

Chapter 1



Introduction and tectonic framework

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Abstract: The extraordinary outcrop conditions provide a unique opportunity to study the geology and tectonics of the Oman Mountains, which record a geological history of more than 800 million years. We provide a summary of the geological evolution of the Oman Mountains with the emphasis on the Jabal Akhdar and Saih Hatat domes. This Memoir comprises seven chapters. This first chapter summarizes the former studies and the tectonic framework. This is followed by a comprehensive description of all geological formations/rock units (Scharf *et al.* 2021a, Chapter 2, this Memoir) including the famous Semail Ophiolite, the fault and fold pattern (Scharf *et al.* 2021b, Chapter 3, this Memoir) and the overall structure (Scharf *et al.* 2021c, Chapter 4, this Memoir). Chapter 5 (Scharf *et al.* 2021d) explains the varied tectonic evolution of the study area, ranging from the Neoproterozoic until present, while Chapter 6 (Scharf *et al.* 2021e) contains the conclusions and a catalogue of open questions. Finally, Chapter 7 (Scharf *et al.* 2021f) provides two over-sized geological maps (1 : 250 000 version available online) and a correlation chart, providing an overview of the geological units/formations. This volume is of interest for all geoscientists, geoscience students and professionals studying the Oman Mountains on the surface as well as in the subsurface because it represents a comprehensive and detailed reference.

The Oman Mountains at the northeastern margin of the Arabian Plate display an impressive geological record in terms of phenomenological diversity and significance since the Precambrian. This record includes (1) the ‘Snowball Earth’ glaciation (e.g. Leather *et al.* 2002; Kilner *et al.* 2005), (2) the Ediacaran ‘Shuram Excursion’ (e.g. Burns and Matter 1993; Le Guerroué *et al.* 2006a, b), (3) the enigmatic Hercynian Unconformity (‘Hercynian Orogeny’; e.g. Glennie *et al.* 1974; Beurrier *et al.* 1986b; Rabu *et al.* 1986; Faqira *et al.* 2009), (4) the Permo-Carboniferous glaciation (e.g. Heward and Penney 2014), (5) the Pangaea rifting and spreading of the Neo-Tethys Ocean during the Late Paleozoic (e.g. Blendinger *et al.* 1990; Béchenec *et al.* 1991), (6) the iconic obduction of the Semail Ophiolite (e.g. Glennie *et al.* 1974; Searle and Malpas 1980; Lippard *et al.* 1986; Goffé *et al.* 1988; Hacker and Mosenfelder 1996; Hacker *et al.* 1996; Cowan *et al.* 2014; Rioux *et al.* 2012, 2013, 2016), (7) high-pressure/low-temperature metamorphism of the continental margin (e.g. Lippard 1983; Le Métour *et al.* 1986b; Goffé *et al.* 1988; El-Shazly *et al.* 1990; Warren *et al.* 2003, 2005), (8) formation and exhumation of the large Jabal Akhdar Dome (JAD) and Saih Hatat Dome (SHD) which shape the Oman Mountains (e.g. Poupeau *et al.* 1998; Saddiqi *et al.* 2006; Hansman *et al.* 2017; Grobe *et al.* 2019), (9) Upper Cretaceous rudist limestones (e.g. Skelton *et al.* 1990; Wyns *et al.* 1992; Philip *et al.* 1995) and organic-rich intrashelf basin environments (e.g. van Buchem *et al.* 2002), (10) surface analogues of subsurface petroleum source and reservoirs rocks (Grantham *et al.* 1988; Koehrer *et al.* 2011; Pöppelreiter *et al.* 2011; Bendias *et al.* 2013; Heward and Penney 2014; Grobe *et al.* 2016), (11) Neogene to active tectonics (e.g. Fournier *et al.* 2006; Mattern *et al.* 2018; Moraetis *et al.* 2018) and (12) a palaeoclimate record for the past 325 ka based on speleothems from cave systems developed in Mesozoic carbonate formations (e.g. Burns *et al.* 1998, 2001). The Semail Ophiolite, as the world’s largest and best preserved ophiolite (e.g.

Searle and Cox 1999), and the Oman Mountains, as the unique case of an obduction orogen, have been the focus of much research interest from the international geoscientific community during the past decades (e.g. Nicolas *et al.* 1996, 2000).

