Chapter 2

The Mesozoic-Cenozoic evolution of the Tethyan region

In this chapter, we review the tectonic evolution of the Tethyan region, the area marked today by the Alpine-Himalayan mountain chain that stretches from the Mediterranean to the Indonesian archipelago (Fig. 2.1). In Section 2.1, the main aspects of the present-day tectonics of this Tethyan region will be outlined. A discussion of the overall Mesozoic-Cenozoic evolution of the area, on the basis of a series of tectonic reconstructions, follows in Section 2.2. The chapter will be concluded in Section 2.3 with an overview of the aspects of the Tethyan evolution that will be investigated in this thesis.

2.1 Present-day tectonics

In the Eastern Mediterranean, the Hellenic trench forms the boundary between the African and Eurasian plates in the Aegean region (Fig. 2.1), and Arabia is in continental collision with Eurasia at the Bitlis suture in Turkey. The relative motion between the African and Eurasian plates is only small (<1 cm/yr), whereas the motion of Arabia to Eurasia is ~2-3 cm/yr (DeMets et al., 1994; McClusky et al., 2000; Sella et al., 2002). On the southern margin of the Eurasian plate, the Anatolian block of Turkey moves westward with ~2.5 cm/yr relative to Eurasia (McClusky et al., 2000). This motion is accommodated along the Bitlis suture and the North Anatolian Fault (e.g. Morris and Tarling, 1996). Faster movements, in a more southwestward direction, are recorded in the Aegean region as a result of additional extension in this area (Jolivet, 2001): Geodetic measurements indicate velocities with respect to Eurasia of ~3 cm/yr for the Aegean (McClusky et al., 2000). Both the Aegean region and Anatolian block are made up of several microcontinents and ophiolitic terranes (e.g. Okay, 2000; Stampfli, 2000; Lips et al., 2001).

In the Middle East, the boundary between Arabia and Eurasia is formed by the Zagros suture zone, and the last remnant of Neo-Tethyan oceanic lithosphere is currently accommodated along the Makran trench south of Iran and Pakistan. GPS results indicate a distributed shortening across the Zagros mountains of ~2-2.5 cm/yr (McClusky et al., 2003). The Arabian
plate itself is rifting from the African plate through the spreading systems in the Red Sea and Gulf of Aden, their relative motion being ~0.5-1.5 cm/yr (DeMets et al., 1994; Sella et al., 2002; McClusky et al., 2003). Large ophiolitic belts are found not only along the Bitlis and Zagros suture zones, but also in the Oman region on the eastern edge of the Arabian peninsula (e.g. Knipper et al., 1986; Robertson and Searle, 1990).

The zone of continental collision between India and Eurasia is formed by the Indus-Tsangpo suture, extending along the margin of the Himalayan chain in Pakistan, northwest India, south Tibet and Myanmar. Although in collision, the present-day motion of India relative to Eurasia is ~3-4 cm/yr (Sella et al., 2002; DeMets et al., 1994). The Owen Fracture Zone and Carlsberg Ridge in the Indian Ocean form the boundary between the Indo-Australian and Africa-Arabian plates. The Arabian vs. Indo-Australian rate of motion along the Owen Fracture Zone is ~1-2 mm/yr (Fournier et al., 2001). The relative motion between the Indo-Australian and African plates is ~2-2.5 cm/yr along the Carlsberg Ridge (DeMets et al., 1994).

The complexity of the present-day tectonics in the Southeast Asian region is the result of the convergence and collision of the Eurasian, Indo-Australian and Philippine Sea plates (e.g. Hamilton, 1979). A major trench system curves around the rigid continental Sunda Block on the Eurasian plate. Along this Sunda-Java trench, Indian Ocean lithosphere of the Indo-Australian plate subducts northward beneath Indonesia at rates up to 8 cm/yr (DeMets et al., 1994). The Australian continental shelf is in collision with the Eurasian continent along the extremely curved Banda arc, and the Halmahera trench is in frontal collision with the Sangihe trench in the Molucca Sea region (e.g. Bowin et al., 1980; Richardson and Blundell, 1996; Rangin et al., 1996). The Philippine and Eurasian plates are converging obliquely along the Philippine archipelago with a relative velocity of about 8 cm/yr (DeMets et al., 1994).

