducting Tethyan lithosphere of 65-85 Ma for the Aegean/Arabian region, and 70-110 Ma for the Indian region. The alternative averages lead to values for the initial lithospheric thickness and thermal factor \(c(200)\) that are slightly different from those used for the reconstruction of ExxonMobil in the previous chapter (see Table 5.7, p. 141).

The total thermal volume of the subducted material is found to be 7.8-9.2 \(10^9\) km\(^3\) for undeformed lithosphere, 6.1-6.9\(10^9\) km\(^3\) for slab thickened by a factor of 2, and 5.1-5.7\(10^9\) km\(^3\) for 3-fold thickened slabs (see Fig. 5.6). The resulting values of the T/P-ratios are similar to those for a separate Aegean/Arabian and Indian region (Table 5.1), with the values for the Indian region being a few percent smaller than those for the Aegean/Arabian region. However, the thermal volumes of the Aegean/Arabian region may be somewhat underestimated, and thus the T/P-ratios overestimated accordingly, due to the relatively small convergence rates in the area (Section 3.3.3). As can be seen from Figure 5.6 and Table 5.1, the values based on
Figure 5.6: Tomographic volumes ($V_t$) vs. predicted thermal volumes ($V_p$) for slabs that either (1) kept their plate-like geometry, (2) thickened by a factor of 2, or (3) thickened by a factor of 3. The values for $V_p$ are calculated for averages of the age of the subducted oceanic lithosphere based on the reconstruction of Stampfli and Borel (2002, 2004) for two end-member spreading scenarios (see p. 87). The predicted bulk volumes for ExxonMobil are representative for subduction scenarios I and II, and those of Stampfli and Borel (2002, 2004) for subduction scenario III. The calculations based on ExxonMobil (from Fig. 4.17, p. 95) are given for reference in the background.

Table 5.1: T/P-ratios ($V_t/V_p$) for two end-member spreading scenarios A and B (see p. 87). Left column: Ratios for averages of the lithospheric age based on ExxonMobil (as in Table 4.3 on p. 94). Right column: Ratios for averages based on the reconstruction of Stampfli and Borel (2002, 2004). The predicted bulk volumes for ExxonMobil are representative for subduction scenarios I and II, and those of Stampfli and Borel (2002, 2004) for subduction scenario III. Values for the lithospheric thickness and thermal factor $c(t)$ used to obtain $V_p$ are given in Table 5.7 (p. 141).
Separate Paleo-Tethyan volume

*Stampfli and Borel* (2002, 2004) do not significantly differ from the values calculated for the averages based on ExxonMobil.

**Conclusions**

Although the variations in the age of the lithosphere upon subduction based on ExxonMobil are significantly different from those based on *Stampfli and Borel* (2002, 2004), the 200-Ma averages are quite similar and the predicted thermal volumes accordingly. The thermal volumes in the Arabian region for subduction scenario II are the same as those for subduction scenario I based on ExxonMobil, and thus similar to subduction scenario III (*Stampfli and Borel*, 2002, 2004) as well. These results indicate that, based on the bulk volumes alone, we cannot distinguish between the different reconstructions. All three subduction scenarios predict volumes of subducted lithosphere that are in agreement with the tomographic bulk volumes when Tethyan slab thickening by at least a factor of 2 is taken into account.

### 5.5 Separate Paleo-Tethyan volume

**5.5.1 Predicted and tomographic slab volumes**

In the Indian region, the Paleo-Tethys closed prior to 200 Ma according to *Stampfli and Borel* (2002, 2004), but only around 140 Ma according to ExxonMobil, *Şengör and Natal’i’in* (1996), and *Dercourt et al.* (1993). Following the reconstruction of ExxonMobil and others, we will separate the volume associated with subduction in the Indian region prior to 140 Ma from that of subduction thereafter to isolate the subducted Paleo-Tethys. We will refer to the Paleo-Tethyan subvolume as $P-T$, and the remaining Neo-Tethyan volume as $N-T$. The Aegean/Arabian region, in which all the volumes are assumed to be $N-T$ in our 200-Myr timespan, will not be discussed here.

**Present thermal signature of subducted material**

The total subducted surface between 200 and 140 Ma is isolated as $P-T$ in the Indian region (lower panel Fig. 5.16, p. 140). The average age of this Paleo-Tethyan oceanic lithosphere upon subduction is assumed to be 65-75 Ma (Fig. 5.5). Furthermore, we take values of the thermal factors $c_1(t)$, $c_2(t)$ and $c_3(t)$ at $t = 200$ Myr. For the remaining Neo-Tethys oceanic lithosphere, subducted between 140 Ma and present, the average age is assumed to be 55-85 Ma. For this $N-T$ volume, we select the thermal factors at $t = 140$ Myr. The values for the initial lithospheric thicknesses and thermal factors used can be found in Table 5.7 (p. 141). The predicted thermal volumes are shown in Figure 5.7. The subducted surface and initial volumes for undeformed slabs are given in Table 5.2.

**Volumes of seismic anomalies**

A first option that will be considered here, is that all tomographic volumes represent remnants of subducted Neo-Tethyan lithosphere only. In that case, we exclude volume $P-T$ from the total predicted thermal volume, and compare this purely $N-T$ volume with the total $2.9\cdot3.7\cdot10^9$
km$^3$ of Indian tomographic volumes. The results for the option with the Paleo-Tethyan volume excluded, referred to as Excl. P-T hereafter, are given in the upper panel of Table 5.2 and left panel of Figure 5.7.

A second option that will be discussed is that the tomographic volumes represent both the $P-T$ volume and the $N-T$ volume. In an attempt to relate the Paleo-Tethys to a particular volume, we select anomaly Hi$^2$ in the tomographic model as a good candidate, following the suggestion made by Van der Voo et al. (1999) (lower panel Fig. 5.17, p. 142). In that case, we compare the predicted $P-T$ volume to the volume of anomaly Hi$^2$, and the predicted $N-T$ volume to the remaining tomographic anomalies. The results for the option with the Paleo-Tethys included, denoted Incl. P-T, are shown in the lower panels of Table 5.2 and right panels of Figure 5.7.

### 5.5.2 Comparison and conclusions

#### Option Excl. P-T

When comparing only the predicted $N-T$ volume to the Indian tomographic anomalies, a T/P-ratio of 0.9-1.1 (spreading scenario A) to 0.7-0.9 (spreading scenario B) is found for undeformed lithosphere (upper panel Table 5.2). This is significantly larger than previously found for the Indian region (e.g. Table 5.1). The same holds for the thermal volumes predicted for slabs thickened by factor of 2 and 3, which are not given separately in Table 5.2, but can be seen in Figure 5.7 (left panel). For both spreading scenarios, the thermal volumes for

![Figure 5.7](image)

**Figure 5.7:** Tomographic volumes ($V_t$) vs. predicted thermal volumes ($V_p$) in the Indian region, divided into a separate Paleo-Tethys ($P-T$) and Neo-Tethys ($N-T$) part for two end-member spreading scenarios (see p. 87). *Left panel (Excl. P-T):* All tomographic volumes discussed in this chapter are assumed to represent Neo-Tethyan slab remnants, so the predicted $P-T$ volume is excluded from the total Indian value. *Right panels (Incl. P-T):* The Paleo-Tethys is compared to anomaly Hi$^2$ of the tomographic volumes (right), and the Neo-Tethyan volumes are compared to the remaining tomographic volumes (left). The calculations for slabs that kept their plate-like geometry (1) can be found in Table 5.2, the factors necessary to perform the calculations for thickened slabs (2/3) are given in Table 5.7 (p. 141).
present thermal volumes (Paleo-Tethys is compared to anomaly Hi). The predicted volumes for the Indian subducted surface are compared to the remaining tomographic volumes. The volumes of the Aegean/Arabian region remain unchanged with respect to the previously found values (e.g. Table 5.1). The predicted volumes for slabs that have thickened in the mantle, calculated with the appropriate factors from Table 5.7 (p. 141), are shown in Figure 5.7.

Table 5.2: Subduction scenario I and II: Comparison of volumes when isolating the subducted surface associated with Paleo-Tethyan lithosphere (P-T) for slabs that kept their plate-like geometry. Column 1: Minimum and maximum tomographic volumes ($V_t$). Column 2: Subducted plate surface ($S$). Column 3: Estimated initial thermal volumes ($V_i$) for two spreading scenarios (see p. 87). Column 4: Predicted present thermal volumes ($V_p$). Column 5: T/P-ratio = $V_i / V_p$.

<table>
<thead>
<tr>
<th>Volumes</th>
<th>$V_{t(omo)}$ (-10$^8$ km$^3$)</th>
<th>$S_{(subducted)}$ (-10$^6$ km$^2$)</th>
<th>$V_{i(initial)}$ (-10$^8$ km$^3$)</th>
<th>$V_{p(predicted)}$ (-10$^8$ km$^3$)</th>
<th>$V_{t(omo)}/V_{p(predicted)}$ (T/P-ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeg/Arab</td>
<td>Incl. P-T</td>
<td>2.44 ±0.08</td>
<td>17.81</td>
<td>1.69 / 1.96</td>
<td>3.37 / 4.25</td>
</tr>
<tr>
<td>Indian N-T</td>
<td>Excl. P-T</td>
<td>2.88 ±0.70</td>
<td>19.58</td>
<td>1.76 / 2.06</td>
<td>3.28 / 4.10</td>
</tr>
<tr>
<td>Indian P-T</td>
<td>Excl. P-T</td>
<td>0.25 ±0.30</td>
<td>2.25</td>
<td>0.21 / 0.25</td>
<td>0.43 / 0.46</td>
</tr>
</tbody>
</table>

undeformed and doubled lithosphere are more similar to the tomographic volumes than found before (compare to right panel of Fig. 4.19, p. 98), and those predicted for tripled lithosphere even smaller.

Option Incl. P-T

When comparing volume N-T to the tomographic anomalies without anomaly Hi$^2$, the T/P-ratios become 0.8-1.0 to 0.6-0.8 for slabs that have remained undeformed (Table 5.2 and middle panel of Fig. 5.7). Including slab thickening, these ratios are somewhat smaller than for option Excl. P-T, and more similar to those calculated earlier for the total Indian region (e.g. as in Table 5.1 and Fig. 4.19, p. 98).

The P-T volume predicted here is approximately twice the volume of anomaly Hi$^2$ without slab deformation (Table 5.2 and rightmost panel of Fig. 5.7). When slab thickening by a factor of 3 is taken into account, probably necessary for this old lithospheric volume, the thermal volume is similar to the tomographic volume. However, subduction of the Paleo-Tethys must have started much earlier than our reconstructed 200 Ma: In the reconstruction of ExxonMobil, used to predict the P-T volume, the northern part of the Paleo-Tethys is likely to have been subducted around this time already (see Table 2.2, p. 20). This suggests that the older (> 200 Ma) part of the Paleo-Tethyan lithosphere cannot be identified as a separate tomographic volume today, or has been accommodated elsewhere. In the previous chapter...
Section 5.6

(Section 4.2), we identified two anomalies underneath Central Asia that were assumed to be related to subduction prior to 200 Ma. These anomalies, cA\(^1\) and cA\(^2\) in Figure 4.6 (p. 75), may well represent remnants of the remaining Paleo-Tethyan lithosphere indeed.

If the \(P-T\) lithosphere has broken off after continental collision of Afghanistan and south Tibet with Eurasia around 140 Ma, the depth and geometry of anomaly Hi\(^2\) may help us to further assess its subduction history. From Figure 5.19 (p. 144) it can be seen that Hi\(^2\) is positioned between 1200 and 2200 km depth, which corresponds to a sinking time of \(\sim\)80-180 Myr for sinking rates of 3 cm/yr in the upper mantle and 1 cm/yr in the lower mantle. Even when considering a certain delay-time for slab break-off, which could be as large as 25 Myr in view of the slow (\(\sim\)1 cm/yr) convergence rates at that time (Van de Zedde and Wortel, 2001), something must have slowed down the upper part of the sinking slab considerably. Moreover, as visible in Figure 4.7 (p. 76, section 95) and Figure 4.8 (p. 77, section F), the most shallow parts of the anomaly can be found in the northwest, i.e. below northwest India. If the slab has subducted northwards, as often proposed (e.g. Dercourt et al., 1993), slab break-off probably occurred on the eastern side of the plate but not, or much later, on the western side. The extreme dip of the anomaly, however, cannot be readily explained by diachronous slab break-off only. This suggests that the direction of subduction was eastward, as proposed to some degree by Stampfli and Borel (2004), or southward (Şengör and Natal’in, 1996), rather than northward. As can be seen in the Triassic reconstruction of Stampfli and Borel (2004) in Figure 2.3 (p. 22), subduction of the eastern Paleo-Tethys partly occurred in a direction parallel to the north Tibetan (nT) block. If the slab has subducted eastward indeed, although in this reconstruction already before 200 Ma, the depth distribution of Hi\(^2\) suggests that the slab did not really break off but more or less remained attached to the surface. It seems plausible that the continental fragments of south Tibet and Afghanistan collided with Eurasia, but that complete slab break-off did not occur, for example, because the zone of subduction - accommodating the further convergence between India and Eurasia - moved towards the southern margin of these blocks instead, and the continental lithosphere did not subduct deep enough to trigger slab detachment.