Due to the massive improvement of Oman’s road system during the last few decades and the excellent outcrops, the country became a field laboratory for tectonometamorphic, sedimentological and stratigraphic studies (e.g. Glennie *et al.* 1973, 1974; Robertson *et al.* 1990; Hacker *et al.* 1996; Saddiqi *et al.* 2006; Rollinson *et al.* 2014) with a research focus on ophiolites and ophiolite obduction (e.g. Lippard *et al.* 1986; Nicolas *et al.* 1996; Gregory *et al.* 1998; Searle and Cox 1999, 2002). We compiled these and many other studies to put forward an overview of the geology, tectonostratigraphy and tectonic evolution of the Oman Mountains, as well as a description of their large-scale structures. We concentrate on the eastern part of the Oman Mountains from the western tip of the JAD to the eastern end of the SHD (fig. A.1 (Scharf *et al.* 2021f, Chapter 7, this Memoir)). To assist the international research community, we provide a newly compiled geological map of the eastern part of the Oman Mountains with the JAD and SHD in order to standardize the compiled tectonic units within a single map. This map is largely based on the geological maps of Oman at the scale of 1:250 000 (Béchenec *et al.* 1992a, b; Le Métour *et al.* 1992; Wyns *et al.* 1992). The map is accompanied by text which is an update on the geological knowledge of the Oman Mountains with some emphasis on the region’s geodynamic history. Moreover, we provide a detailed topographic map and several simplified geological cross-sections, as well as an extensive tectonostratigraphic chart (fig. A.2 (Scharf *et al.* 2021f, Chapter 7, this Memoir)).

The JAD consists of autochthonous rocks and is divided into the WNW-striking main dome (c. 85 km × 35 km) and NNE-oriented subdome attached to the NE of the main dome (25 km × 10 km; fig. A.1 (Scharf *et al.* 2021a,

Chapter 2, this Memoir)). This NNE-oriented subdome is parallel to the Semail Gap and is known as the Nakhl Subdome (fig. A.1 in [Scharf *et al.* 2021f](#), Chapter 7, this Memoir). In the NE, the Nakhl Subdome sharply bends towards the ESE and extends for *c.* 8 km until Fanja. The overall shape of the JAD is not circular, as expected for a tectonic dome, and may be attributed to the reactivation of faults within the subsurface during doming (see ‘Post-obduction deformation’ in Chapter 5 ([Scharf *et al.* 2021d](#))).

The SHD has an overall elongated shape and is aligned NW–SE from Fanja for *c.* 95 km towards the SE. The NE–SW extent ranges between 25 and 50 km. We define the SHD as the area consisting of (par-)autochthonous rocks that are surrounded by the Hawasina nappes and/or Semail Ophiolite to the NW and SW, as well as the ocean to the NE. Its southeastern margin is blanketed by Cenozoic shallow-marine sedimentary rocks near Tiwi (fig. A.1). The southeastern border or margin of the SHD is therefore not well defined. Between both domes near Fanja, a WNW–ESE-oriented structural and topographic depression is exposed (‘Fanjah Saddle’ of [Coffield 1990](#)). The autochthonous rocks west and east of the saddle rise 1.3 km above the saddle surface, which consists of allochthonous rocks. The fold axes of the JAD and SHD plunge below the 10-km-wide Fanjah Saddle at an angle of 20–40° ([Coffield 1990](#)). Roughly N–S-striking high-angle normal faults with dip directions towards the centre of the saddle cut the flanks of the JAD and SHD ([Coffield 1990](#)).

[Lees \(1928\)](#) introduced the Semail Nappe and recognized the allochthonous nature of the Hawasina nappes (see [Heward 2016](#) for a summary of the pioneering expedition of Lees and others during the 1920s). The first descriptions of the Semail Ophiolite after the introduction of plate-tectonic theory were by [Reinhardt \(1969\)](#) and [Allemann and Peters \(1972\)](#).

The entire Oman Mountains were first mapped at a scale of 1:500 000 by [Glennie *et al.* \(1974\)](#). They introduced the main rock units of the Oman Mountains, the pre-Permian metasedimentary successions, the Arabian Platform sediments, the Hawasina nappes, the Semail Ophiolite and the post-obduction sedimentary rocks. Further mapping was carried out by the United States Geological Survey (USGS) in the vicinity of the SHD ([Bailey 1981](#)). Geologists of the Open University (UK) mapped the Semail Ophiolite ([Lippard *et al.* 1986](#)). French workers of the Bureau de Recherches Géologiques et Minières (BRGM) mapped the Central and Southeastern Oman Mountains at a scale of 1:100 000 ([Béchenec *et al.* 1986a, b](#); [Beurrier *et al.* 1986a, b](#); [de Gramont *et al.* 1986](#); [Hutin *et al.* 1986](#); [Janjou *et al.* 1986](#); [Le Métour *et al.* 1986a, b](#); [Rabu *et al.* 1986](#); [Villey *et al.* 1986a, b, c](#); [Roger *et al.* 1991](#); [Wyns *et al.* 1992](#)). This map series was extended by the sheet of Ibra (Southeastern Oman Mountains) at a scale of 1:100 000 ([Peters *et al.* 2005](#)). Detailed mapping of the entire Semail Ophiolite was carried out and summarized by [Nicolas *et al.* \(2000\)](#). Eight geological maps of the Muscat-Seeb area have been published at a scale of 1:25 000 ([Kajima and Ishii 2012](#); [Kajima and Otake 2012](#); [Kajima *et al.* 2012a, b, c, d, e, f](#)).