Figure 2.1: Tectonic framework of the Tethyan region, with Anat. = Anatolian Block. The arrows indicate present-day plate motions relative to Eurasia. Trenches and suture zones (black lines): Hellenic Trench (HT), North Anatolian Fault (NAF), Bitlis Suture (BS), Zagros Suture (ZS), Makran Trench (MT), Indus-Tsangpo Suture (ITS), Sunda-Java Trench (SJT), Sangihe Trench (ST), Halmahera Trench (HHT), and Banda Arc (BA). Other plate boundaries (grey lines): Red Sea (RS) and Gulf of Aden (GA) rifts, Owen Fracture Zone (OFZ), Carlsberg Ridge (CR).
2.2 Tethyan evolution according to various reconstructions

The Mesozoic-Cenozoic evolution of the Tethyan region will be reviewed on the basis of six different tectonic reconstructions, namely those of
1. Van der Voo (1993), referred to as Van der Voo in the following discussion, and giving an overview of the available paleomagnetic data from Carboniferous times onwards;
2. Dercourt et al. (1993), referred to as Dercourt hereafter, a reconstruction from the Early Triassic until present;
3. Şengör and Natal’in (1996), referred to as Şengör, a reconstruction from Late Triassic times onwards;
4. Yang (1998), referred to as Yang, a more general description of the eastern Tethyan evolution depicted in a Carboniferous-Triassic and Triassic-Tertiary configuration;
5. Norton (1999), referred to as ExxonMobil, a digitised reconstruction from the Early Ordovician until present;
6. Stampfli and Borel (2002, 2004), referred to as Stampfli, a reconstruction from the Early Ordovician to Late Cretaceous times.

Whereas the tectonic reconstructions of Van der Voo, Dercourt, Şengör, Yang, and ExxonMobil can be viewed upon as classical continental drift models, the recent plate tectonic reconstructions of Stampfli are constrained by dynamic plate boundaries. That is to say, oceanic surface has been added or removed to major continents and terranes in order to reconstruct the ancient plate boundaries through time.

Comparison of the rifting and accretion times of the several tectonic fragments is not straightforward, as they usually have different names and geometries in each reconstruction. For many continental fragments, only few or poor-quality data are available. The uncertainties generally increase going backwards in time, and are highly dependent on the tectonic fragment involved. Because of the uncertainties in the paleo-positions of the separate fragments, and in view of the more global approach of this research, we will concentrate here on the motions of the larger continental blocks in the reconstructions. Also the definition of the several oceanic basins varies from reconstruction to reconstruction: Oceans can be viewed upon as a single unit or as consisting of separate parts, and the direction of subduction is not always explicitly defined. Moreover, the reconstructions are usually given as a series of maps for which scale, projection, as well as the relative directions of motions of the fragments are missing. Therefore, the amount of convergence, which will be of interest for this study, is often hard to estimate. The reconstruction of ExxonMobil is totally digitised, and can thus be used to accurately determine the amount of convergence involved. Since we will primarily work with the reconstruction of ExxonMobil in later chapters, we will give special attention to this reconstruction in the discussion below.

2.2.1 Definition of tectonic fragments and terranes

In the discussion of the Tethyan evolution, many different continental fragments will come across. Each reconstruction usually has another interpretation of the geometries and names of the fragments involved. The names and present-day locations of the tectonic fragments of the Tethys region that are used in this section are illustrated in Figure 2.2. In this figure, both
Section 2.2

the names and the shown accretion times, c.q. the moments at which the fragments accreted to Eurasia, are taken from the reconstruction of ExxonMobil. Summarised in Table 2.1 are the accretion times of the main tectonic fragments of Figure 2.2 as proposed by the different reconstructions discussed in this paper. In Table 2.2, the spreading and closure times of the oceanic basins in the Tethyan region, as proposed by the reviewed reconstructions, are shown. The fragments in Table 2.1 and Table 2.2 are often referred to differently in the various reconstructions. Therefore, an overview of the names of the fragments used in these tables, and the alternatives used in Figure 2.2 and other reconstructions, is given in Table 2.3. The several stages in the evolution of the Tethyan region according to the reconstructions of Stampfli and ExxonMobil are illustrated in Figures 2.3 to 2.8.

### 2.2.2 Definition of oceanic domains and suture zones

Throughout the Tethyan evolution, three large oceanic domains are generally recognised: First (see Figs. 2.3/2.4 and upper panels of 2.7/2.8), the **Paleo-Tethys** is the Paleozoic ocean south of the Hun Superterrane (see Table 2.3), and the Cimmerian blocks form the southern margin of the Paleo-Tethys. Closure of the Paleo-Tethys, associated with the collision of the Cimmerian blocks with Eurasia, is proposed before the end of the Triassic in most reconstructions. Secondly (see Figs. 2.4/2.5 and middle panels of 2.7/2.8), the **Neo-Tethys** is a Late Carboniferous-Permian (Dercourt, Şengör, Stampfli) or Late Triassic-Early Cretaceous (ExxonMobil, Van der Voo, Yang) ocean that separated the Cimmerian blocks from Gondwana. The eastern Mediterranean Sea is considered to be part of the Neo-Tethys as well. After final closure of the Paleo-Tethys, the Neo-Tethys started to subduct underneath Eurasia instead. The larger Arabian and Indian continents form the southern margin of the Neo-Tethys, thus closure of this ocean is associated with the continental collisions of Arabia and India with Eurasia. The third oceanic domain, although not strictly Tethyan, is the Indo-Australian oceanic lithosphere that was formed while India separated from Gondwana during Late Jurassic to Cretaceous times (see lower panels of 2.7/2.8).