Conclusions

Our results indicate that anomaly Hi\(^2\) could represent part of the subducted Paleo-Tethyan lithosphere if (1) the subducted slab has thickened by a factor of 3, (2) the remaining part of the Paleo-Tethyan lithosphere has been accommodated elsewhere (e.g. at the locations of anomalies cA\(^1\) and cA\(^2\)) or is not detectable by tomographic means at present, and (3) the slab did not completely detach from the surface until 80 Ma at least. As all three points seem plausible, we will assume that Hi\(^2\) is the Paleo-Tethyan slab remnant indeed in the following. The ancient direction of the subducting slab cannot be well constrained anymore, although the geometry of the anomaly suggests a southeastward rather than a northward direction of subduction.
5.6 Slab volumes after ridge subduction

5.6.1 Consequences of spreading center subduction

The oceanic spreading centers between converging and colliding continents, either active or not, eventually subduct underneath the overriding continental margins. In tectonic reconstructions, the timing of ridge subduction is typically associated with the emplacement time of ophiolites. Based on thermo-mechanical modelling results, it has been suggested that very young (<30 Ma) oceanic lithosphere can break up during the early phase of its subduction and lead to the incorporation of a thin sheet of oceanic lithosphere into the forearc region (Van den Beukel, 1990). Upon closure of the oceanic basin, this sheet can be incorporated into the orogenic belt as ophiolites indeed.

If an oceanic ridge continues to spread when it subducts, asthenospheric material can fill the space between the diverging plates and a slab window is formed. Such continuous spreading, however, requires the young plates to remain coherent during subduction which has been suggested to be unlikely by Van den Beukel (1990). If the subducted ridge stops spreading, the major thermal differences between the two subducting plates rapidly disappear because of thermal diffusion (DeLong et al., 1979; Daniel et al., 2001). Daniel et al. (2001) argued that continuing separation but at a greatly diminished rate is the most plausible hypothesis for spreading center subduction in southern Chili. However, Van Wijk et al. (2001) showed that a complete slabless window is not needed to explain observed heat flow, magmatism and tomography for the subducted Farallon ridge in North America: Model results for a normal ridge thermal structure of a stalled slab were found to fit the data equally well.

Either with or without continuous separation between the leading and trailing plates after ridge subduction, the thermal anomaly associated with the young and warm ridge segment is likely to be small relative to the older parts of the subducted oceanic lithosphere. The ridge segment will be thermally re-equilibrated with the surrounding mantle, and thus not detectable by seismic tomographic means, relatively fast. As a result, the anomalous volume associated with the subducted oceanic lithosphere may be imaged as two separate subvolumes. In this section, we will assume that the thermal volumes associated with the subducted oceanic lithosphere will split into two subvolumes at the time of ridge subduction. Because the leading plate is composed of progressively younger and warmer lithosphere, and the trailing plate of progressively older and cooler lithosphere instead, the material subducted prior to ridge subduction is likely to be somewhat more equilibrated with its surroundings than the material subducted thereafter.

5.6.2 Predicted and tomographic slab volumes

Subduction scenario I For this subduction scenario, we assume that the Neo-Tethyan spreading ridge subducted around 80 Ma (ExxonMobil, Şengör and Natal’in, 1996; Dercourt et al., 1993) and caused the subducted material to split into two subvolumes in both the Aegean/Arabian and Indian region. In the following, we will refer to the volumes associated with subduction prior to ridge subduction and thereafter as BRS and ARS (Before and After Ridge Subduction), respectively.
Section 5.6

**Subduction scenario II** For subduction scenario II in the Arabian region (Dercourt et al., 1993; Şengör and Natal'in, 1996), the proposed asymmetric age distribution within the Neo-Tethyan lithosphere will have resulted in two different volumes as well: One basically consisting of all Neo-Tethyan lithosphere, and one very small volume subducted underneath the obducted ridge. As this subduction scenario will not result in separate BRS and ARS subvolumes, we do not have to predict new thermal volumes here.

**Subduction scenario III** For this third subduction scenario, Stampfl and Borel (2002, 2004) propose Neo-Tethyan ridge subduction to have occurred around 140 Ma, and obduction of the Semail Ocean spreading ridge onto the Arabian continent at 80 Ma, in the western part of the area. This may have caused the subducted material to split into three separate volumes instead of the two considered in subduction scenario I. In the Indian region, the Neo-Tethyan ridge is proposed to have been subducted around 120 Ma, and the Spongtang oceanic back-arc basin between ~65-50 Ma, which would result into yet another division of subvolumes.

**Present thermal signature of subducted material**

**Subduction scenario I** For the BRS group, we take the total surface subducted prior to 80 Ma in the Aegean/Arabian region (Fig. 5.16, p. 140), and that between 140 and 80 Ma - thus without the Paleo-Tethyan volume addressed in the previous chapter - in the Indian region. For the ARS group, we put the surface subducted since that time. As a result of the subdivision, the average ages of the lithospheric basins in groups BRS and ARS change significantly (Fig. 5.5). Especially the young age of BRS in the Aegean/Arabian region for spreading scenario A, namely 35 Ma, is remarkable. As discussed in Section 3.3.3, values of the thermal factor \(c_1(t)\) are very uncertain for such young ages, and \(c_2(t)\) and \(c_3(t)\) may underestimate the actual values with 10-20%. The age-dependent values of the thermal factors for the BRS volumes are taken at \(t = 200\) Myr in the Aegean/Arabian region, and 140 Myr in the Indian region. For the ARS volumes, we use the appropriate values at \(t = 80\) Myr instead. The values for the average ages, initial thicknesses, and thermal factors used for each group can be found in Table 5.7 (p. 141).

**Subduction scenario III** In the Arabian region, additional subducted material is expected from the Semail Ocean in this subduction scenario. As the Semail oceanic basin is proposed to have overridden the complete Neo-Tethys between 140-80 Ma, we assume that the maximum size of the basin equals the surface subducted between Arabia and Eurasia from 80 Ma until the onset of continental collision at 22 Ma. The surface of the Semail Ocean is therefore an additional \(4\times10^6\) km\(^2\) (i.e. 80-22 Ma surface in the Arabian region of Fig. 5.16, p. 140). In the Indian region, additional subducted material may result from the Spongtang back-arc basin, but this amount is not very clear. We approximate the maximum size of this basin, analogous to that for the Semail Ocean, by the surface subducted between India and Eurasia between 65 Ma - the start of its subduction - and 48 Ma - the time of first continental collision. For subduction scenario III, we select for BRS the total surface subducted prior to 140 Ma and 120 Ma in the Aegean/Arabian and Indian region, respectively. In the ARS group, we put the
Slab volumes after ridge subduction

surface of the Neo-Tethys that has been subducted underneath the back-arc basins, c.q. the 140-22 Ma surface in the Arabian region, and the 120-43 Ma surface in the Indian region. The convergence calculated for the final period of continental collision, i.e. 22-0 Ma and 43-0 Ma, is added to the Semail and Spongtang surfaces, as these are the last oceanic basins to be subducted. See Table 5.7 (p. 141) for an overview of the averages ages, lithospheric thicknesses and thermal factors used. Again, the predicted BRS volumes for spreading scenario A have relatively young ages, which may result in underestimates of the actual thermal volumes.

Volumes of seismic anomalies

The relative distribution of the volumes associated with BRS and ARS is predicted from the assumed subduction scenario, but their actual position within the mantle has to be inferred from the plate motions in an absolute frame of reference. Here we consider the reference frames discussed in Section 5.3, namely those of Müller et al. (1993), O’Neill et al. (2003) and Eurasia fixed (see Figs. 5.2-5.4, pp. 108-110), to establish the approximate locations of the subduction zones in each subduction scenario.

Similarly to the overview of the horizontal extent of the seismic anomalous bodies in three different depth intervals (Figs. 4.4-4.6, pp. 73-75), we have plotted the vertical distribution of these anomalies in two bands of cross-sections in Figures 5.8 and 5.9. For the Arabian anomalies, the contour lines represent a projection of the maximum size of the anomalies between the vertical cross-sections 40 and 80 as in Figure 4.1, p. 69 (cf. section 55 and 75 in Fig. 4.7, p. 76). Note that the Arabian continental margin was not exactly perpendicular to these cross-sections further back in time (e.g. 80 Ma reconstruction in Fig. 5.2, p. 108). The tomographic anomalies in the Indian region are a projection of their maximum extent between sections 90 and 120 as in Figure 4.1, p. 69 (cf. section 95 and 115 in Fig. 4.7, p. 76). In the Indian region, the approximate direction of subduction was in the plane of this projection.

Figure 5.8: Vertical distribution of tomographic anomalies in the Arabian region. The contour line of each anomalous body is a projection of its maximum extent approximately between cross-sections 40 and 80 as in Figure 4.1 (p. 69) and Figure 5.17 (p. 142).
Section 5.6

Figure 5.9: Vertical distribution of tomographic anomalies in the Indian region. The contour line of each anomalous body is a projection of its maximum extent approximately between cross-sections 90 and 120 as in Figure 4.1 (p. 69) and Figure 5.17 (p. 142).

Subduction scenario I In the Aegean/Arabian region, the Eurasian southern margin is positioned approximately above anomalies SI and IA around the 80 Ma of ridge subduction in the EU frame (lowerleft panel Fig. 5.2, p. 108). However, in the HS frame (Fig. 5.3, p. 109) the trench system is situated just above the southernmost anomalies Eg and SA instead. Although Eg and SA are positioned relatively far south, it seems plausible that the BRS material - subducted prior to 80 Ma underneath Eurasia - can be found in the tomographic volumes Eg and SA (Fig. 5.17, p. 142). Because the Eurasian continental margin has moved only northwards since that time in all three reference frames considered here, we associate the remaining tomographic anomalies with the ARS volumes. In the Indian region, the Eurasian continental margin is situated right above anomaly Ic at 80 Ma in both the EU and HS frame. Because Eurasia has moved further northwards since that time, both the BRS and ARS volumes in the subduction scenario are likely to be represented by Ic and the more northerly positioned anomalies. However, from our earlier analyses (e.g. Fig. 5.7 for the P-T/N-T volumes in the Indian region) we found that all tomographic volumes are needed to explain the predicted thermal volumes, also the southernmost anomaly Io. Although Io seems to be too far south to be explained by subduction scenario I, we will consider it as BRS volume for the moment (see Fig. 5.17, p. 142) and will discuss the implications below. This will leave the remaining anomalies as to be associated with the ARS volumes, except for anomaly Hi that is assumed to represent the Paleo-Tethyan lithosphere (Section 5.5).

Subduction scenario II In this subduction scenario for the Arabian region, almost the complete Neo-Tethys has been subducted as one single volume underneath the Eurasian margin, and a small amount of subduction is accommodated at the Arabian margin around 80 Ma. As the Arabian continental margin is positioned above Eg and SA at this time in both the EU and HS frame (Figs. 5.2-5.3), this small slablet could be associated with anomalies Eg and SA. In that case, the Neo-Tethyan (N-T) volumes accommodated along the Eurasian margin may be represented by the remaining anomalous volumes.

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Because the Eurasian continental margin is positioned above Eg and SA during the Cenozoic in the HS frame (Fig. 5.3), as discussed above, part of N-T may be incorporated in these anomalies. Again, however, the continental margins are just north of Eg and SA in the EU frame (Fig. 5.2). In the MHS frame (Fig. 5.4), the positions seem to be too far west for adequately predicting the tomographic volumes in the eastern Arabian region. As the westward shift of MHS relative to HS is not well constrained (O’Neill et al., 2003), the location of the continental margins could have been more to the east, and more similar to those of the EU frame. Thus, in reference frames other than HS, it is not likely that remnants of N-T are accommodated in Eg and SA in this subduction scenario.

### Subduction scenario III

Although the hotspot reference frame is uncertain prior to 84 Ma, the BRS volumes in the Arabian region seem to have been subducted not far south of the present Zagros suture zones - and probably above anomalies SI and IA² in any case - around 120 Ma (lowerright panels Figs. 5.2 and 5.3). Semail back-arc spreading will have resulted in ARS subduction much further south, with its southernmost extent around the position of the northern Arabian continental margin at 80 Ma. Both the EU and HS frame suggest that this location was above anomalies Eg and SA, although in the HS frame Arabia seems to be positioned too far south to be associated with Eg. Subduction of the Semail Ocean must have been accommodated along the northward moving Eurasian margin since that time. We will test here whether the ARS volumes can be associated with anomaly Eg and SA, and both the BRS and Semail volumes with the remaining anomalies. Note that this is the opposite of the division assumed for subduction scenario I and displayed in Figure 5.17 (p. 142).