Two important compilations of the subsurface stratigraphy and nomenclature were produced by [Hughes Clarke \(1988\)](#) and [Forbes *et al.* \(2010\)](#). The latter provided a comprehensive chart showing the subsurface stratigraphy of Oman ([Forbes *et al.* 2010](#), their enclosure 1). Two Special Publications of the Geological Society of London ([Robertson *et al.* 1990](#); [Rollinson *et al.* 2014](#)) represent significant advancements to the understanding of the geology and tectonics of the Oman Mountains. A summary booklet describing the geology and origin of the Oman Mountains was published by [Glennie \(1995\)](#). His work was the first step in understanding the geology of northern Oman for geologists, non-geologist scientists

and engineers from the oil industry. This booklet became so famous and in such demand that a second edition was released ([Glennie 2005](#)). [Searle \(2007\)](#) wrote a review article about the Permo-Mesozoic evolution of the eastern Arabian Platform and margin with the adjacent Hawasina Basin. This work also targets the obduction of the Semail Ophiolite as well as the post-obduction evolution of parts of the Oman Mountains.

Many informative popular science and geoguide books, including the most recent and well-illustrated work of [Al-Kindi \(2018\)](#) and [Searle \(2019\)](#), have been published during the past decades, outlining the unique and spectacular geology of the Sultanate. With its description of numerous fascinating outcrops, the geological field guide of [Hoffmann *et al.* \(2016\)](#) could be used as a companion document to this book.

The formations at the surface in our study area may have different names to coeval deposits in the subsurface. The latter are commonly used by researchers in the oil industry (e.g. [Hughes Clarke 1988](#); [Sharland *et al.* 2004](#); [Forbes *et al.* 2010](#)). We use the surface names in our manuscript, but will also provide the subsurface names for clarity (Chapter 2 and fig. A.2 ([Scharf *et al.* 2021a,f](#), Chapter 2 and 7, this Memoir)).

We first describe in detail all major geological formations and tectonic units ([Scharf *et al.* 2021a](#), Chapter 2, this Memoir), provide the regional fault and fold pattern ([Scharf *et al.* 2021b](#), Chapter 3, this Memoir) and characterize the large-scale structure of the study area ([Scharf *et al.* 2021c](#), Chapter 4, this Memoir). This is followed by a comprehensive description of the entire tectonic evolution of the Oman Mountains from the Neoproterozoic until present ([Scharf *et al.* 2021d](#), Chapter 5, this Memoir). This chapter includes a lithospheric scale series of cross-sections, depicting the kinematics and dynamics of the different deformation events with a tectono-metamorphic synthesis. The conclusions and a catalogue of open questions, based on the available literature complete this memoir ([Scharf *et al.* 2021e](#), Chapter 6, this Memoir). A compiled geological map at a scale of 1:250 000 and a tectonostratigraphic chart are enclosed in the appendix, providing a handy comprehensive overview (fig. A.1 and fig. A.2 ([Scharf *et al.* 2021f](#), Chapter 7, this Memoir)). Note that in the literature the transcription of proper Arabic names into English commonly results in different spellings of the same feature; for example, the vowels in the name ‘Semail’ as in ‘Semail Ophiolite’ may be transcribed as ‘Samail’ or ‘Sumail’.

Tectonic framework

The eastern part of the Arabian Peninsula (Fig. 1.1) was the site of several tectonic events. Recently, [Callegari *et al.* \(2020\)](#) documented the first evidence of the Cadomian Orogeny in northern Oman. This event is documented by tight to isoclinal folds with an amplitude of a few to tens of metres in the Hajir Formation of the JAD. The shortening direction during this event was NE–SW-aligned (in present coordinates). The age of deformation was at some time after deposition of the Fara Formation and before the Angudan event, that is, between *c.* 540 and 525 ± 5 Ma ([Callegari *et al.* 2020](#); section ‘F1 folds’ in [Scharf *et al.* 2021b](#), Chapter 3, this Memoir). The Cadomian Orogeny was followed (and probably overlapped) by the Neoproterozoic–Early Cambrian East African Orogeny (*sensu* [Stern 1994](#)), resulting in the Angudan Unconformity that coincides with the final stage of the East African Orogeny (*c.* 550–510 Ma; [Loosveld *et al.* 1996](#); [Al-Husseini 2000](#); [Immerz *et al.* 2000](#); [Koopman *et al.* 2007](#); [Forbes *et al.* 2010](#); [Al-Kindi and Richard 2014](#); [Droste 2014](#), fig. 6a). This orogeny is associated with the continent–continent collision of East and West Gondwana. Some authors use the