Before the final closure of the Paleo-Tethys, slab roll-back is expected to have triggered, among others, the opening of various back-arc oceanic basins along the whole Eurasian margin in Permo-Triassic times. For example, in the reconstruction of Stampfli we can see that back-arc oceans like the **Meliata, Maliac, Pindos, and Karakya Oceans** opened, and stopped spreading, before the end of the Triassic (Figs. 2.3 and 2.4). Some of the back-arc basins must have closed together with the last remnants of the Paleo-Tethys. Other basins remained open even after the Paleo-Tethys closure, and have disappeared with the complex collision of the Cimmerian terranes later. The northward subduction of the Neo-Tethys also resulted in Mariana-type back-arc spreading and subsequent intra-oceanic subduction (see also Fig. 2.5). For example, the **Vardar Ocean** opened by the subduction of the Meliata Ocean underneath the Neo-Tethys (Stampfli), or as a branch of the Neo-Tethys directly (Şengör). In the reconstruction of Stampfli, the Neo-Tethys was subducting beneath the back-arc **Semail Ocean** in Cretaceous times. The Neo-Tethys, Semail Ocean and Vardar Ocean closed simultaneously during the Cretaceous.

A suture can be defined as the place where a former oceanic basin used to separate two con-
Tethyan evolution according to various reconstructions

Figure 2.2: The tectonic fragments as discussed in this chapter, as well as their accretion times, according to the reconstruction of ExxonMobil (Norton, 1999). The collision of Arabia with Eurasia occurred around 22 Ma. Accreted at 48 Ma: Vardar, Pelagonia, Menderes, Antalya, Taurides, Bitlis area, and India. Accreted around 80-70 Ma: Kirsehir, Daralagez. Accreted between 140 and 110 Ma: Sakarya/Karakaya complex, Helmand, Ladakh-Kohistan arc, Lhasa. Accreted between 200 and 180 Ma: Sanandaj-Sirhan, Kavir area, Yazd, Tabas, Lut, Sistan. Accreted prior to 200 Ma: Pontides, Farah. The tectonic fragments north and east of the Pontides-Farah-Lhasa line (including the North Tibet, South China, Indochina, and Sibumasu block of Table 2.1) all accreted onto the Eurasian margin before 200 Ma, and are therefore not shown separately.
tinental fragments. Such a zone will form a stratigraphic, structural, metamorphic and magmatic boundary between both continental units. The larger suture zones within the Tethyan region include the Izmir-Ankara(-Erzincan) suture, separating the Menderes-Taurides-Kirşehir blocks from the Pontides. This suture probably contains the remnants of both the Paleo-Tethys and the Vardar oceanic basin. Suture zones in the Aegean region are likely to be connected to this Izmir-Ankara suture, but due to the more recent extension and collisional processes within the area it is difficult to identify these. More to the east, the Bitlis suture zone is the boundary between the Anatolide-Tauride block of Turkey and the Arabian plate, and has resulted from the Tertiary closure of the Neo-Tethys. The Zagros suture is the eastern continuation of the Bitlis suture zone, marking the boundary between the Arabian platform and the earlier accreted fragments in the Middle East. Remnants of the Semail Ocean must have been included here as well. Finally, the Indus-Tsangpo suture is associated with the closure of the Neo-Tethys between Greater India and the Helmand/Lhasa block.

### 2.2.3 Mesozoic-Cenozoic evolution

#### Pre-Jurassic (> 200 Ma)

According to the reconstruction of ExxonMobil, the South China block starts its collision with Siberia around 225 Ma. Blocks like North Tibet, Indochina and Sibumasu are all part of South China, and thus Eurasia, before the end of the Triassic (~205 Ma). The Late Triassic accretion of Sibumasu onto Eurasia is associated with the closure of the northern part of the Paleo-Tethys. Amalgamation of the other Cimmerian terranes (see Table 2.3) with Eurasia, and the subsequent closure of the southern Paleo-Tethys, is proposed in Early Cretaceous times only. More to the west, also the Pontides already forms part of Eurasia before the Jurassic. The several blocks of Iran are positioned close to the Eurasian margin, but are not yet accreted to it. Moreover, South Tibet and Afghanistan are still part of the Gondwana margin, as are the Menderes-Taurides and Kirşehir blocks.