In the Indian region, anomaly Hi² is again assumed to represent the Paleo-Tethyan lithosphere, although in the shown HS frame this anomaly seems to be a good candidate for the BRS volume as well (lowerright Fig. 5.3). In the EU frame, however, the southern Eurasian margin is positioned right above anomaly Ic instead. As the hotspot reference frame is very uncertain this far back in time, we consider here the possibility that the BRS volumes are part of Ic, e.g. represented by its lowermost anomalies. With the Neo-Tethys subducting underneath the southward migrating Spongtang Ocean until 65 Ma, the ARS volumes are coupled to both anomaly Io and Ic, even though they seem to be separated in the tomographic images. Again, this is the opposite of the division for subduction scenario I and displayed in Figure 5.17. Around 65 Ma, the Indian continental margin is positioned right above the southern, shallow anomalies of Io in all three reference frames. Note that the EU and HS frame seem to predict India somewhat too far east, and the MHS frame too far west instead. Anomaly Hi¹ is assumed to represent part of the ARS volumes as well. However, as will be discussed later, this anomaly may also be associated with the separate Spongtang oceanic lithosphere instead.

### 5.6.3 Comparison and conclusions

#### Aegean/Arabian region

**Subduction scenario I**  For spreading scenario A and undeformed slabs, the predicted BRS volume is somewhat larger than the tomographic volumes (left panel Fig. 5.10), and the T/P-
ratios of 0.6-0.8 (Table 5.3) are similar to those found before (e.g. Table 5.1). However, for spreading scenario B the predicted volumes are much larger than the tomographic volumes, with a T/P-ratio of 0.3-0.4 only. When taking into account slab thickening, the volumes for spreading scenario A remain similar because of the young age of the BRS lithospheric basin in this scenario (see Fig. 5.10). The predicted volumes in spreading scenario B will decrease significantly with increasing factors of thickening, but not enough to level with the tomographic volumes. For the ARS volumes, the T/P-ratio for undeformed slabs is 1.2-1.6 for both spreading scenarios (Table 5.3), which is quite high. The predicted thermal volumes cannot account for the large volume of the tomographic anomalies, and to do this the volumes need to be 25-50% larger (Fig. 5.10). Taking into account slab thickening will further lower the thermal volumes, and increase the difference with the tomographic volumes even more.

The results displayed in Figure 5.10 suggest that, if both subduction scenario I and the associated ARS/BRS subdivision are correct, spreading scenario B is very unlikely. For spreading scenario A, however, the calculated volumes for BRS are probably underestimated due to the young lithospheric age of this basin. An even larger volume of BRS would certainly leave no room for the implicitly assumed spreading and additional amount of subduction. One possible solution would be to let the ridge subduct earlier in time so that the thermal volume will become smaller for BRS and larger for ARS. However, to change the volumes significantly, a larger timeshift is necessary than is justified by the reconstructions followed here (ExxonMobil, Şengör and Natal’in, 1996; Dercourt et al., 1993). Another solution would be to conclude that all subducted material, ARS as well as BRS, have basically subducted right underneath the Zagros Suture indeed - as one would infer from the absolute plate motions discussed above (Figs. 5.2-5.4). For a factor of 3 thickening, the BRS and ARS predicted vol-

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**Figure 5.10:** Subduction scenario I: Tomographic volumes ($V_t$) vs. predicted thermal volumes ($V_p$), divided into a part before ridge subduction (BRS) and a part after ridge subduction (ARS), for two end-member spreading scenarios (see p. 87). Note that the ARS volumes are similar for both spreading scenarios due to the relatively old age of this part of the oceanic lithosphere. The calculations for undeformed slabs (1) can be found in Table 5.3, the factors necessary to perform the calculations for thickened slabs (2/3) in Table 5.7 (p. 141).
umes are only little more than the ARS tomographic volume shown in Figure 5.10. However, this would leave the volumes of anomalies Eg and SA unexplained and exclude the possibility of additional subduction by intermediated spreading.

Considering the depth ranges of the tomographic anomalies, Eg and SA of the older BRS group can be found mainly between ~1000-1800 km and 800-2000 km depth, respectively (Fig. 5.19, p. 144). However, lower mantle anomalies SI and IA^2 of the younger ARS group are positioned between 1000-2200 km and 800-2000 km depth. Especially in the western part of the region, anomaly SI (~younger group ARS) can be found lower than anomaly Eg (~older BRS), with a relatively large volume between 1400-2200 km depth.

The deep position of SI can only be explained by subduction after 80 Ma when we assume average sinking rates of about 4 cm/yr in the upper mantle and 2 cm/yr in the lower mantle. However, this would imply that the ~800-1000 km of the top of the older anomalies Eg and SA would correspond to sinking times of ~25-35 Myr only, which is not in agreement with subduction prior to 80 Ma. Assuming slower sinking rates of 3 and 1 cm/yr, the 800-1000 km can be reached within ~40-60 Myr, which is still somewhat fast but seems reasonable. In that case, however, the ≥2000 km deep bottom of anomalies SI and IA^2 would correspond to a total sinking time of ~160 Myr, which is far too much for this subduction scenario. Although the implications of the depth intervals of the several anomalies are somewhat speculative, their agreement with the proposed subduction scenario I is not very satisfactory.

### Table 5.3: Subduction scenario I: Comparison of volumes as in Table 5.2, but now with the predicted N-T volumes divided into a part before (BRS) and after (ARS) ridge subduction at 80 Ma, for two end-member spreading scenarios (see p. 87). Associated with BRS are the tomographic volumes Eg and SA in the Aegean/Arabian, and anomaly Io in the Indian region. The other tomographic anomalies, except for anomaly Hi^2 that is considered as Paleo-Tethys (P-T), are associated with the ARS groups. The subdivision of the subducted surface is illustrated in Figure 5.16. The predicted volumes for slabs that have thickened in the mantle, calculated with the appropriate factors from Table 5.7 (p. 141), are shown in Figure 5.10.

<table>
<thead>
<tr>
<th>Volumes</th>
<th>( V_{\text{tom/o}} ) (-10^9 km^3)</th>
<th>( S_{\text{subducted}} ) (-10^8 km^2)</th>
<th>( V_{\text{initial}} ) (-10^9 km^3)</th>
<th>( V_{\text{predicted}} ) (-10^9 km^3)</th>
<th>( V_{\text{tom/o}}/V_{\text{predicted}} ) (T/P-ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Aeg/Arab</td>
<td>1.78–2.25</td>
<td>7.20</td>
<td>0.79 / 0.79</td>
<td>1.43 / 1.43</td>
<td>1.24 – 1.57 / 1.24 – 1.57</td>
</tr>
<tr>
<td></td>
<td>0.60–0.83</td>
<td>10.61</td>
<td>0.80 / 1.11</td>
<td>1.05 / 2.40</td>
<td>0.63 – 0.79 / 0.28 – 0.35</td>
</tr>
<tr>
<td>Indian</td>
<td>1.67–2.14</td>
<td>13.34</td>
<td>1.40 / 1.47</td>
<td>2.49 / 2.66</td>
<td>0.67 – 0.86 / 0.63 – 0.81</td>
</tr>
<tr>
<td></td>
<td>0.96–1.27</td>
<td>6.24</td>
<td>0.45 / 0.62</td>
<td>0.83 / 1.22</td>
<td>1.16 – 1.53 / 0.79 – 1.04</td>
</tr>
<tr>
<td>P-T</td>
<td>0.25–0.30</td>
<td>2.25</td>
<td>0.21 / 0.23</td>
<td>0.43 / 0.46</td>
<td>0.58 – 0.70 / 0.55 – 0.65</td>
</tr>
</tbody>
</table>

**Subduction scenario II** The original subducted surface and present thermal volumes of the slablet subducted at the Arabian continental margin is small, but not known. To explain the 0.66-0.83·10^9 km^3 of anomalies Eg and SA by the thermal volume of the slablet alone, the
initial volume must have been a factor 1.8, 1.4 or 1.2 smaller, depending on the amount of slab thickening assumed (similar to the ARS values as for subduction scenario I in Table 5.7, p. 141). The original subducted surface of the slablet would equal this initial volume divided by the 105-110 km lithospheric thickness appropriate for the 95-155 Ma average of the age of the lithosphere (see Section 5.4). Depending on the spreading scenario and the amount of thickening, a 0.66-0.83\(\times\)10\(^9\) km\(^3\) thermal volume can thus be associated with a subducted surface of about 3.3 to 6.6\(\times\)10\(^6\) km\(^2\). As can be seen in Figure 5.16 (p. 140), such a surface is actually quite large for the Arabian region and is similar to the surface subducted in the area during the past 90-50 Ma. This is clearly in contradiction with the proposed position of the spreading centre close to the Arabian continental margin. For the elongated Arabian continental margin, this surface would require an average \(~\)1000-2000 km of convergence, c.q. distance between the continent and the spreading center.

Figure 5.11: Subduction scenario II: Tomographic volumes (\(V_t\)) vs. predicted thermal volumes (\(V_p\)) for two end-member spreading scenarios (see p. 87). The tomographic volumes subducted near the Arabian continental margin (AC) and underneath Eurasia (EU) equal those of BRS and ARS, respectively, for subduction scenario I (Fig. 5.10). The predicted thermal volumes correspond to the bulk Aegean/Arabian volumes for which the calculations can be found in Table 4.3 (p. 94). As discussed in Section 5.4, the predicted \(N-T\) volume in this subduction scenario corresponds to the bulk Aegean/Arabian volume (e.g. Table 4.3 and Fig. 4.19, pp. 94 and 98). Only if the slabs have thickened by a factor of 3, and for spreading scenario A, the \(N-T\) volumes fit the tomographic 1.78-2.25\(\times\)10\(^9\) km\(^3\). As subduction is implicitly assumed in spreading scenario A, the northern parts of anomalies Eg and SA may contain \(N-T\) material. If this is indeed the case, only the southern parts of these anomalies need to be explained by the slablet discussed above. The southern anomalies of Eg and SA can all be found below 1200 km depth, which can be reached in \(~\)80 Ma for sinking rates of 3 cm/yr in the upper mantle and 1 cm/yr in the lower mantle.

However, although the HS reference frame allows \(N-T\) subduction above anomalies Eg and SA, the positions of the trench systems in the EU and MHS frames are too far north to come to a similar conclusion (Figs. 5.2-5.4). Moreover, in the HS frame also the Arabian continental
Slab volumes after ridge subduction

margin is positioned relatively far south. At 80 Ma, the approximate emplacement time of the Oman ophiolites, only subduction along the northern half of Arabia could explain the southernmost volumes of Eg and SA.

Subduction scenario III

As can be seen in Figure 5.12 (top panel, p. 130), the predicted volumes for the BRS group and Semail Ocean together are much smaller than the tomographic anomalies associated with these volumes: Even if the slabs have not thickened in the lower mantle, although very unlikely for the BRS volumes, the predicted total volume of 1.2\text{-}1.4\times10^9 km^3 results in T/P-ratios between 1.3\text{-}1.9 (Table 5.4). The predicted volumes are likely to be underestimated, as discussed above (p. 120 or Section 3.3.3), but even with a maximum 20% increase the results suggest that Neo-Tethyan and Semail lithospheric spreading during the subduction of these oceans has accounted for the missing volume. On the contrary, however, the predicted ARS volume is much too large to be explained by the appointed anomalies Eg and SA alone. Even when a factor 3 of slab thickening is taken into account, the T/P-ratio is still only 0.4\text{-}0.5 for both spreading scenarios.

Apparently, the subdivision of the tomographic anomalies for subduction scenario III is not correct. Our results suggest a somewhat different subduction scenario: As trench migration is an effective mechanism for generating shallow dipping slabs (e.g. Griffiths et al., 1995; Guillou-Frottier et al., 1995; Christensen, 1996; Olbertz et al., 1997), and the Neo-Tethyan ARS volume progressively disappeared underneath the spreading Semail back-arc basin, the slabs may have flattened down over the full width of the basin. Flattened slab structures below trenchward migrating, still active subduction zones have been globally imaged by seismic tomography, e.g. underneath the Izu-Bonin, Sunda and Tonga island arcs (e.g. Kárason and van der Hilst, 2000; Hall and Spakman, 2002). If this has been the case, the oldest part of the ARS volume might be incorporated in volumes SI and IA\textsuperscript{2} together with the BRS and Semail volumes, and only the youngest part of the ARS volume in Eg and SA. This scenario implies that the apparent division between anomalies Eg/SA and SI/IA\textsuperscript{2} is not related to ridge subduction, and has another origin.