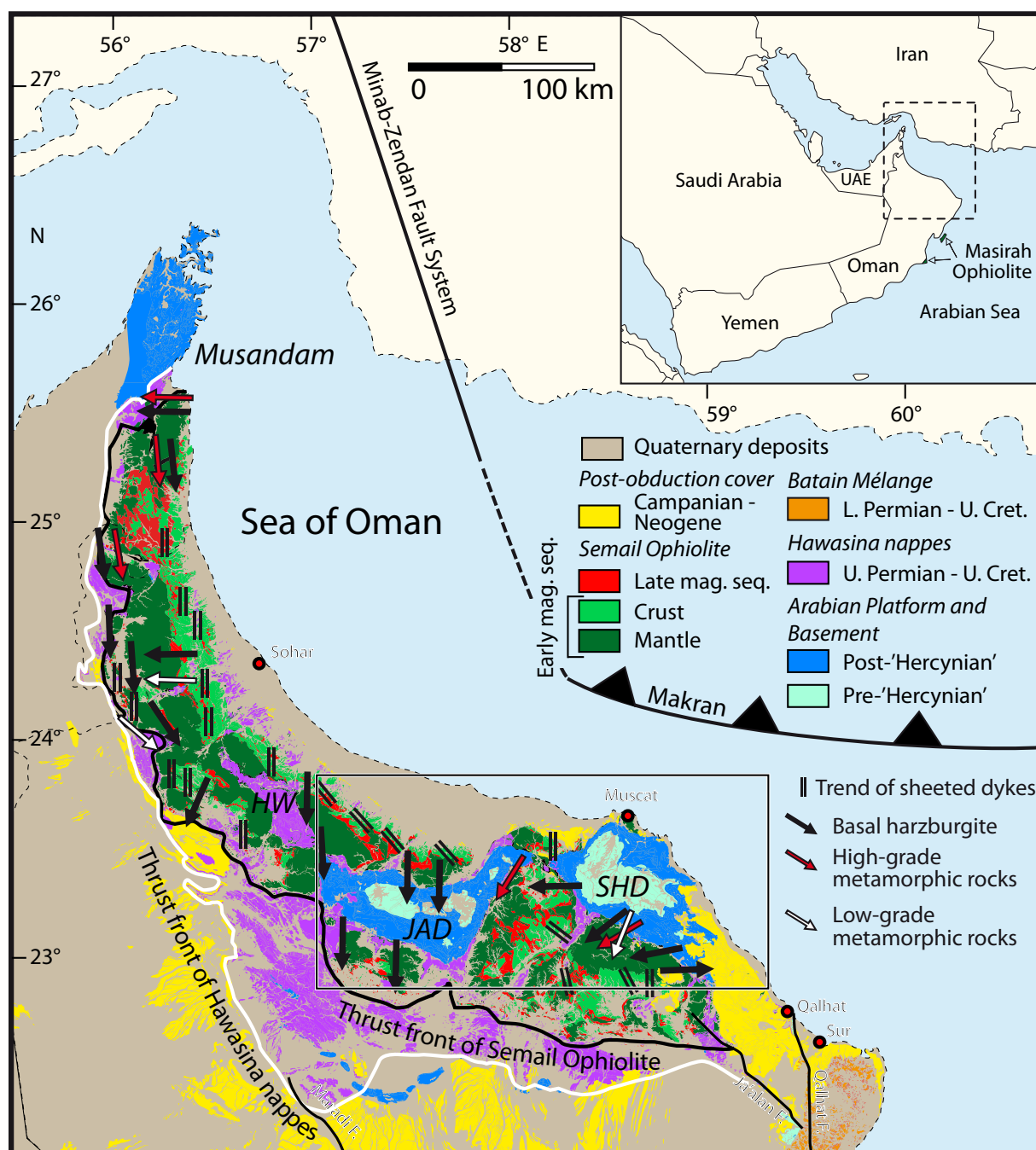


Fig. 1.1. Tectonic overview map of the northeastern Arabian Peninsula. Because of the scale, the metamorphic sole (black) below the ophiolite is only visible in certain areas. All arrows indicate the movement direction of the Semail Ophiolite during the Cenomanian–Maastrichtian. HW, Hawasina Window; JAD, Jabal Akhdar Dome; SHD, Saih Hatat Dome. Map modified after the Geological Map of Oman, 1:1 000 000, Ministry of Petroleum and Minerals (Béchenec *et al.* 1993). Batain Mélange after Shackleton *et al.* (1990), Schreurs and Immenhauser (1999) and Immenhauser *et al.* (2000). Orientation of sheeted dykes and movement direction of the Semail Ophiolite is after Hacker *et al.* (1996). The Makran– and Minab–Zendan thrusts are from Regard *et al.* (2005). The Ja’alan and Qalhat faults are drawn after Fournier *et al.* (2006) and the Maradi Fault is drawn after Filbrandt *et al.* (2006). Parts of the northern Oman Mountains are drawn after the geological map from the United Arab Emirates (UAE) (British Geological Survey 2006). The box outlines the main figure A.1 (Scharf *et al.* 2021f, Chapter 7, this Memoir). Inset shows the greater study realm and the occurrence of the Masirah Ophiolite.

term ‘Malagasy Orogeny’ in Arabia as a synonym for the latest part of the East African Orogeny (e.g. Collins and Pisarevsky 2005). We use the phrase ‘East African Orogeny’. We also use the name ‘Angudan Unconformity’ throughout the text.