Like the reconstruction of ExxonMobil, the other reconstructions discussed here also assume North Tibet, Indochina and South China to be part of Eurasia by the Late Triassic. Only Van der Voo proposes accretion of Indochina and South China, and subsequent closure of the northern Paleo-Tethys, in the Early Jurassic. As for the closure of the southern part of the Paleo-Tethys, the reconstructions of Dercourt, Şengör and Van der Voo agree with ExxonMobil on a closing time after the Triassic. On the contrary, Stampfli and Yang assume a complete Paleo-Tethys closure by the Late Triassic: Stampfli proposes the Iran, Afghanistan, and South Tibet blocks to accrete onto Eurasia simultaneously with the pre-Jurassic collision of Sibumasu. Yang assumes that South Tibet is moving northward with the Neo-Tethys instead of the Paleo-Tethys, so that the Paleo-Tethys is already completely closed with the Sibumasu-Eurasia accretion. In the reconstruction of Stampfli, several back-arc oceans are formed in the western Tethyan region in pre-Jurassic times, e.g. the Meliata, Malic and Pindos Oceans. However, spreading within these basins has already ceased before they start to subduct by the end of the Triassic. The ExxonMobil reconstruction does not explicitly define these oceans, but the rifting Mediterranean fragments are separated by intermediate basins as well.
### Accretion times of Tethyan continental blocks

<table>
<thead>
<tr>
<th>Timespan</th>
<th>Stampfli</th>
<th>Yang</th>
<th>Şengör</th>
<th>Dercourt</th>
<th>Van der Voo</th>
<th>ExxonMobil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Triassic</td>
<td>North Tibet South China &lt;br&gt; ↓ *)&lt;br&gt;Afghanistan South Tibet</td>
<td>North Tibet South China &lt;br&gt;Indochina Indochina</td>
<td>North Tibet South China &lt;br&gt;Indochina Iran</td>
<td>North Tibet South China Indochina Pontides Sibumasu</td>
<td>North Tibet South China &lt;br&gt;Indochina Pontides Sibumasu</td>
<td>North Tibet South China Indochina Iran</td>
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<tr>
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<td>Iran Pontides</td>
<td>Pontides</td>
<td>South China Indochina Sibumasu</td>
<td>Iran</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~150 Late Jurassic</td>
<td>Sibumasu</td>
<td>Iran Afghanistan South Tibet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~100 Early Cretaceous</td>
<td>Sibumasu Afghanistan &lt;br&gt;South Tibet</td>
<td>Afghanistan South Tibet</td>
<td>Sakarya Afghanistan South Tibet</td>
<td></td>
<td></td>
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<tr>
<td>~100 Late Cretaceous</td>
<td>Sakarya Kirşehir &lt;br&gt;South Tibet</td>
<td>Sakarya Kirşehir</td>
<td>Kirşehir east Taurides</td>
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<td></td>
</tr>
<tr>
<td>~50 Early Tertiary</td>
<td>Menderes</td>
<td>Taurides</td>
<td>Taurides west Taurides</td>
<td>Menderes</td>
<td></td>
<td></td>
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Table 2.1: Approximate accretion times of the main tectonic blocks in the Tethyan region, c.q. the moments at which the blocks formed part of Eurasia, as proposed by the different reconstructions discussed in this chapter. Not all blocks are incorporated in all reconstructions. The shown reconstructions are from Stampfli = Stampfli and Borel (2002, 2004), Yang = Yang (1998), Şengör = Şengör and Natal’ in (1996), Dercourt = Dercourt et al. (1993), Van der Voo = Van der Voo (1993), and ExxonMobil = Norton (1999). The Tertiary accretion times of the Arabian and Indian subcontinents are the same in all reconstructions, and are therefore not shown here. See Table 2.3 for comparison of the names of the blocks with the alternatives used in Figure 2.2 and other reconstructions. *) Including Indochina, Pontides, Sibumasu and Iran.
### Opening and closure times of Tethyan oceanic basins