By taking half of the predicted ARS volumes as to be represented by the tomographic BRS instead of ARS anomalous volumes, the balance between the volumes improves (Fig. 5.12): For slabs thickened by a factor of 2, the predicted volume of BRS, half of ARS, and Semail together will be 1.8\text{-}2.0\times10^9 km^3, which is quite similar to the tomographic volume of 1.8\text{-}2.3\times10^9 km^3 (T/P-ratio ∼1.0\text{-}1.2). If thickened by a factor of 3, certainly realistic for the old and large ARS volume, the total of these slab volumes will be 1.6\text{-}1.7\times10^9 km^3, which is even smaller (T/P-ratio ∼1.1\text{-}1.4). The remaining volume of ARS, 0.9\text{-}1.0\times10^9 km^3 in this case, is still larger than the 0.7\text{-}0.8\times10^9 km^3 of the tomographic anomalies, but not as much as before. Evidently, the actual division of the volumes is unknown, and a somewhat larger part of the predicted ARS volume can have been subducted in the northern part of the region just as well.

As mentioned above, the ≥2000 km depth of the bottoms of anomalies SI and IA\textsuperscript{2} (Fig. 5.19, p. 144) could be reached in a time >160 Myr for sinking rates of ∼3 cm/yr in the upper and 1 cm/yr in the lower mantle. This would be in agreement with the subduction of ARS material prior to 140 Ma. Also the depths of the other anomalies seem to be in general agreement with
Section 5.6

<table>
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<tr>
<th>Volumes</th>
<th>( V_{\text{tomo}} ) ((-10^6 \text{ km}^3))</th>
<th>( S_{\text{subducted}} ) ((-10^6 \text{ km}^3))</th>
<th>( V_{\text{initial}} ) ((-10^6 \text{ km}^3))</th>
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<td>0.52</td>
<td>0.91</td>
<td>?</td>
<td></td>
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<td>6.85 – 8.65 / 3.56 – 4.50</td>
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<td>–</td>
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</tbody>
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Table 5.4: Subduction scenario III: Comparison of volumes when dividing the predicted N-T volumes into a part before and after ridge subduction, as in Table 5.3, but now at 140 Ma in the Arabian region, and 120 Ma in the Indian region. The convergence during the Cenozoic continental collisions is added to the volumes of the Semail (Sml.) and Spontang (Spt.) oceanic back-arc basins. The predicted volumes for slabs that have thickened in the mantle, calculated with the appropriate factors from Table 5.7 (p. 141), are shown in Figure 5.12.

scenario III for these sinking rates: The major part of anomaly SI (~1400-2000 km depth) and IA\( ^2 \) (1100-1400 km depth) would correspond to sinking times of 100-160 Ma and 70-100 Myr, respectively, which would be in accordance with subduction between 140-80 Ma. The somewhat deeper position of the eastern anomaly SA with respect to the western anomaly Eg (e.g. Fig. 5.19) may reflect the diachronous subduction of the Neo-Tethys underneath the Semai Ocean (e.g. see Early Cretaceous reconstruction of Fig. 2.5, p. 24). The ~800-1000 km of the top of anomalies Eg and SA would correspond to sinking times of ~40-60 Myr, which is only little shorter than expected for subduction prior to 80 Ma. Anomalies eT, Ca, Zs and IA\( ^1 \), as well as the upper (<1100 km) anomalies of IA\( ^2 \), are likely to represent the remnants of the Semail oceanic lithosphere subducted in the past 80 Myr.

Indian region

Subduction scenario I The predicted BRS volumes in the Indian region are approximately similar to the tomographic BRS volumes (right panel Fig. 5.10, p. 124). If all slabs have thickened by a factor of 2 or 3, the thermal volumes of the BRS group are clearly smaller than the tomographic volumes. This would leave room for additional lithospheric spreading, although it has to be acknowledged again that the BRS volumes are somewhat underestimated for spreading scenario A (Section 3.3.3). The T/P-ratios of 1.2–1.5 and 0.8–1.0 for undeformed slabs are indeed much larger than the previously found values (Table 5.3 vs. Table 5.1). For the ARS group, a factor of 3 thickening would be needed for the predicted volumes to become smaller than the tomographic volumes (Fig. 5.10), which is similar as found before.

Anomaly Io that was appointed as BRS volume (Fig. 5.17, p. 142) can be found in a large depth interval, and mainly between 800-2000 km depth (Fig. 5.19, p. 144). Very slow sinking
Slab volumes after ridge subduction

rates are required to make the top of anomaly Io fit with subduction of the BRS slab prior to the proposed 80 Ma. Remarkably, the most shallow parts of this anomaly (i.e. in the 660-1100 km depth interval, e.g. see Fig. 4.2, p. 70) are found far south of the southernmost position of the Eurasian margin (Fig. 5.3, p. 109).

Anomaly Ic from the ARS group is positioned between 1000-2200 km depth, which is even deeper than the older BRS group (Fig. 5.19). Only with faster (~2 cm/yr) sinking rates in the lower mantle, this deep level can be reached within the required ~80 Myr. As slabs have been found to sink faster in regions with abundant subduction in the same area (e.g. Steinberger, 2000), the relatively high convergence rates between ~90-50 Ma in the Indian region (Fig. 5.16, p. 140) may have led to these faster sinking rates indeed. Anomaly Hi was identified separately from anomaly Ic because their geometries and positions are clearly different (e.g. Fig. 4.2, p. 70), but they belong to the same oceanic basin according to this scenario.

As opposed to the Aegean/Arabian region, subduction scenario I seems to adequately predict the subdivision of the volumes in the Indian region. On the other hand, the lateral distribution of the volumes can - again - not be readily explained by its simple evolution.

Subduction scenario III In this subduction scenario, the predicted volume of the BRS material subducted prior to 120 Ma is small. In the lower panel of Figure 5.12 this N-T-BRS volume is compared with the lower 1800-2200 km part of anomalies Ic and Io. The 0.35-10⁹ km³ volume of Ic and Io in this depth interval (Fig. 5.19) can be explained by the 0.3-10⁹ km³ of N-T-BRS if slab thickening by a factor of 3 is taken into account. The predicted ARS volume is similar to the remaining tomographic volumes in the region if the slabs have kept their plate-like geometry (see Table 5.4), but is smaller if the slabs have thickened in the mantle (Fig. 5.12), which is likely to be the case. Because of the relatively old age of the subducting oceanic lithosphere (Table 5.7, p. 141), the predicted thermal volumes for the different spreading scenarios are similar. If the subducted slabs have thickened by a factor of 3, the T/P-ratios of 1.2-1.6 actually leave room for the additional volume that was predicted for the Sponhtang oceanic basin as well. Analogous to the Arabian region, the southward migrating Sponhtang back-arc may have caused the N-T slab to flatten down over the whole width of anomalies Io and Ic between ~120 and 65 Ma.

As discussed for subduction scenario I, the 1000-2200 km depth of anomaly Ic and 800-2000 km depth of anomaly Io could be reached in ~35-95 Myr and 25-85 Myr, respectively, with sinking rates ≥2 cm/yr in the lower mantle. The ARS material subducted since 120 Ma can have reached these depths easily. Whereas in the previous subduction scenario the top of anomaly Io needed to be explained by subduction prior to 80 Ma, this needs to be prior to ~65-50 Ma in scenario III only. For sinking rates of 1 cm/yr in the lower mantle, the 90-50 Ma timespan of subduction would correspond to a depth interval of ~1000-1400 km, which is actually where most of the material of anomalies Ic and Io can be found. In that case, the 1400-1800 km anomalies would correspond to sinking times of 90-130 Myr, and could be explained by the subduction of ARS.
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Figure 5.12: Subduction scenario III: Tomographic volumes ($V_t$) vs. predicted thermal volumes ($V_p$), divided into a part before ridge subduction (BRS) and a part after ridge subduction (ARS), for two end-member spreading scenarios (see p. 87). **Aegean/Arabian region** (upper panel): Ridge subduction at 140 Ma, and subduction of a separate Semail Ocean after 80 Ma. **Indian region** (lower panel): Ridge subduction at 120 Ma, and possible subduction of a separate Spongtang Ocean after 65 Ma. See text for further details and discussion. The calculations for undeformed slabs (1) can be found in Table 5.4, the factors necessary to perform the calculations for thickened slabs (2/3) in Table 5.7 (p. 141).
Slab volumes after ridge subduction

material since 120 Ma. Furthermore, the lower 1800-2000 km of these anomalies selected for the BRS volumes would correspond with sinking times ≥ 130 Myr.

With a sinking rate of 2 cm/yr in the lower mantle, the 1400 km depth of anomaly Hi must have been reached in a total 50-60 Myr, which is in agreement with the subduction of the Spongṭang basin since ~65 Ma. However, for a 1 cm/yr sinking rate, the 1400 km depth of Hi would require subduction since 90 Ma already. The 500-km deep top of anomaly Hi could be reached in only 10-20 Myr with normal upper mantle sinking rates, which would require a large delay-time for slab break-off after continental collision around 48 Ma. This will be discussed separately in Section 5.7 on the Cenozoic continental collisions.

The idea that the >1400 km deep volumes of anomalies Ic and Io are the result of subduction prior to 90 Ma may provide a solution for another interesting phenomenon in the Indian region: As can be seen in Figure 4.2 and 4.3 (pp. 70-71), anomaly Ic can be found over the full width of our trench system, and actually connects to the deep mantle anomalies beneath Indonesia below ~1000 km depth. Only the small part of anomaly Ic close to Hi is found above 1000 km (cf. Fig. 5.2), and within the restricted area (e.g. see Fig. 4.5). On the contrary, anomalies Hi and Hf fade away east of section 115, and also the larger part of anomaly Io underneath the Indian Ocean is restricted to the western part of the Indian region. In fact, anomaly Io can only be found east of ~section 115 below 1400 km depth. An explanation for this feature could be that the fast northward motion of the Indian continent since 90 Ma resulted in a large-scale strike-slip motion on the eastern boundary of the plate, similar to the motion that has produced the gap between Arabian and Indian anomalies on the western side. Such a process has been suggested by Stampfli and Borel (2002, 2004) indeed (e.g. Fig. 2.6, p. 25), and may have affected the geometry of anomaly Io since 90 Ma. Ic has probably been affected only since ~50 Ma, as this would correspond to the sinking time needed to reach the ~1000-km depth of the anomalies extending east of section 115.

Conclusions

For the investigated subduction scenarios (p. 106), we found that:

**Subduction scenario I** can well explain the tomographic volumes in the Arabian and Indian region if the N-T slabs have thickened by a factor 2 at least. However, in all three reference frames the southern anomalies are positioned too far south to be explained by subduction at the Eurasian continental margin alone.

**Subduction scenario II**, for the Arabian region, does predict subduction at the right location, as opposed to scenario I. However, we found that subduction scenario II can only explain the tomographic volumes if (a) the Eurasian continental margin has been as far south in Late Mesozoic times as suggested by the fixed hotspot reference frame of Müller et al. (1993), (b) the total N-T slab has thickened by a factor of 2 at least, and (c) the distance between the Tethyan spreading ridge and the Arabian continental margin has been larger - in the order of 1000 km - than proposed by the tectonic reconstructions discussed here.

**Subduction scenario III** includes the opening of two large back-arc oceanic basins at the Eurasian margin, and is therefore least sensitive to the exact position of Eurasia. This subduction scenario was found to well explain the absolute locations of the tomographic anomalies in all three reference frames. Moreover, the scenario predicts thermal volumes - including
those of the separate Semail and Spongtag oceanic basins - that are in agreement with the
tomographic volumes as well, if (a) the $N-T$ and back-arcs slabs have thickened by at least
a factor of 2 and 3, respectively, and (c) trench migration due to the Semail and Spongtag
back-arc spreading has caused extensive flattening of the subducting $N-T$ slabs.

We clearly prefer scenario III - based on the most recent reconstruction of Stampfli and Borel
(2004) - for the Late Mesozoic-Cenozoic subduction of Tethyan lithosphere in the Indian
region. The relative small, and westwardly decreasing, distances between the Arabian and
Eurasian continental margins make it difficult to distinguish between the proposed scenarios
for the Arabian region. However, as the absolute plate motions are quite uncertain, and
subduction scenario II requires additional constraints that seem to be in contradiction with the
tectonic reconstructions underlying the scenario (Dercourt et al., 1993; Şengör and Natal'in,
1996), we prefer scenario III for the Arabian region as well. It thus appears that the tectonic
model that explicitly incorporated the evolution of the plate boundaries through time (see
Section 2.2, p. 15) can best explain the tomographic anomalous volumes associated with
subducted Tethyan lithosphere.