The Hercynian Orogeny in Europe was caused by the convergence of Gondwana and Laurasia. The ‘Hercynian Orogeny’ in the northwestern Arabian Plate is manifested in the regional pre-Carboniferous uplift and erosion as well as arch formation (see Faqira *et al.* 2009). Additionally, Abbo *et al.* (2018) concluded that the ‘Hercynian’ event in the Arabian Plate was not a significant deformation event, but rather a

thermal event. The same authors suggested that the large-scale Paleozoic arches and basins across NE Africa and Arabia formed due to a mantle disturbance. Terminologically, we are following Faqira *et al.* (2009) and use the term ‘Hercynian’ (in quotes), but we are not suggesting that the Hercynian Orogeny (*sensu lato*) and related deformation and/or folding took place in Oman; rather, it seems to have been a thermal event (Abbo *et al.* 2018). In the subsurface of Oman, a significant truncation of Lower Paleozoic strata below the mid-Carboniferous exists. This truncation is related to salt movements and reactivation of basement trends (Droste 1997,

fig. 3; Konert *et al.* 2001; Svendsen 2004). The ‘Hercynian’ event in Oman is only evidenced by ‘Hercynian’ K/Ar crystallization ages in pre-Permian formations of the SHD at 327 ± 16 Ma (Glennie *et al.* 1974) and of the JAD at 329 ± 11 and 321 ± 10 Ma of chlorite samples from the Mu’aydin Formation. (Beurrier *et al.* 1986b). Moreover, pre-‘Hercynian’ rocks commonly display NE-trending fold axes in the JAD (Mann and Hanna 1990). The NE-trending folds are unconformably overlain by sedimentary rocks of the Haima Super-group in the subsurface south of the Oman Mountains. The deformation is therefore Early Cambrian in age and not related to an ‘Hercynian’ event (Droste, H. 2018, pers. comm.). A pre-Amdeh age for the folding and thrusting in the Huqf area has been suggested by Le Métour *et al.* (1995). There is a major erosional gap with an angular unconformity between the pre-Permian rocks and the Permian Saiq Formation in the JAD and SHD (Le Métour *et al.* 1986b; Villey *et al.* 1986c). The age of the youngest rocks below the unconformity of the JAD and SHD is *c.* 540 Ma (Fara Formation) and *c.* 460 Ma (Amdeh Formation), respectively. These two aspects have been linked to the ‘Hercynian’ movements in the JAD area (Beurrier *et al.* 1986b, fig. 14; Rabu *et al.* 1986, fig. 16). Furthermore, block faulting has been attributed to the ‘Hercynian’ movements by Beurrier *et al.* (1986b), Le Métour *et al.* (1986b), Rabu *et al.* (1986) and Villey *et al.* (1986c). The trend of the aforementioned fold axes is in line with the trend of ‘Hercynian’ arches (Faqira *et al.* 2009, fig. 2). The ‘Hercynian Unconformity’ is also known as the ‘pre-Permian unconformity’ (e.g. Chauvet *et al.* 2009), the ‘mid-Carboniferous tectonic event’ (Al-Husseini 2004) and the ‘Pre-Unayzah unconformity’ in Saudi Arabia (Al-Husseini 2004; Fig. 1.1).

The ‘Hercynian’ event was followed by the break-up of Gondwana between Arabia and the Cimmerian continental blocks as well as between Arabian and India (e.g. Blendinger *et al.* 1990; Robertson and Searle 1990; Stampfli and Borel 2002; Chauvet *et al.* 2009; D4 in fig. A.2; fig. 5.18c). The timing of continental rifting is Late Carboniferous–Permian (see section on ‘Pangaea rifting and formation of the Neo-tethys Ocean and Hawasina Basin’ in Chapter 5 (Scharf *et al.* 2021d)). The break-up of Gondwana resulted in the formation of the Batain Basin SE of Oman and the Hawasina Basin NE of Oman during the Early and mid-Permian, respectively (e.g. Béchenneq *et al.* 1992a, b; Immenhauser *et al.* 2000; see also sections on ‘Hawasina nappes’ in Chapter 2 (Scharf *et al.* 2021a) and ‘Pangaea rifting and formation of the Neo-Tethys Ocean and Hawasina Basin’ in Chapter 5 (Scharf *et al.* 2021d)). Divergence between Arabia and the Cimmerian continental blocks continued to form the Neo-Tethys Ocean, while extension between Arabia and India aborted. Mostly deep-sea sediments with some limestone were deposited in the Hawasina Basin from the mid-Permian to the Late Cretaceous (e.g. Glennie *et al.* 1974). These rocks were thrust onto the Arabian margin and platform and were themselves overthrust by the Semail Ophiolite during the Late Cretaceous (e.g. Glennie *et al.* 1974; section ‘Intraoceanic thrusting, formation and obduction of the Semail Ophiolite’ in Chapter 5 of this Memoir (Scharf *et al.* 2021d)).