<table>
<thead>
<tr>
<th>Timespan</th>
<th>Stampfli</th>
<th>Yang</th>
<th>Şengör</th>
<th>Dercourt</th>
<th>Van der Voo</th>
<th>ExxonMobil</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Closure</td>
<td>Closure</td>
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<tr>
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<td>Paleo-Tethys</td>
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<td></td>
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</tr>
<tr>
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<td>Spreading</td>
<td>Spreading</td>
<td>Closure</td>
<td>Spreading</td>
<td>Closure</td>
</tr>
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<td>northern</td>
<td>separating</td>
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</tr>
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<td></td>
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<td>Menderes</td>
<td></td>
<td></td>
<td>Kaişehir</td>
</tr>
<tr>
<td>Late Jurassic</td>
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<td>Spreading</td>
<td>Spreading</td>
<td>Closure</td>
<td>Spreading</td>
<td>Spreading</td>
</tr>
<tr>
<td></td>
<td>Vardar Ocean</td>
<td>Vardar Ocean</td>
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<td>southern</td>
<td>separating</td>
<td>Kaişehir</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Menderes</td>
<td></td>
<td></td>
<td>Kaişehir</td>
</tr>
<tr>
<td>~150Early Cretaceous</td>
<td>Spreading</td>
<td>Closure</td>
<td>Closure</td>
<td>Closure</td>
<td>Closure</td>
<td>Closure</td>
</tr>
<tr>
<td></td>
<td>Semail Ocean</td>
<td>southern</td>
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<td>southern</td>
</tr>
<tr>
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<td>Paleo-Tethys</td>
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<td>Paleo-Tethys</td>
</tr>
<tr>
<td>~100 Late Cretaceous</td>
<td>Obduction</td>
<td>Closure</td>
<td>Obduction</td>
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<td>Obduction</td>
<td>Obduction</td>
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<tr>
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<td>Semail Ocean ridge</td>
<td>northern</td>
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<tr>
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<tr>
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**Table 2.2:** Approximate opening and closure times of the oceanic basins in the Tethyan region according to the reconstructions discussed in this chapter. The shown reconstructions are from Stampfli = Stampfli and Borel (2002, 2004), Yang = Yang (1998), Şengör = Şengör and Natal’ in (1996), Dercourt = Dercourt et al. (1993), Van der Voo = Van der Voo (1993), and ExxonMobil = Norton (1999). See Table 2.3 for comparison of the names of the blocks with the alternatives used in Figure 2.2. *) Early Cretaceous separation of Menderes from Gondwana as well.
Table 2.3: Overview of the names of the various fragments as given in Table 2.1/2.2, and the alternatives as used in Figure 2.2 and other reconstructions. The North Tibet, South China, Indochina, and Pontides blocks belong to the Hun Superterrane. This terrane formed, together with the Kazakhstan block, the northern margin of the Paleo-Tethys. Iran, Afghanistan, South Tibet, and Sibumasu are usually referred to as the Cimmerian blocks or Mega-Lhasa terranes. They formed the southern margin of the Paleo-Tethys and northern margin of the Neo-Tethys. 1) With the Pontides, the whole sliver extending from the Aegean Sea to the Lesser Caucasus is addressed, thus including fragments like the southern Caucasus, Alborz and Kopet Dagh. 2) The Sibumasu terrane derives its name from the regions of Siam (Thailand or Shan-Thai block), Burma (Myanmar), Malaysia and Sumatra. 3) San/Sir = Sanandaj-Sirhan.
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**Figure 2.3:** Triassic reconstruction of Stampfli and Borel (2004), see Fig. A.2 in the Appendix for a colour version.

**Early Jurassic (~200-160 Ma)**

After the Late Triassic, seafloor spreading in the Central Atlantic induces the rotation of Gondwana relative to Eurasia. In the reconstruction of ExxonMobil, the Iranian blocks are amalgamated with Eurasia since the Late Triassic - Early Jurassic. Northward subducting oceanic lithosphere of the Neo-Tethys is now accommodated along an arc system south of the Pontides and Iran. More to the east, Afghanistan and South Tibet have rifted from the Gondwana margin. These terranes are drifting towards Eurasia while the oceanic lithosphere of the southern Paleo-Tethys is subducting further northward.

As discussed above, the northern part of the Paleo-Tethys is already closed in the Triassic according to the reconstructions of ExxonMobil, Dercourt and Şengör. In Early Jurassic, the
northern part of the Paleo-Tethys is closed in the reconstruction of Van der Voo as well. Like ExxonMobil, also Dercourt and Şengör propose collision of Iran and Pontides with Eurasia around the Late Triassic to Early Jurassic, indicating that the Neo-Tethys has started to subduct in the western Tethyan region. In these reconstructions, the southern Paleo-Tethys is still subducting in the eastern part of the area. According to Stampfli and Yang, the Paleo-Tethys is already totally closed by this time so that only the Neo-Tethys is subducting northward underneath Eurasia. In the reconstruction of Stampfli, the Vardar Ocean develops as an oceanic back-arc basin, caused by the subduction of the Meliata Ocean underneath the Neo-Tethys. The ocean opens within the Paleo-Tethys suture zone, thereby separating the
Taurides-Menderes-Kireçhisar block from the Pontides again. During the Jurassic, the Vardar Ocean consumes the Meliata and Maliac oceanic basins. In the reconstruction of Şengör, the Vardar Ocean is an Early Jurassic branch of the Neo-Tethys.