5.7 Slab break-off after Cenozoic continental collisions

5.7.1 Timing of Tethyan slab break-off

Continent-continent collisions can cause slabs to break off and sink into the mantle (Van den
Beukel, 1992; Davies and von Blanckenburg, 1995; Wong A Ton and Wortel, 1997; Van de
Zedde and Wortel, 2001). The process of slab break-off depends on a wide range of parame-
ters, including the thermal structure of the subducting plate and the convergence velocity. In
general, subduction of colder continental lithosphere will lead to a deeper break-off depth af-
after a longer timespan. Faster subduction rates also result in break-off at deeper levels, but after
a much shorter timespan. Van de Zedde and Wortel (2001) showed that fast (about 6 cm/yr)
subduction of continental lithosphere can lead to slab detachment at 140-330 km downdip
distance from the trench, corresponding to $\sqrt{40-120}$ km depth, already 3-5 Myr after the
onset of continental collision. Slower subduction rates (about 1 cm/yr) have been found to
lead to slab detachment at 130-250 km downdip distance from the trench, corresponding to
$\sqrt{35-80}$ km depth, after 17-25 Myr only.

Following the reconstruction of ExxonMobil, we assume that the Arabia vs. Eurasia and India
vs. Eurasia continental collisions occurred around 22 Ma and 48 Ma, respectively (Fig. 2.2,
p. 17). In the period of continental collision in the Arabian region, the rate of subduction,
i.e. the trench-normal component of the relative velocity vector, ranged from 2.2 cm/yr in the
west to 2.8 cm/yr in the east. During the collision event in the Indian region, the subduction
velocities dropped from 12 to 5 cm/yr in the west, and from 13 to 6 cm/yr in the east.
We assume here that the Arabian and Indian continents had an average thermal structure
(Pollack et al., 1993), with a surface heat flow of 60 mW/m$^2$. Following Van de Zedde and
Wortel (2001), the subduction rates of $\sim 3$ cm/yr in the Arabian region are likely to have
causd the subducting slab to break off $\sim 10$ Myr after the onset of continental collision,
thus around 12 Ma. This could be somewhat later in the western part of the area, where the subduction rate of 2 cm/yr could have caused the slab to detach ~12 Myr after collision, i.e. around 10 Ma. For the Indian region, the high subduction rates (> 6 cm/yr) can be associated with slab break-off after ~5 Myrs only, thus around 43 Ma. Again, the somewhat lower subduction rates in the west could have led to a later break-off time. For both regions, slab break-off is assumed to have occurred at a 300-km downdip distance from the trench, corresponding to a depth of ~100 km. We assume that the detached volumes of lithospheric material have descended into the mantle vertically. Recently, Keskin (2003) argued that slab steepening and break-off beneath Eastern Turkey has been the major controlling mechanism for the rapid block uplift and volcanism in the region around 10-11 Ma. Kohn and Parkinson (2002) suggested that slab break-off in the Himalaya around 40-45 Ma caused the production of K-rich lavas - associated with subcontinental lithosphere being exposed to asthenospheric upwelling (Chung et al., 1998) - by 40 Ma. The break-off times for the Arabian and Indian slabs inferred from the Van de Zedde and Wortel (2001) models are in agreement with these studies.

5.7.2 Predicted and tomographic slab volumes

From the thermal volumes predicted for the subducted plate surfaces, as well as from the tomographic volumes, we separate the part that we expect to have broken off after continental collision to isolate the smaller volumes that will be completely detached from the volumes lower in the mantle today (Fig. 5.13). In the following, we will refer to the volumes that have been detached after continental collision, and are continuous (C) with the deeper (D) volumes, as CD. The volumes that are still attached (A) to the surface after slab break-off (B), and thus not continuous with the volumes deeper in the mantle, are denoted by AB.

**Figure 5.13:** Isolation of the volumes that are still attached to the surface after slab break-off (AB) from the volumes that have been detached after continental collision and are still continuous with the deeper volumes (CD). If no slab break-off took place, as in the Aegean region, the whole slab is denoted CD.

Subducted plate surfaces

For the Arabian region (upper panel Fig. 5.16, p. 140), *group CD* is the slab that we expect to have been detached at 12 Ma after continental collision around 22 Ma. Here, *group AB* consists of the slab left attached after break-off, which corresponds to ~300 km of convergence, as well as the surface subducted since that time. In subduction scenarios I and II, the ARS volume of the Neo-Tethys discussed in the previous section will be used to create an AB and CD volume. Note that the oceanic lithosphere in the Aegean region is not assumed to
be detached from the surface: It is kept in group CD because the upper mantle volumes will be continuous with the volumes lower in the mantle still, as opposed to the volumes in group AB. In subduction scenario III, only the volume of the Semail oceanic basin will be split up. For the Indian region (lower panel Fig. 5.16, p. 140), group CD is the slab that we expect to have broken off at 43 Ma after continental collision around 48 Ma, corrected for the down-dip depth of detachment. Again, the Neo-Tethyan ARS slab will be used to create an AB and CD volume in subduction scenarios I and II. In subduction scenario III, the CD volume is the remaining part of the Spongtang Ocean only.

Because the top 230 km of the tomographic model has not been taken into account, we approximate the convergence likely to be accommodated in this depth interval (see also Section 4.3, p. 81): For the part of the Tethyan region that is at present in continental collision, the amount of convergence that needs to be subtracted from the total value will be about 100 km. For 100 km of convergence, the surface that is accommodated in the top 230 km will be $0.31 \cdot 10^6$ km$^2$ in the Arabian and $0.22 \cdot 10^6$ km$^2$ in the Indian region. When taking into account these estimates, the surface of group AB decreases with 15% in the Arabian region, and with 4% in the Indian region. The values shown in the second column of Table 5.5 are corrected for the part assumed to be accommodated in the top 230 km.

**Present thermal signature of subducted material**

Including the effect of continental collision will not change the average age of the subducted oceanic basins discussed in the previous sections. To calculate the initial lithospheric thicknesses and the thermal factors, we therefore use the ages of the ARS part of the Neo-Tethys (subduction scenarios I and II) and the Semail/Spongtang lithosphere (subduction scenario III) here (Table 5.7, p. 141). Calculations with the thermal structure of continental instead of oceanic lithosphere could increase the volumes a little more.

For the material of group CD we use the values for $c_1(t)$, $c_2(t)$, and $c_3(t)$ that were used for the ARS Neo-Tethys and Semail/Spongtang oceans in the previous section. After slab break-off, the detached material will sink further down into the mantle, and warm mantle material will fill the gap above it. The slabs of group AB will therefore penetrate into relatively unperturbed mantle again, leading to lower thermal factors. For the Indian region, we therefore use the values at $t = 43$ Myr, and for the Arabian region at $t = 12$ Myr. The predicted volumes for undeformed slabs are shown in Figure 5.14 and Table 5.5-5.6. For these slabs, the volumes estimated with $c_1(t)$ may overestimate the actual values with at most 10% (Section 3.3.3), but this will not significantly change the results. Because of the brief residence times $t$ in the mantle, the differences of $c_2(t)$ and $c_3(t)$ with $c_1(t)$ are only small, and the associated thermal volumes accordingly. Moreover, the AB volumes are approximately similar for both spreading scenarios, and for all three subduction scenarios.

**Volumes of seismic anomalies**

Anomalies Ca, Zs and IA$^1$ in the upper mantle of the Arabian region (upper panel Fig. 5.17, p. 142) are assumed to represent the material still attached to the surface after slab break-off, and are considered as group AB. For subduction scenarios I and II, the complete Aegean
similar to the maximum volumes, and do not depend on the possible amount of thickening. Volumes are thus somewhat larger than the minimum tomographic volumes, and approximately 0.7-1.2 (see Table 5.5 and 5.6). As can be seen in Figure 5.14 (left), the predicted thermal volumes as in Table 5.3, but now when incorporating slab break-off after continent-continent collisions in the Arabian at 22 Ma and Indian region at 43 Ma. From the tomographic volumes for the Arabian region we have separated Ca+Zs+IA\(^2\), and for the Indian region HK+sT, for the group AB that represents the material assumed to be still attached to the surface after break-off (Fig. 5.17). The volumes that are detached, or still continuous with the deeper volumes, are denoted CD. The subdivision of the subducted surface is illustrated in Figure 5.16. Lowermost panel: Alternative calculations for the Indian region to illustrate the effect of slab detachment at 20 Ma instead of the 43 Ma assumed above (break-off depth not taken into account). The predicted AB volumes are corrected for the surface that is expected to be accommodated in the top 230 km of the Earth. Subduction scenario II, not shown here, results in approximately the same AB volumes as scenario I. For the discussed AB slabs, the predicted volumes including slab thickening, calculated with the appropriate factors from Table 5.7 (p. 141), are shown in Figure 5.14.

### 5.7.3 Comparison and conclusions

#### Arabian region

In the Arabian region, the T/P-ratios for the upper mantle group AB are found to be 0.6-1.0 to 0.7-1.2 (see Table 5.5 and 5.6). As can be seen in Figure 5.14 (left), the predicted thermal volumes are thus somewhat larger than the minimum tomographic volumes, and approximately similar to the maximum volumes, and do not depend on the possible amount of thickening.

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<th>(S_{\text{subducted}} (\times 10^9 \text{ km}^3))</th>
<th>(V_{\text{initial}} (\times 10^9 \text{ km}^3))</th>
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<td>1.03 / 1.03</td>
<td>1.60–1.96 / 1.60–1.96</td>
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| Indian-43 |                     |                      |                     |                      |                     |
| AB      | 0.08–0.13          | 4.97               | 0.52 / 0.55       | 0.81 / 0.85       | 0.10–0.16 / 0.09–0.15 |
| ARS CD  | 1.50–2.01         | 8.15               | 0.96 / 0.90       | 1.52 / 1.62       | 1.05–1.32 / 0.98–1.24 |

| Indian-20 |                     |                      |                     |                      |                     |
| AB      | 0.08–0.13          | 1.71               | 1.80 / 1.80       | 2.25 / 2.25       | 0.32–0.52 / 0.32–0.52 |
| ARS CD  | 1.50–2.01         | 11.41              | 1.19 / 1.25       | 2.13 / 2.27       | 0.75–0.94 / 0.70–0.89 |

Table 5.5: Subduction scenario I: Comparison of ARS part of N-T volumes as in Table 5.3, but now when incorporating slab break-off after continent-continent collisions in the Arabian at 22 Ma and Indian region at 43 Ma. From the tomographic volumes for the Arabian region we have separated Ca+Zs+4IA\(^2\), and for the Indian region HK+sT, for the group AB that represents the material assumed to be still attached to the surface after break-off (Fig. 5.17). The volumes that are detached, or still continuous with the deeper volumes, are denoted CD. The subdivision of the subducted surface is illustrated in Figure 5.16. Lowermost panel: Alternative calculations for the Indian region to illustrate the effect of slab detachment at 20 Ma instead of the 43 Ma assumed above (break-off depth not taken into account). The predicted AB volumes are corrected for the surface that is expected to be accommodated in the top 230 km of the Earth. Subduction scenario II, not shown here, results in approximately the same AB volumes as scenario I. For the discussed AB slabs, the predicted volumes including slab thickening, calculated with the appropriate factors from Table 5.7 (p. 141), are shown in Figure 5.14.
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<th>$S_{\text{slab detached}}$ ($\times 10^9$ km$^3$)</th>
<th>$V_{\text{initial}}$ ($\times 10^9$ km$^3$)</th>
<th>$V_{\text{predicted}}$ ($\times 10^9$ km$^3$)</th>
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<td>AB</td>
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<td>0.19 / 0.19</td>
</tr>
<tr>
<td>Sml. CD</td>
<td>?</td>
<td>3.50</td>
<td>0.33 / 0.33</td>
<td>0.58 / 0.58</td>
<td>?</td>
</tr>
<tr>
<td>Indian-20</td>
<td>AB</td>
<td>0.08–0.13</td>
<td>4.97</td>
<td>0.47 / 0.47</td>
<td>0.74 / 0.74</td>
</tr>
<tr>
<td>Spt. CD</td>
<td>0.40–0.65</td>
<td>4.40</td>
<td>0.42 / 0.42</td>
<td>0.67 / 0.67</td>
<td>0.60 – 0.97 / 0.60 – 0.97</td>
</tr>
<tr>
<td>Indian-43</td>
<td>AB</td>
<td>0.08–0.13</td>
<td>1.71</td>
<td>1.16 / 1.16</td>
<td>0.22 / 0.22</td>
</tr>
<tr>
<td>Spt. CD</td>
<td>0.40–0.65</td>
<td>7.66</td>
<td>0.73 / 0.73</td>
<td>1.16 / 1.16</td>
<td>0.35 – 0.56 / 0.35 – 0.56</td>
</tr>
</tbody>
</table>

Table 5.6: Subduction scenario III: Comparison of volumes when incorporating slab break-off as in Table 5.5, but now for ages of the Semail (Sml.) and Spon塘 (Spt.) oceanic lithosphere based on Stampfli and Borel (2002, 2004). For the discussed $AB$ slabs (i.e. left attached after break-off), the predicted volumes including slab thickening, calculated with the appropriate factors from Table 5.7 (p. 141), are shown in Figure 5.14.