Large-scale obduction of the prototypical Semail Ophiolite onto the Arabian passive margin during the Late Cretaceous, and the ophiolite sequence itself, have been well researched (e.g. Allemann and Peters 1972; Glennie *et al.* 1974; Searle and Malpas 1980; Coleman and Hopson 1981; Hacker *et al.* 1996; Searle and Cox 1999, 2002; Searle *et al.* 2004; Rioux *et al.* 2016; Soret *et al.* 2017; Guilmette *et al.* 2018). The recent analysis of Guilmette *et al.* (2018) advocates that initial intra-oceanic subduction was induced at *c.* 104 Ma. At *c.* 96 Ma the subduction zone matured and a self-sustained subduction started with a supra-subduction zone spreading centre (e.g. Rioux *et al.* 2016). The newly formed oceanic lithosphere

was coevally thrust (obducted) onto Arabian lithosphere. Thrusting lasted until *c.* 68 Ma (Lippard 1983; Goffé *et al.* 1988; Hacker *et al.* 1996; Searle and Cox 1999; El-Shazly *et al.* 2001; Warren *et al.* 2003, 2005; Rioux *et al.* 2016; section ‘Intraoceanic thrusting, formation and obduction of the Semail Ophiolite’ in Chapter 5 of this Memoir (Scharf *et al.* 2021d)). More than 400–450 km of obduction are considered for the extended part of the Arabian Crust (Cooper 1988; Searle 2007) and another 150 km for the Arabian Platform of more regular thickness as quantified by map analysis. The entire thrust range therefore amounts to > 550–600 km. Thrusting of the ophiolite ensued to the SW (Hacker *et al.* 1996). Today, the ophiolite covers an area of > 10 000 km² and is *c.* 550 km long and *c.* 150 km wide (Searle and Cox 1999). The ophiolite measures several kilometres in thickness, which decreases towards the south (Al-Lazki *et al.* 2002; Aldega *et al.* 2017; Carminati *et al.* 2019). According to Reinhardt (1969), Glennie *et al.* (1974), Coleman (1981), Lippard *et al.* (1986), Nicolas (1989) and Searle and Cox (1999), the Semail Ophiolite is composed of *c.* 8–12 km of upper mantle peridotites (mainly harzburgite) and *c.* 2.5–8 km of oceanic crustal rocks; according to Rabu *et al.* (1986) and Villey *et al.* (1986b, c), the entire ophiolite thickness measures 8–9 km. Hacker and Mosenfelder (1996) provided an inferred pre-emplacement thickness of the Semail Ophiolite of 15–20 km.

Obduction is linked to plate convergence between Arabia and Eurasia and the closure of the intervening oceanic lithosphere (Dercourt *et al.* 1993; Stampfli and Borel 2002; Stampfli and Kozur 2006). Convergence was not only expressed by the obduction of the Semail Ophiolite. While the mantle and crust of the future Semail Ophiolite still formed in a supra-subduction zone spreading centre, the northeastern part of the Arabian passive margin was subducted to the NE beneath the future ophiolite (e.g. Lippard *et al.* 1986; El-Shazly and Coleman 1990; Searle *et al.* 1994; Searle and Cox 1999; Searle *et al.* 2004; Saddiqi *et al.* 2006; Rioux *et al.* 2012, 2013, 2016; Cowan *et al.* 2014; for more details on the direction of obduction and rotation during thrusting see van Hinsbergen *et al.* 2019 and section on ‘Intraoceanic thrusting, formation and obduction of the Semail Ophiolite’ in Chapter 5 of this Memoir (Scharf *et al.* 2021d)). Eventually, the subducted plate segment was metamorphosed under high-pressure/low-temperature conditions (e.g. Lippard 1983; Le Métour *et al.* 1986b; Goffé *et al.* 1988; El-Shazly *et al.* 1990; Searle *et al.* 1994, 2004; Warren *et al.* 2003, 2005), and the Semail Ophiolite was thrust on the Arabian Plate (e.g. Searle *et al.* 2004). A slab break-off may have triggered rapid exhumation of the Arabian crustal slab with its blueschist and eclogite facies, exposed in the northeastern SHD (e.g. Searle *et al.* 2004).