**Late Jurassic to Early Cretaceous (~160-100 Ma)**

Spreading in the northern and southern Atlantic commences in the Early Cretaceous, increasing the motion of Africa relative to Eurasia. Furthermore, rifting between India and Gondwana initiates the opening of the Indian Ocean. In the reconstruction of ExxonMobil, Afghanistan and South Tibet collide into Eurasia around 140 Ma. After amalgamation of blocks like South Tibet and Iran, the region is left with only one single, long-stretched subduction zone along which the Neo-Tethys subducts northward underneath Eurasia. From 120
Tethyan evolution according to various reconstructions

**Figure 2.6:** Late Cretaceous reconstruction of Stampfli and Borel (2004), see Fig. A.5 in Appendix for a colour version.

To 90 Ma, continental fragments like Kirşehir and Menderes-Taurides are separated from the Northeast African continent by active spreading.

In agreement with ExxonMobil, also Şengör and Dercourt propose that the Afghanistan and South Tibet blocks (the remaining parts of the Cimmerian terranes) are not yet accreted to Eurasia, and thus the Paleo-Tethys not yet closed, until the Early Cretaceous. Opposed to this, Van der Voo suggests that the Paleo-Tethys is completely closed in the Late Jurassic. As discussed above, ExxonMobil proposes rifting of Kirşehir and Menderes-Taurides around Late Jurassic - Early Cretaceous only, while Stampfli proposes the separation of Menderes-Taurides-Kirşehir already in the Early Jurassic. Also in the Late Jurassic reconstructions of Dercourt and Şengör, these blocks are positioned half-way between Gondwana and Eurasia. Compared to the ExxonMobil reconstruction, Dercourt, Şengör and Stampfli thus propose an
earlier rifting of Menderes-Taurides and Kırşehir. By the end of the Jurassic, the Vardar Ocean of Stampfli has totally replaced the Meliata Ocean, and subduction of the Vardar Ocean itself starts. Also according to Şengör, subduction of the Vardar branch starts around this time. For the Early Cretaceous, Stampfli proposes the development of the Semail and Spontang back-arc oceans, overriding the complete Neo-Tethys, in the Middle East and Indian region, respectively.

**Late Cretaceous (~100-65 Ma)**

In the Late Cretaceous, the Indian continent rifts from Gondwana and moves northward along a major transform fault. South of the continent, the present Indian Ocean of the Indo-Australian plate is formed. In the Mediterranean, separate smaller fragments are moving further northward towards their present-day positions. All major suture zones in Greece and Turkey are thought to have closed in Cretaceous or Early Cenozoic times. In the ExxonMobil reconstruction, the block formed of Kırşehir and the eastern Taurides collides into Eurasia, and the Pontides subduction zone closes accordingly, between 80 and 70 Ma. This zone is known today as the eastern part of the Izmir-Ankara(-Ercinzan) suture. Neo-Tethyan oceanic lithosphere is now subducting along the Izmir-Ankara arc south of Sakarya, and the Taurides arc south of Kırşehir and the eastern Taurides. Between 90 and 70 Ma, the ridge axis separating Arabia and India has an extension northeast of the Arabian platform that obducts onto the Arabian continental margin.

According to Dercourt and Şengör, the oceanic spreading ridge of the Neo-Tethys subducts underneath Eurasia in the Indian region, and obducts onto the Arabian margin in the Middle East, around Late Cretaceous times (~90-80 Ma). In agreement with ExxonMobil, the Kırşehir blocks become attached to Eurasia around the Middle Cretaceous in these reconstructions. On the contrary, Stampfli proposes Neo-Tethyan ridge subduction in the western part of the region around 140 Ma being the trigger for the opening of the Semail Ocean (see above). Around 90-80 Ma, the Semail Ocean in this reconstruction has totally consumed the Neo-Tethys, and starts to subduct itself. The reconstruction of Stampfli suggests that most ‘Neo-Tethys’ ophiolites do not originate from the Neo-Tethys itself, but from its back-arc basins. In the Stampfli and Şengör reconstructions, spreading in the Vardar Ocean ceases by the Middle Cretaceous, and the basin itself subducts during the Late Cretaceous.

**Tertiary (~65-0 Ma)**

The Cenozoic evolution of the Tethyan region is relatively well defined, and the several reconstructions only show minor differences for this timespan. In the Tertiary, the Menderes-Taurides and other Eastern Mediterranean blocks finally accrete onto Eurasia. In the Exxon-Mobil reconstruction, the Menderes-Taurides block collides with Eurasia around 48 Ma. Convergence between Africa and Eurasia is now accommodated along the Hellenic arc, and northward subduction of the last remnants of the Neo-Tethys starts around the Miocene when Cyprus accretes to Eurasia (~13 Ma). Extension within the Aegean region since ~10 Ma is associated with outward migration of the Hellenic arc.
Tethyan evolution according to various reconstructions

The most recent Tertiary developments in the Middle East include the separation of Arabia from the African continent through the spreading in the Red Sea and Gulf of Aden since 30 Ma. Collision of the Arabian continent with Eurasia, and the formation of the Makran accretionary zone, occurs around 22 Ma. This results in further deformation of the fragments at the southern margin of Eurasia. The Iran subduction zone is closed, and is recognised as the Bitlis-Zagros suture zone today. The last remnants of the Neo-Tethys (or Semail Ocean) are now subducting along the southern margin of Makran only.