The top of the detached slab in the Arabian region will have reached a depth of about 600 km after 12 Myrs of sinking from 100 km downwards at a rate of 3 cm/yr. Although with a somewhat higher sinking rate (say 5 cm/yr) the material will have reached the lower mantle indeed, some of the material may still reside in the upper mantle of this region today. Anomalies SI and IA$^2$, positioned underneath the Bitlis and Zagros Sutures in the Arabian region (Fig. 5.17, p. 142), can be found in the lower mantle only (Fig. 5.19, p. 144): In the eastern part of the region, the depth of the top of IA$^2$ is in agreement with the previous suggestions, as is the ~700-km depth of the bottom of $AB$ volume IA$^1$ (e.g. section 75 in Fig. 4.7, p. 76). However, anomaly SI seems to be too deep to be explained by realistic sinking velocities, and $AB$ volume Zs above SI (Fig. 5.17) extends down to a 1000-km depth instead (e.g. section 55 in Fig. 4.7). The 1000-km depth of the bottom of Zs and the top of SI would require an earlier slab detachment in this region.

As can be seen in Figure 5.17 (p. 142), the most shallow anomalies above SI can be found in anomaly $eT$. Whereas the westernmost part of $eT$ is continuous to the surface, the easternmost part is positioned right underneath anomaly Ca in the Caucasus (compare upper and middle panel of Fig. 5.17). Together with the clear gap between anomalies $eT$ and Ca across the 660-discontinuity (e.g. section 35 of Fig. 4.7), this may indicate that the lower mantle volume of $eT$ represents the detached part of the upper mantle volume Ca, and that break-off did not occur in the westernmost part of the Arabian region. If this is case indeed, the upper mantle part of anomaly $eT$ thus bounds the region where slab break-off has occurred (around section 36), and the predicted volume of group $AB$ should consist only of the Arabian surface east of section 36. This would somewhat decrease the volumes of group $AB$, but will not change the results significantly.

The lack of slab break-off west of section 36, a deep ~1000-km extent of the tomographic
Figure 5.14: Subduction scenario I (~II): Tomographic volumes ($V_t$) vs. predicted thermal volumes ($V_p$) for the slabs in group $AB$, i.e. the volumes that were left attached to the surface after slab break-off (see Fig. 5.13). In the Arabian region, the break-off time is assumed to be 12 Ma. In the Indian region, both slab break-off at 43 Ma and 20 Ma is considered. The values of $V_p$ are corrected for the part assumed to be accommodated in the top 230 km. The dotted lines for the predicted $AB$ volumes indicate the values for subduction scenario III. The calculations for undeformed slabs (1) can be found in Table 5.5/5.6, the factors necessary to perform the calculations for thickened slabs (2/3) in Table 5.7 (p. 141).

$AB$ volume in the central area (sections 45-60), and a ~660-km boundary between the upper and lower mantle anomalies east of section 60, may illustrate the lateral variation in the response on the continental collision event (see also section C in Fig. 4.8, p. 77). As tectonic reconstructions generally suggest a first continental contact along the width of the Zagros suture zone, approximately between section 40 and 70 of our trench system, this may indicate that slab break-off occurred relatively quickly in the central Arabian region. There is no consensus on when precisely collision between the Arabian and Eurasian plates began. The age estimates of collision range from Early Miocene, as assumed here (e.g. Gealey, 1988; Norton, 1999; Şengör and Natal’in, 1996), to Oligocene times (e.g. Dercourt et al., 1993; Jolivet and Faccenna, 2000). An earlier collision time could have led to slab detachment before 12 Ma in the central Arabian region. Subsequently, the tear in the slab may have propagated along the suture zone towards the east and west, leading to slab break-off around the expected 12 Ma underneath Turkey, as well as southern Iran. In the most western part of the Arabian region, convergence velocities may have been too low to lead to slab detachment.

An alternative explanation for III could be that no Cenozoic slab break-off occurred, and that the complete Semail oceanic lithosphere is represented by the tomographic volumes of group $AB$. However, as can be seen in Table 5.6, the total thermal volume predicted for the Semail remnants is much too large to be explained by these tomographic volumes alone. When assuming that the Semail oceanic basin had completely overridden the Neo-Tethys by a time later than the 80 Ma taken in Section 5.6, the predicted thermal volumes will decrease significantly (about 30% when using 65 Ma instead of 80 Ma) but not enough to level with the tomographic volumes.
Section 5.7

Indian region

For the upper mantle group AB in the Indian region, a T/P-ratio of 0.1-0.2 is found for both spreading scenarios, and all three subduction scenarios (Table 5.5-5.6). As can be seen in Figure 5.14, the predicted volume is much larger than can be found in the tomographic model. One explanation for this discrepancy is that the missing tomographic anomalies all reside in the uppermost 230 km of the mantle, which seems not unlikely from Figure 4.7 (e.g. section 95) and Figure 4.8 (e.g. section E and F), and that the estimates made for the top 230 km are too simple for this region. The continuing convergence between India and Eurasia is not necessarily accompanied with the actual subduction of (continental) lithosphere into the mantle, and is probably accommodated partly by the further deformation of the older continental fragments and lithospheric thickening as illustrated schematically in Figure 5.15. Another explanation is that slab break-off took place much later than 43 Ma, in which case a larger slab volume CD will be found in the lower mantle today, and a smaller volume AB attached to the surface. This alternative scenario will be discussed below.

Figure 5.15: Continuing convergence between India and Eurasia after continental collision, possibly leading to slab break-off, is likely to be accommodated partly by the further deformation of the older continental fragments and lithospheric thickening.

Starting from a break-off depth of 100 km, the top of the detached Indian slab can have reached a depth of about 900 km in 43 Myrs, with a modest sinking rate of 3 cm/yr in the upper mantle and 1 cm/yr in the lower mantle. As completely detached material may sink even faster (e.g. Bunge et al., 1998; Han and Gurnis, 1999; Steinberger, 2000), reaching the lower mantle cannot have been a problem for this material. Indeed, the bulk of the anomalies in the Indian region is positioned below 800 km depth (Fig. 5.19, p. 144). However, anomaly Hi1 - found right beneath the Indus-Tsangpo Suture (Fig. 5.17) - covers a ~500-1500 km depth interval (Fig. 5.19), which allows for even lower sinking velocities or a later break-off time.

Note that in subduction scenarios I and II, the predicted CD volumes are much larger than the tomographic volumes (Table 5.5), even when slab thickening would be incorporated (not shown separately, but see thermal factors in Table 5.7). In subduction scenario III, the Spong-tang CD volume fits the maximum tomographic volumes of Hi1 well (Table 5.6). However, when slab thickening would be taken into account, the predicted volume becomes clearly smaller than the tomographic volumes (see thermal factors in Table 5.7).
Slab break-off after Cenozoic continental collisions

Alternative scenario for Indian slab break-off

Within the Himalayan chain, two periods of magmatic activity are generally recognised: An early igneous phase (~55-45 Ma) associated with continental subduction, and a later episode (~35-20 Ma) caused by decompression of depleted mantle, c.q. partial melting (e.g. Harrison et al., 1998; Bertrand et al., 2001; Danishwar et al., 2001; Kohn and Parkinson, 2002; Mahéo et al., 2002). Kohn and Parkinson (2002) concluded that slab break-off in the Himalaya occurred no earlier than 45-55 Ma, as mentioned above, but they also argue that possibly a younger break-off age (~22 Ma) could be accommodated by placing greater emphasis on younger (ca. 25 Ma) K-rich lavas. Likewise, Chung et al. (1998) proposed that the occurrence of the two potassic magma suites suggests a diachronous break-off of the Indian slab, i.e. around 40 Ma in the east, and 20 Ma in the west. Also Mahéo et al. (2002) found that slab break-off in the Himalayas starting around 25-20 Ma could well explain the magmatic activities in west Tibet.

To examine the effect of slab detachment at 20 Ma instead of 43 Ma, we consider here the surface of 19.9 \times 10^6 \text{ km}^2 that must have been subducted prior to 20 Ma in the Indian region. Using adjusted values for the thermal factors (see Table 5.7, p. 141), we arrive at predictions for the thermal AB volumes of 0.2-0.3 \times 10^9 \text{ km}^2 still attached to the surface. As can be seen in Figure 5.16 and Table 5.5-5.6, these attached volumes differ a factor 0.3-0.5 with the tomographic volumes within the upper mantle, which is still an overestimate but is in better agreement than the previous calculations. Within 20 Myrs time, the slab volume can have sunk to about 600 km depth when sinking at 3 cm/yr, which is still deep enough to properly explain the top of anomaly Hi\textsuperscript{1} (Fig. 5.19, p. 144). Note that in subduction scenarios I and II, the predicted CD volumes are now much larger than the tomographic volumes (Table 5.5), but they would be in agreement when incorporating slab thickening (see thermal factors in Table 5.7). In subduction scenario III, the Spongtau CD volume is approximately twice the tomographic volume of Hi\textsuperscript{1} (Table 5.6). If slab thickening by a factor of 3 would be taken into account, the predicted volume would be ~25\% smaller, but still larger than anomaly Hi\textsuperscript{1}.

Conclusions

For the Arabian region, our results indicate that slab break-off probably occurred first, and before 12 Ma, in the northern Zagros suture zone. Propagation of this tear led to slab detachment around 12 Ma in the east as well as in the western part of the region until ~40° longitude.

In the Indian region, slab detachment at 20 Ma is found to best explain the size and depths of the volumes assumed to be left attached at the surface after break-off. If detachment occurred already at 43 Ma, a large amount of lithosphere must have been accommodated in the upper 230 km of the Earth. An intermediate scenario was found to best explain the detached volumes lower in the mantle: Such diachronous slab break-off, starting at 43 Ma in the eastern Himalayas but occurring only around 20 Ma in the central and western Himalayas, would be in accordance with geological studies (e.g. Chung et al., 1998).
Section 5.7

**Figure 5.16:** Division in separate oceanic basins for both the Aegean/Arabian (top) and the Indian (bottom) region as discussed for subduction scenario I. The alternative subdivision for subduction scenario III, based on the reconstruction of Stampfli and Borel (2002, 2004), is given in grey as well. In these figures: PT/NT = Paleo vs. Neo-Tethys (Indian region only, Section 5.5), BRS/ARS = Before vs. After Ridge Subduction (Section 5.6), and CD/AB = Continuous with Deeper slabs vs. still Attached after Break-off (Section 5.7).
Slab break-off after Cenozoic continental collisions

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>yl (km)</th>
<th>t (Myr)</th>
<th>c1(t)</th>
<th>c2(t)</th>
<th>c3(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeg/Arab</td>
<td>65/125</td>
<td>95/110</td>
<td>200</td>
<td>2.0/2.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Indian</td>
<td>60/80</td>
<td>95/105</td>
<td>200</td>
<td>2.0/2.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

5.4: Whole Tethys: ExxonMobil (~ Subduction scenarios I & II)

5.4: Whole Tethys: Stampfli (~ Subduction scenario III)

| Age/Arab | 65/85   | 95/105  | 200   | 2.0/2.1 | 1.6  | 1.3  |
| Indian   | 70/110  | 100/110 | 200   | 2.0/2.2 | 1.6  | 1.3  |

5.5: Separate Paleo-Tethys in Indian region (~ Subduction scenarios I & II only)

| Indian | N-T   | 55/85  | 90/105 | 140   | 1.9/2.0 | 1.5  | 1.3 |
|        | P-T   | 65/75  | 95/100 | 200   | 2.0/2.1 | 1.6  | 1.3 |

5.5: Separate Paleo-Tethys in Indian region (~ Subduction scenarios I & II only)

| N-T | 55/85  | 90/105 | 140 | 1.9/2.0 | 1.5  | 1.3 |
|     | 65/75  | 95/100 | 200 | 2.0/2.1 | 1.6  | 1.3 |

5.5: Separate Paleo-Tethys in Indian region (~ Subduction scenarios I & II only)

| Age/Arab | 125/185 | 110/110 | 80  | 1.8/1.8 | 1.4  | 1.2 |
| Aeg/Arab | 35/96   | 75/105  | 200 | 1.3/2.2 | 1.5/1.6 | 1.3 |
| Indian   | 85/115  | 105/110 | 80  | 1.8/1.8 | 1.4  | 1.2 |
| Indian   | 40/70   | 80/100  | 140 | 1.7/2.0 | 1.5  | 1.3 |

5.5: Separate Paleo-Tethys in Indian region (~ Subduction scenarios I & II only)

| Indian | 60      | 95      | 80    | 1.7    | 1.4  | 1.2 |
|        | 95/125  | 105/110 | 140   | 2.0/2.0 | 1.5  | 1.3 |
| BRS     | 35/65   | 75/95   | 200   | 1.3/2.0 | 1.5/1.6 | 1.3 |
|        | 65      | 95      | 50    | 1.6    | 1.3  | 1.1 |
|        | 110/150 | 110/110 | 120   | 2.0/2.0 | 1.5  | 1.3 |
| BRS     | 35/75   | 75/100  | 200   | 1.3/2.1 | 1.5/1.6 | 1.3 |