A second ophiolite obduction affected the southeastern part of the Oman Mountains. The Masirah Ophiolite (or ‘Eastern Ophiolite Belt’ of Gnos *et al.* 1997; Immenhauser *et al.* 1998) is a fragment of oceanic lithosphere thrust onto the easternmost margin of Oman (e.g. Moseley and Abbotts 1979; Mountain and Prell 1990; Ries and Shackleton 1990; Shackleton and Ries 1990; Marquer *et al.* 1995; Schreurs and Immenhauser 1999; Immenhauser *et al.* 2000; Fig. 1.1). The sole of the ophiolite is not exposed, which makes it difficult to tectonically interpret its history of thrusting, emplacement and uplift. The Masirah Ophiolite derived from oceanic lithosphere of the ‘Somalia-Mozambique-Madagascar (SoMoMa) Ocean’ with a formation age of latest Jurassic to earliest Cretaceous (e.g. Smewing *et al.* 1991; Immenhauser 1995; Peters *et al.* 1995; Gnos *et al.* 1997; Marquer *et al.* 1998; Schreurs and Immenhauser 1999). Latest Jurassic ages (*c.* 150 Ma) are concluded based on U–Pb zircon studies and Ar/Ar dating on plagioclase of gabbro dykes (Peters *et al.* 1995), K–Ar ages on gabbros (Smewing *et al.* 1991) and dating of radiolarian cherts

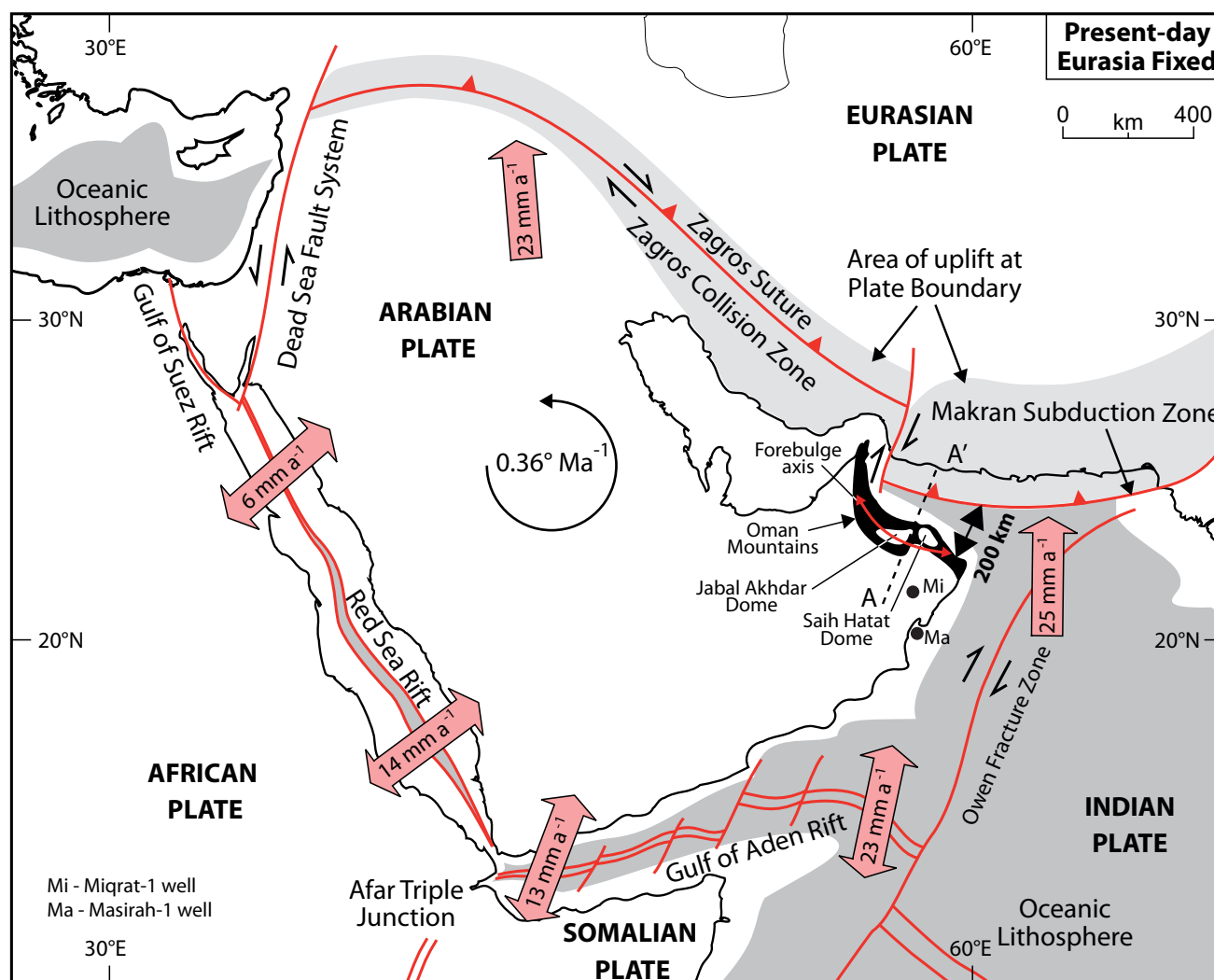


Fig. 1.2. Present tectonic frame of the Arabian Peninsula slightly modified after [Hansman *et al.* \(2017\)](#). Plate velocity from GPS information ([Sella *et al.* 2002](#); [McClusky *et al.* 2003](#); [Reilinger *et al.* 2006](#); [Vigny *et al.* 2006](#); [ArRajehi *et al.* 2010](#)). Forebulge axis in the Oman Mountains is after [Rodgers and Gunatilaka \(2002\)](#). Cross-section for the trace (A-A') is depicted in figure 5.14 ([Scharf *et al.* 2021d](#), Chapter 5, this Memoir).