In the eastern part of the Tethyan region, the evolution is dominated by the first indentation of Greater India into Eurasia around 48 Ma. Although in continental collision, northward convergence between India and Eurasia continues. Due to the collision, the Iranian blocks start an anti-clockwise rotation towards their present-day position. Furthermore, the collision of India causes deformation of Afghanistan, South Tibet, and older continental blocks on the Eurasian margin.

In the Indonesian region, Indo-Australian oceanic lithosphere is actively subducting underneath the Indonesian archipelago. An accretionary sliver forms in the western Andaman, and Borneo rotates anti-clockwise, between 48 and 15 Ma. Around 10 Ma, the Andaman Sea opens due to the oblique plate convergence along the trench system. More to the east, the first continental fragments of the Australian plate arrive at the Eurasian Sunda Block in the Sulawesi and Banda arc region around 20 Ma. The Tertiary evolution of the Indonesian region will be discussed in more detail in Chapter 6 on the basis of the regional reconstructions of Rangin et al. (1990a,b) and Lee and Lawver (1995).
Figure 2.7: Six stages in the evolution of the Tethyan region according to the plate tectonic reconstruction of ExxonMobil (Norton, 1999) with the Eurasian plate held fixed to its present-day position. Some of the fragments discussed in this section are marked for reference: IB = Iranian blocks, AT = Afghanistan/South Tibet, Ar. = Arabian continent, and In. = Indian continent (see Figs. 2.2 and 2.8 for more details on the smaller blocks). The Southeast Asian blocks are not separately shown here because their accretion times predate the timespan of our interest. Also indicated are the Paleo-Tethys (PT), Neo-Tethys (NT), and Semail (Sm) oceanic basins. From upperleft to lowerright we can see at 220 Ma: Closure northern Paleo-Tethys (= Accretion Iranian blocks), 180 Ma: Northward drift Afghanistan and South Tibet, 140 Ma: Closure southern Paleo-Tethys (= Accretion Afghanistan/South Tibet), 110 Ma: Northward drift Kırşehir and Taurides-Menderes, 80 Ma: Spreading and obduction Semail Ocean, and 50 Ma: Closure Neo-Tethys (= Accretion Kırşehir and Taurides-Menderes). Each map is plotted in a Mercator projection with the great circle starting at (0°N,65°E) with azimuth 90° as an equator. The shown box is the approximate area plotted in Figure 2.8.
Figure 2.8: Six stages in the evolution of the Eastern Mediterranean and Middle East according to ExxonMobil (Norton, 1999). In this figure: [1] = Pontides/Farah, [2] = Iranian blocks, [3] = Kırşehir/east-Taurides, and [4] = Menderes/west-Taurides (see Fig. 2.2 for further details). Also indicated are the Paleo-Tethys (PT), Neo-Tethys (NT), and Semail (Sm) oceanic basins. From upperleft to lowerright we can see at 220 + 180 Ma: Accretion Iranian blocks (= Closure northern Paleo-Tethys), 140 Ma: Rifting Kırşehir and east-Taurides, 110 Ma: Rifting Menderes and west-Taurides, 80 Ma: Accretion Kırşehir and east-Taurides, and 50 Ma: Accretion Menderes and west-Taurides (= Closure Neo-Tethys). The Pontides and Farah blocks already accreted onto the Eurasian margin prior to 200 Ma. Each map is plotted in a Mercator projection with the great circle starting at (35°N,35°E) with azimuth 90° as an equator.
Section 2.3

2.3 Evolutionary aspects of main importance for this thesis

The Mesozoic-Cenozoic closure of the Tethys Ocean has been dominated by the movements of the African-Arabian and Indo-Australian plates relative to Eurasia. The characteristics of the various regions within the Tethyan area show some remarkable differences: In the *Eastern Mediterranean*, several microcontinents amalgamated with Eurasia during Cenozoic times, thereby closing the intermediate oceanic basins. If active spreading within these basins has occurred while they were already subducting, this will have increased the amount of subduction in the region. The Cimmerian blocks in the *Middle East* accreted to Eurasia largely by Early Jurassic times already. During the Cenozoic, the western part of the area might have been affected by the accretion of the Eastern Mediterranean microcontinents, but the larger part of the region is only influenced by the Arabian continental collision with Eurasia. The *Himalayan area* is, of course, highly influenced by the Cenozoic indentation of India into Eurasia. Furthermore, accretion of the fragments north of India (Afghanistan, South Tibet) already occurred in Early Cretaceous, and no intermediate oceanic basins are proposed for this area since that time. If additional spreading occurred in the Neo-Tethys or its back-arc basins, this will have affected the amount of subduction.