5.5: Separate Paleo-Tethys in Indian region (~ Subduction scenarios I & II only)

| Indian | AB-43  | 85/115  | 105/110 | 43    | 1.6/1.6 | 1.3 | 1.2 |
|        | 85/115  | 105/110 | 20    | 1.3/1.3 | 1.2  | 1.1 |

5.5: Separate Paleo-Tethys in Indian region (~ Subduction scenarios I & II only)

| Indian | AB-43  | 65      | 95      | 43    | 1.6    | 1.3 | 1.2 |
|        | AB-20  | 65      | 95      | 20    | 1.3    | 1.2 | 1.1 |

5.5: Separate Paleo-Tethys in Indian region (~ Subduction scenarios I & II only)

Table 5.7: Overview of the values used to predict the initial and present thermal volumes of the lithosphere subducted in the Tethyan region. For the various oceanic basins in this chapter are given here: The average lithospheric age upon subduction for spreading scenario A (left) and B (right) as on p. 87, the initial thermal thickness y_i of oceanic lithosphere of this age, and the residence time t of the slab within the mantle. The last three columns give the thermal factors with which the initial thermal volumes will be multiplied to approximate the present thermal volumes of the subducted lithosphere: \( c_1(t) \) for a subduction process where the slabs kept their plate-like geometry and did not thicken, \( c_2(t) \) for slabs that have thickened by a factor of 2, and \( c_3(t) \) for slabs that have thickened by a factor of 3.
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Figure 5.17: Overview of the tomographic anomalies that are considered to represent volumes of subducted Tethyan lithosphere between 230-660 km depth (upper panel), 660-1100 km depth (middle panel), and 1100-2560 km depth (lower panel). The contour line of every body is a projection of its maximum horizontal extension in the given depth interval. In these figures the colours indicate the subdivision of the volumes in this chapter: White (upper + middle panel only) = AB volumes discussed in Section 5.7; Lightest grey (middle + lower panel only) = BRS volumes of Section 5.6 for subduction scenario I; Middle grey (all panels) = ARS volumes of Section 5.6 for subduction scenario I; Darkest grey (lower panel only) = Possible P-T volume addressed in Section 5.5.
Figure 5.18: Distribution of the total minimum and maximum volumes of the separate tomographic anomalies. Shown depths range from 0-2889 km, with the anomalies integrated over a depth interval of 230-2560 km. The volumes of the anomalies range from 0-500 $10^3$ km$^3$, except for the volume of anomaly Gr (lower right panel) that ranges from 0-1000 $10^3$ km$^3$. Rightmost panels: The approximate time (Myrs) needed for subducted material to reach the shown depths when sinking with a rate of 3-4 cm/yr in the upper mantle and 1-2 cm/yr in the lower mantle. Note that slab break-off after continental collision is assumed to occur at 100 km depth.
Figure 5.19: As in Figure 5.18. In this figure, the volumes of anomalies Eg, SA, SI and $IA^2$ (left four panels) range from 0-1000 km$^3$, and those of Io and Ic (third column panels) from 0-2000 km$^3$. The volume of anomaly $Hi^1$ (upperright panel) ranges from 0-1500 km$^3$, whereas the volume of anomaly $Hi^2$ (lowerright panel) ranges from 0-500 km$^3$ only.
Reconstructing the Tethyan history of subduction

5.8 Reconstructing the Tethyan history of subduction

5.8.1 Subduction scenarios for the Indian and Arabian regions

We here propose a scenario for the Late Mesozoic-Cenozoic subduction of the Neo-Tethyan oceanic lithosphere in the Indian and Arabian regions. This preferred model is based on the plate tectonic reconstruction of Stampfli and Borel (2004), to which we add our interpretation of the subduction process, and take into account also the absolute motion of the continental margins and the effects of the Cenozoic continental collisions as discussed above. Because the Paleo-Tethyan lithosphere has probably subducted prior to 200 Ma, it will not be discussed further here.

Illustrated in Figure 5.20 and 5.21 are the reconstructed scenarios for the Arabian region since 140 Ma and the Indian region since 120 Ma. The cross-sections for each region are representative for the bands of integrated tomographic anomalies shown in Figures 5.8 and 5.9 (p. 121). As the Arabian continental margin has not been exactly perpendicular to these sections (e.g. see Fig. 5.17), the southernmost anomalies in Figure 5.8 are the result of subduction further south - i.e. in a section further east - than illustrated in Figure 5.20.

Based on our analyses in the previous sections, we divide the subduction history into four phases:

1. Subduction of the Neo-Tethys underneath the Eurasian continental margin, followed by ridge subduction in Early Cretaceous times. The absolute positions of the continental margins are uncertain prior to 80 Ma, and are taken here with the Eurasian craton held fixed. The subducted part of the Neo-Tethyan lithosphere sinks down into the mantle slowly.

2. Subduction of the remaining part of the Neo-Tethys underneath the southward extending back-arcs of the Arabian Semail and Indian Spongtag Oceans, followed by the collision of the arcs onto the approaching Arabian/Indian continental margins. The relative fast trench migrations cause the slabs to flatten and spread over the full width of the back-arc basins.

3. After complete closure of the Neo-Tethys, around 80 Ma in the Arabian region and 65 Ma in the Indian region, the back-arc oceanic basins are being subducted underneath the Eurasian margin. As the Arabian/Indian continents move further northwards, the subducted Neo-Tethyan lithosphere is left behind within the underlying mantle.

4. Subduction of Arabian continental lithosphere underneath Eurasia causes the Semail slab to break off around 12 Ma, but probably somewhat earlier in the central Arabian region. Due to subduction of Indian continental lithosphere, detachment of the Spongtag slab starts at 43 Ma in the eastern Himalayas, but occurs only around 20 Ma in the central and western part of the Indian region.
Section 5.8

Figure 5.20: Reconstruction of the subduction history for the Arabian region from 140 Ma to present. The evolution is shown in an absolute reference frame, with the arrows indicating the uncertainties in the absolute position of the continental margins (prior to 80 Ma unknown). Key: EU = Eurasia, AR = Arabia, NT = Neo-Tethys, SML = Semail. The cross-section for the present-day configuration is largely representative for the band of integrated tomographic anomalies shown in Figure 5.8 (p. 121). Note that in that figure, the southernmost anomalies are the result of subduction further south - i.e. in a section further east, than illustrated in here.
Figure 5.21: Reconstruction of the subduction history for the Indian region from 120 Ma to present. The evolution is shown in an absolute reference frame, with the arrows indicating the uncertainties in the absolute position of the continental margins (prior to 80 Ma unknown). Key: EU = Eurasia, IND = India, PT = Paleo-Tethys, NT = Neo-Tethys, SPT = Spongtang. The cross-section for the present-day configuration is representative for the band of integrated tomographic anomalies shown in Figure 5.9.
Section 5.8

Implications for the Arabian region

Slab volumes As illustrated in Figure 5.22, our preferred scenario implies that the part of the Neo-Tethyan lithosphere subducted before its ridge forms the present lowermost (depths $\geq 2000$ km) volumes of anomalies SI and IA$^2$. The remaining part of the lithosphere can be found both in these anomalies ($\sim 1100-2000$ km depth) as well as in the southern anomalies Eg and SA ($\sim 800-2000$ km depth). The Semail Ocean is incorporated in the top of anomalies SI and IA$^2$ again.

Our results for the preferred subduction scenario indicate that the Neo-Tethyan and Semail slab volumes in the Arabian region must have thickened by a factor of 3 to make their predicted thermal volumes fit to the tomographic volumes.

Moreover, the thermal volumes predicted for Arabian slab break-off around 12 Ma, and somewhat earlier underneath the central Zagros suture, are in agreement with the tomographic anomalies restricted to the upper mantle in this area.

![Figure 5.22: Interpretation of the vertical distribution of tomographic anomalies in the Arabian region (left panel, as in Fig. 5.8) in terms of subducted Tethyan oceanic lithosphere (right panel, as present-day reconstruction in Fig. 5.20). Note (see Fig. 5.17) that the southernmost part of the tomographic anomalies Eg and SA (left panel) are assumed to be the result of subduction in a section further east than illustrated in the right panel.](image)

Lithospheric spreading during subduction If thickened by a factor of 3, the predicted Neo-Tethyan and detached Semail volumes are larger than the minimum tomographic volumes associated with these slabs, but smaller than the maximum volumes. The ratios leave room for an additional $0.2-0.4 \times 10^9$ km$^3$ volume, depending on the spreading scenario. The additionally subducted material is possibly the combined result of lithospheric spreading within the Neo-Tethys during its subduction, and the drifting and intermediate spreading of smaller continental fragments in the Mediterranean. As the latter will be addressed separately below (Section 5.8.2), we will here investigate the implications for the spreading rates for the case that the whole additional volumes is caused by Neo-Tethyan spreading.

We perform the same thermal calculations for predicting the present thermal volumes of subducted material, but in a reversed order, to establish the original subducted surface of the additional $0.2-0.4 \times 10^9$ km$^3$ volume. Using the thermal factors and lithospheric thicknesses
Reconstructing the Tethyan history of subduction

as for the Neo-Tethyan oceanic basins (Table 5.7, p. 141), we arrive at an original surface of

\[ 1.5-3.2 \times 10^6 \text{ km}^2 \]

assuming that all these slabs have thickened by a factor of 3 in the mantle. If Neo-Tethyan spreading occurred over the full width of the Africa-Arabian continental margin, and during the entire 200-140 Ma time interval, this surface would require an average total spreading rate of 0.5-1 cm/yr. If the Neo-Tethyan ridge has been active in the Arabian region only, the average spreading rate must have been about 1-1.5 cm/yr.

Implications for the Indian region

Slab volumes Our preferred scenario for the Indian region implies that the Neo-Tethyan lithosphere subducted before its oceanic ridge (∼120 Ma) is incorporated in the lowermost, say \( \geq 1800 \) km, volumes of anomaly Ic (Fig. 5.23). The second part of the Neo-Tethyan lithosphere can be found today in anomaly Ic (∼1100-1800 km depth), as well as the southern anomaly Io (∼800-2000 km depth). The Spongtang lithosphere is accommodated north of the Neo-Tethyan volumes and visible at present as anomaly Hi. Our results for the preferred subduction scenario indicate that the Neo-Tethyan slab volumes must have thickened by a factor of 2 to make their predicted thermal volumes fit to the tomographic volumes. To leave room for additional subduction, however, the oceanic lithosphere must have thickened by a factor 3. The Spongtang lithosphere has probably thickened by a factor of 3 as well. Spongtang slab detachment starting at 43 Ma but occurring primarily around 20 Ma can best explain both the depth and volumes of the tomographic anomalies underneath the Himalayas. This, however, implies that the continuing convergence between the Indian and Eurasian continents must have been partly accommodated by the deformation of earlier accreted continental blocks and lithospheric thickening above 230 km depth.

![Figure 5.23: Interpretation of the vertical distribution of tomographic anomalies in the Indian region (left panel, as in Fig. 5.9) in terms of subducted Tethyan oceanic lithosphere (right panel, as present-day reconstruction in Fig. 5.21).](image)

Lithospheric spreading during subduction If thickened by a factor of 3, the predicted Neo-Tethyan slab volumes in the Indian region are only slightly more than the minimum tomographic anomalies of Io and Ic. The difference with the maximum volume of these anomalies is \( 0.4-0.5 \times 10^6 \) km³, depending on the spreading scenario. Whereas this volume
Section 5.8

could be partly explained by material of the Spongtang oceanic basin, it is more likely that
the active spreading of the Neo-Tethyan lithosphere during its subduction added to the amount
of subduction significantly.

Using similar thermal calculations for the Neo-Tethyan lithosphere as in the above sections
(Table 5.7, p. 141), we find that the 0.4-0.5 \( \times 10^9 \) km\(^3\) volume corresponds to an additional sub-
ducted plate surface of \( \sim 2.9-4.0 \times 10^6 \) km\(^2\) if the slabs have thickened by a factor of 3. For con-
tinuous spreading within the Indian Neo-Tethys during the 200-120 Ma period before ridge
subduction, this would correspond to an average full spreading rate of about 1.5-2.5 cm/yr.

5.8.2 Accretion but continuous subduction in the Aegean region

The westernmost part of the Tethyan region has not been given specific attention in the pre-
vious, as we have focussed primarily on the large-scale subduction in the combined Aegean-
Arabian and Indian regions. In the Aegean area, however, the creation and subduction of sev-
eral intermediate oceanic basins must have affected the amount of subduction significantly.
Moreover, the present-day situation is completely different from that of the rest of the Tethyan
region as subduction of the last remnants of Tethyan oceanic lithosphere along the Hellenic
trench system (Points 1-20 in Fig. 4.11, p. 82) is ongoing. We therefore investigate here the
volumes of subducted lithosphere for the first 20 sections of the Aegean region.