([Moseley 1990](#)). The SoMoMa Ocean separated Gondwana into western (Africa and Arabia) and eastern (Madagascar and India) segments (fig. 5.18f). Formation of the ocean resulted in the gentle extension and uplift of the eastern Arabian margin and the Hawasina Basin (D5 in fig. A.2; [Rabu 1987](#); [Béchenneq *et al.* 1992a, b](#); section 'Arabian Platform' in Chapter 5 ([Scharf *et al.* 2021d](#)). Geochemical analyses reveal that the ophiolite represents a young mid-ocean ridge that had formed during early drift between eastern and western Gondwana ([Rollinson 2017](#)). Later, the ocean basin underwent transpression as a result of convergence between India and Arabia, and was obducted and/or emplaced to the WNW for a few tens of kilometres as the 'Masirah Ophiolite' onto the easternmost tip of the Arabian Platform at the Cretaceous–Cenozoic boundary until the early Eocene (*c.* 65–55 Ma; [Smewing *et al.* 1991](#); [Peters *et al.* 1995](#); [Gnos *et al.* 1997](#); [Peters and Mercolli 1997](#); [Marquer *et al.* 1998](#); [Schreurs and Immenhauser 1999](#); [Immenhauser *et al.* 2000](#); [Gaina *et al.* 2015](#); fig. 5.18i). The Masirah Ophiolite therefore remained a part of the oceanic lithosphere for *c.* 80 Ma from its formation to its obduction (e.g. [Rollinson 2017](#)). The Hawasina and Haybi Complex were thrust along with the Semail Ophiolite during the Coniacian–Campanian from NE to SW. By contrast, the Masirah Ophiolite was thrust along with the Batain Mélange onto the eastern Oman margin during the Cretaceous–Cenozoic ([Schreurs and Immenhauser 1999](#); [Fig. 1.1](#)).

The Lower Permian to Upper Cretaceous sediments of the Batain Mélange derived from the Batain Basin, located east of Oman as part of the SoMoMa Ocean ([Schreurs and Immenhauser 1999](#); [Immenhauser *et al.* 2000](#)). The Batain Basin is older (latest Carboniferous to Early Permian; [Immenhauser *et al.* 2000](#)) than the Hawasina Basin (Late Permian). Although the sediments of the Hawasina nappes and the Batain Mélange derived from different basins, the stratigraphy is similar (see [Immenhauser *et al.* 1998, 2000](#)).

The Semail and Masirah ophiolites differ in origin, tectonic setting, age of oceanic lithosphere formation (Neo-Tethys Ocean during the Cenomanian compared with SoMoMa Ocean during the latest Jurassic–earliest Cretaceous), time of obduction onto the Arabian Margin (late Cretaceous compared with latest Cretaceous–early Eocene) and direction of obduction (SW-ward compared with WNW-ward). Generation of the Semail Ophiolite is associated with a spreading centre in a supra-subduction zone setting with coeval formation and thrusting (e.g. [Rioux *et al.* 2016](#)), whereas the Masirah Ophiolite formed at a conventional mid-ocean ridge with its emplacement at *c.* 80 Ma after formation (see [Rollinson 2017](#) for further comparison and discussion).

The Oligocene–Miocene to recent regional tectonic setting of the Arabian Plate is summarized in [Figure 1.2](#). The north-eastern plate margin corresponds to the Arabia–Eurasia collision zone, forming the Zagros and Makran mountains (e.g.

Glennie *et al.* 1974; Robertson and Searle 1990; Loosveld *et al.* 1996; Immenhauser *et al.* 2000). Deformation in the Zagros Mountain Belt started before *c.* 25–23 Ma (e.g. Agard *et al.* 2011), amounts to 440 km of shortening (Montheureau 2011) and is still active (Vernant *et al.* 2004). Arabia is bounded in the west by the left-lateral Dead Sea Transform Fault that accommodated a displacement of 100–105 km (Walley 1998). The age of the fault is > 14 Ma (Bayer *et al.* 1988; Makris and Rihm 1991). The southwestern and southern margins of the Arabian Plate are defined by the spreading axes of the Red Sea and Gulf of Aden, respectively. Continental extension in the southern Red Sea area started during *c.* 27.5–23.8 Ma (Bosworth *et al.* 2005; Reilinger and McClusky 2011). Seafloor spreading between the Arabian and African plates (i.e. the Gulf of Aden) commenced at 20 Ma (Fournier *et al.* 2010). The southeastern boundary of Arabia is marked by the 8-Ma-old Owen Transform Fault. Dextral motion along this fault ensues at a rate of $3 \pm 1 \text{ mm a}^{-1}$ (Fournier *et al.* 2008).

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