In this thesis, we will investigate whether the different characters of the regions are reflected in the volume, location and geometry of the subducted material. Below, we will give an overview of those aspects of the tectonic evolution that will be of importance for our analysis of the Tethyan region, and the comparison between the different reconstructions. As they will be discussed in more detail in Chapter 4 and 5, we also indicate the sections in which each particular aspect is primarily addressed. Because the reconstructions of Van der Voo and Yang comprise more general descriptions of the Tethyan evolution (see p. 15), only the reconstructions of Dercourt, Şengör, ExxonMobil, and Stampfl will be discussed in the following.

**The motion along the Owen Fracture Zone (4.4)** The Owen Fracture Zone in the Middle East is associated with the strike-slip motion of the Indo-Australian plate relative to the Africa-Arabian plate during the Cenozoic. Only in the plate model of Dercourt, Neo-Tethyan lithosphere north of India is proposed to have been subducted westward along the plate boundary as well. The large-scale motion of India can be expected to have influenced the process of subduction and thus the resulting geometry of the subducted material.

**The subduction of the Paleo-Tethys (5.5)** The northern Paleo-Tethys closed around Late Triassic according to all reconstructions, and we therefore expect no active spreading within the Paleo-Tethys since that time. Most reconstructions propose the Paleo-Tethyan oceanic lithosphere has been subducted northward underneath Eurasia. However, a more eastward subduction of the Paleo-Tethys has been proposed by Stampfl, and southward subduction underneath the Cimmerian blocks by Şengör. For a large oceanic basin like the Paleo-Tethys, the ancient direction of subduction will have had a large effect on the present-day location of the subducted oceanic lithosphere.
The effect of continental collision (5.5/5.7) We expect that we can see the effect of the Cenozoic collisions of the Arabian and Indian continents with Eurasia in the geometry and position of the subducted material. Although the Afghanistan and South Tibet blocks are much smaller than the Arabian and Indian continents, their collisions - associated with the closure of the Paleo-Tethys - may have affected the slab morphology and its present position in the mantle as well.

Neo-Tethyan ridge spreading and subduction (5.6) Spreading within the Neo-Tethys has been active after the rifting of the Iranian blocks from Gondwana. The eventual subduction of the Neo-Tethyan spreading ridge is proposed by ExxonMobil, Şengör, and Dercourt in the Late Cretaceous (~90-80 Ma), but already in Early Cretaceous (~140-120 Ma) by Stampfli. Evidently, we expect no active spreading within the Neo-Tethys after ridge subduction. Moreover, it is likely that the morphology of the subducted material will have been affected by ridge subduction, although later processes may have overprinted these effects.

The role of the back-arc oceanic basins (5.6) In the reconstruction of Stampfli, the Semail Ocean in the Middle East, and the Spongtagt Ocean in the Indian region, came into existence right after the Neo-Tethyan ridge subducted in Early Cretaceous. Spreading within these back-arc oceans occurred at the direct expense of the Neo-Tethys, and the Semail/Spongtagt oceanic ridges obducted onto the Gondwana margin by the end of the Cretaceous. Although the existence of these back-arc basins will have led to additional subduction in the region, the absence of Neo-Tethyan lithospheric spreading will probably have neutralised this amount. Because the Neo-Tethys is proposed to have been subducted northeastwardly underneath the Semail Ocean, the locations and geometries of subducted material may give an indication of the Semail vs. Neo-Tethyan spreading and subduction history.

Additional convergence by drifting Mediterranean fragments (5.8) In the western part of the region, separate rifting of continental fragments has been proposed in addition to the large-scale Africa vs. Eurasia motion (ExxonMobil, Şengör, Dercourt). On the contrary, Stampfli assumes that rifting and spreading of the oceanic basins between these fragments already took place before the Jurassic, and instead proposes the Cretaceous opening of a Vardar back-arc ocean. Because Stampfli assumes no Neo-Tethyan oceanic spreading where the Vardar Ocean is active, we expect the differences between Vardar vs. Neo-Tethyan spreading to be relatively small. Apart from the additional amount of convergence, we expect that subduction of intermediate basins along different trench systems will have led to a different distribution of subducted material than subduction of one single (Neo-Tethyan) oceanic basin. Also, the Cretaceous subduction of a single oceanic basin with the size of the Vardar Ocean may be visible as a separate identity today.