Phases of subduction Based on the reconstruction of ExxonMobil, the subduction history
of the Aegean region can be divided into four phases (see Fig. 2.8, p. 29), namely (1) before
140 Ma: Neo-Tethys subduction along the Pontides arc, prior to spreading of intermedi-
ate fragments; (2) 140-80 Ma: Additional subduction due to the spreading of the various
fragments which is accommodated along the Pontides arc, and accretion of Kirşehir to Eur-
asia; (3) 80-48 Ma: Subduction accommodated along the Izmir-Ankara arc, and accretion
of Menderes to Eurasia; and (4) 48-0 Ma: Subduction of the remaining Tethyan lithosphere
underneath the present Hellenic arc. Dercourt et al. (1993) and Şengör and Natal’in (1996)
propose similar subduction histories, although with other geometries of the intermediate frag-
ments, and somewhat different rifting and accretion times (see Chapter 2).

In the reconstruction of Stampfli and Borel (2002, 2004) on which our preferred subduction
scenario for the Arabian and Indian region is based (see Figs. 2.3-2.6, pp. 22-25), however,
these phases are different. We here distinguish (1) Additional subduction of the Triassic
Maliac oceanic basin due to the spreading of the overriding Vardar Ocean; (2) Subduction
of the Vardar Ocean, and accretion of the Pelagonian zone to Eurasia; (3) Subduction of the
Pindos basin, and accretion of the Ionian zone to Eurasia; and (4) Subduction of the Neo-
Tethyan remnants as in the other reconstructions.

Additional surface According to the reconstruction of ExxonMobil, Menderes is adjacent
to northeast Africa until \( \sim 140 \) Ma and already close - although not yet accreted - to Eurasia
around 80 Ma. As can been seen in Figure 2.8 (p. 29), the motion of Kirşehir relative to Eur-
asia has been only little more than that of Menderes vs. Eurasia, and has probably influenced
the amount of subduction east of section 25 only. To approximate the additional amount of
convergence in the western Aegean region, we calculate the surface subducted due to the motion of Menderes relative to Eurasia between 140 and 80 Ma.

For our westernmost 20 sections (~10° width), we find in a total surface of 2.9×10^6 km^2 to be subducted in the past 200 Ma, instead of the 2.1×10^6 km^2 calculated from the African-Eurasian convergence alone, of which the larger part (almost 60%) belongs to phase (2). In the reconstruction of Stampfli and Borel (2004), the Maliac Ocean that was additionally subducted had a size of about 1×10^6 km^2 (i.e. ~10°x10°) (see Fig. 2.4, p. 23), whereas the maximum size of the Vardar Ocean seems to be at most 2×10^6 km^2 (~20°x10°) around 120 Ma (Fig. 2.5, p. 24). Also in this reconstruction, the additional 0.8×10^6 km^2 thus seems to be a reasonable surface to be subducted in the western 10° of the Aegean region considered here.

Again we take into account the fact that the top 230 km of the tomographic model has not been incorporated in our analysis. From a simple geometric point of view, the convergence accommodated in this depth interval will be ~200 km for a 45° slab dip below a 100-km thick plate. For the first 20 sections in the Aegean region, this yields a total surface of 0.2×10^6 km^2 to be subtracted from the surface of the latest phase of subduction (4). The most recent trench migration of the Hellenic trench system is not incorporated in the total surface. However, because this has probably caused flattening of the slab in the uppermost mantle only, the additional subduction may not be embodied in our tomographic anomalies either.

Including the additional surface, but corrected for the upper 230 km, the total subducted lithosphere yields an average convergence along our trench system of about 2400 km. During the 140-80 Ma timespan of phase (2), the subduction of 60% of this plate can be associated with an average convergence rate of 2.5 cm/yr. During the other phases, however, the convergence rates have been 1-1.5 cm/yr only.

**Predicted thermal volumes** Similar to the previous calculations, we predict the present thermal volume that can be associated with the subducted material. Because of the uncertainties in the exact spreading and subduction times of the intermediate basins, we make sure to end up with an upper limit of the predicted volumes by using an average 100-Ma age for all lithosphere. Much more important in this analysis are the shorter residence times in the mantle, namely t = 200, 140, 80 and 48 Myr for the four phases, respectively.

The slab material subducted in the oldest three phases is likely to have thickened by a factor of 2 or 3, but the slab of the most recent and still ongoing phase of subduction has probably not yet thickened significantly. Therefore, we take estimates of the thermal factors c_2(t) and c_3(t) for phase (1)-(3), and c_1(t) for phase (4), to predict the total thermal volume for the western Aegean region. However, if we would use c_2(t) and c_3(t) for phase (4) as well, the results will be comparable due to the brief residence time in the mantle.

We find a total thermal volume of 0.42-0.49×10^6 km^3, depending on the amount of slab thickening. From this volume, 17-18% belongs to phase (1), 55-57% to phase (2), 12-14% to phase (3), and 12-14% to phase (4). The volumes for the active phase (4) of subduction may be somewhat overestimated, with at most 10% (Section 3.3.3), but this will not change these values significantly.

**Comparison to tomographic volumes** We compare the predicted volumes to the most western anomaly Gr beneath the Hellenic trench (e.g. see Figs. 4.7 (p. 76, section 15) and
Section 5.8

4.18 on p. 97). There is no evidence for other tomographic anomalies than Gr that may be related to one of the older phases of Aegean subduction. East of section 20, anomaly Gr is found only in the lower mantle, and east of section 25 below 1100 km depth only (Figs. 4.4-4.6, pp. 73-75). Throughout the westernmost 20 sections investigated here, the volume of anomaly Gr is 0.53-0.63×10⁹ km³. The 0.4-0.5×10⁹ km³ predicted for the thermal volume of the Aegean slab is in agreement with the size of anomaly Gr, and even allows for more subduction, e.g. from the Kirşehir block (ExxonMobil), or by a larger Vardar Ocean (Stampfli and Borel, 2002, 2004).

**Location of subducted material**  If subduction has been accommodated along the apparently separate trench locations displayed in the tectonic reconstruction of ExxonMobil, we may be able to see three separate slab volumes as well, and also a subducted oceanic basin like the Vardar Ocean (Stampfli and Borel, 2002, 2004) may be detectable as a separate identity today. The fact that we only see one tomographic anomaly in the Aegean region gives the impression that, although subduction along separate trench systems is proposed, the underlying lithospheric plates have continued their subduction without significant distortions. Whereas speculated on this scenario before (e.g. Faccenna et al., 2003), we found that the approximate present thermal volume of the subducted slab material is in agreement with the volume of this tomographic anomaly indeed.

The depth distribution of anomaly Gr clearly shows that most of the material is positioned between ~750 and 1800 km depth (Fig. 5.18, p. 143). As can be seen in Figure 4.7 (p. 76), the bulk anomaly of Gr continues down to ~1600 km depth, and a somewhat separate volume is situated more south - and deeper - than the main anomaly. This lower ~1600 km part of anomaly Gr has a volume of 19-22% of the total 0.53-0.63×10⁹ km³. The bulk volume between 750 and 1600 km depth is about 65-69% of these values, and the upper mantle subvolume 13-14%. As the rates of convergence have been relatively small, assuming an average sinking rate of 2 cm/yr in the upper mantle and 1 cm/yr in the lower mantle seems reasonable. In that case, the 750-1600 km depth interval of the bulk subvolume would require sinking times of ~50-130 Myr, which would correspond to our phase (2) and (3) of abundant subduction. Phase (1) could be associated with the lowermost ~1600 km subvolume, and phase (4) with the upper mantle volume. Indeed, the relative amounts of the tomographic subvolumes correspond to those of the predicted thermal volumes for the same phases, namely ~20% for phase (1) and ~70% to phase (2) and (3) at most, and about 10-15% for phase (4).

The continuous subduction scenario sketched above for the reconstructions of ExxonMobil, Dercourt et al. (1993) and Şengör and Natal’in (1996) is schematically illustrated in Figure 5.24 for a section across the present Hellenic arc (cf. section 15 of Figure 4.7, p. 76). Herein, we took into account the predicted volumes of the subducted lithosphere, the possible slab thickening, and the approximate distribution of the material. For the absolute locations of the continental margins we considered their motions in the HS and MHS reference frames (see Figs. 5.3-5.4, pp. 109-110). However, the HS frame seems to predict locations for the
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Figure 5.24: Schematic scenario for the subduction in the eastern Mediterranean as proposed by Exxon-Mobil, Dercourt et al. (1993) and Şengör and Natal’în (1996). The figures illustrate the accretion of continental fragments and the single, continuous subduction process of the underlying lithosphere. The evolution is shown for a section across the present Hellenic arc in an absolute reference frame (prior to 80 Ma uncertain). The numbers indicate the four phases of subduction as discussed in the text. Key: A = Africa, M = Menderes, K = Kırşehir, EU = Eurasia. See text for alternative scenario proposed by Stampflì and Borel (2002, 2004).
trench systems that are too far south and east to explain the position of anomaly Gr. Therefore, we prefer the MHS frame in which the locations of the trenches appear to be at the appropriate latitudes, although probably somewhat too far west as discussed before (e.g. Section 5.6). The four phases of subduction that were derived from the reconstruction of Stampfli and Borel (2002, 2004) would result in a different scenario than illustrated in Figure 5.24. For example, when comparing the 80-Ma situation with their Late Cretaceous reconstruction (Fig. 2.6, p. 25), fragment K would correspond to the just accreted Pelagonian zone and M to the Ionian zone, with the Pindos basin in between. Slab (1) would represent the detached Maliac basin, and slab (2) the subducted Vardar Ocean. Although significantly different from the scenario sketched above, the general conclusion that the continental fragments have been accreted during a single, continuous subduction process of the underlying lithosphere will hold.

**Conclusions**  When considering the separate rifting and accretion of intermediate continental fragments in the eastern Mediterranean, the decreasing lithospheric ages and especially residence times in the mantle are found to largely compensate the increasing subducted lithosphere. Our results indicate that the total thermal slab volume calculated for the westernmost Aegean region can be explained by the size of the single tomographic anomaly (Gr) underneath the present Hellenic trench system. This suggests that the subduction of the lithosphere underlying the various fragments and basins has been continuous in this area since at least Early Cretaceous times.

**5.9 Conclusions**

Three broadly accepted subduction scenarios for the Tethyan oceanic lithosphere and its spreading ridges, based on the reconstructions of Norton (1999), Dercourt et al. (1993), Şengör and Natal’in (1996), and Stampfli and Borel (2002, 2004), have been investigated by comparing the predicted thermal volumes of the subducted lithosphere to the tomographic mantle structure underneath the Tethyan region. We found that from the bulk volumes predicted by the three different subduction scenarios alone, we cannot distinguish the tectonic reconstructions underlying the scenarios.

To discriminate between the different reconstructions, we have predicted the subvolumes associated with the particular oceanic basins proposed in each subduction scenario. We compared these to the separate tomographic anomalous volumes in the Tethyan region by systematically analysing the amount, location and timing of subduction with the size, position and geometry of the tomographic anomalies. We found that the subduction scenario based on the reconstruction of Stampfli and Borel (2004), comprising the opening of large back-arc oceanic basins within the Eurasian margin, can best explain both the volumes and the positions of the anomalous volumes.

One of the key issues in evaluating the different subduction scenarios has appeared to be the absolute motions of the ancient trench systems in the past. Our results give the impression that the fixed hotspot reference frame considered here (Müller et al., 1993) predicts locations of the continental margins that are too far south and east with respect to the relevant tomographic anomalies. The moving hotspot reference frame used (O’Neill et al., 2003) results in absolute
positions that seem to be at the appropriate latitudes, but too far west with respect to the
tomographic anomalies instead.
Our results further suggest that most lithosphere subducted in the Tethyan region has thick-
ened by a factor of 3 in the mantle, which seems to be reasonable in view of the large amount
of subducted material that entered the lower mantle. If this has been the case indeed, the
differences between the predicted thermal volumes and tomographic volumes leave room for
average spreading rates of about 1-1.5 cm/yr in the Arabian region, and 1.5-2.5 cm/yr in the
Indian region, during subduction of the Neo-Tethys. Late Miocene slab break-off underneath
the Zagros suture zone, and diachronous Eocene to Miocene break-off below the eastern
to western Himalayas, has been found to best explain the associated slab volumes. Finally,
Paleo-Tethyan lithosphere seems to be imaged in the lower mantle underneath the Himalayas,
but the larger and older part of the Paleo-Tethys must have been subducted elsewhere or is no
longer detectable as a separate anomalous volume today.
In spite of the limitations of our approach, we found that the method does enable us to suc-
cessfully integrate the information contained in plate tectonic reconstructions and seismic
tomographic models, and put further constraints on the subduction history of an ocean that is
entirely lost today.