Geodynamics of collision and collapse at the Africa–Arabia–Eurasia subduction zone – an introduction

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Shortly after the recognition of plate-tectonics, Wilson (1966) proposed his now famous cycle describing the creation and demise of ocean basins. His original four stages still form the basis for plate-tectonic discussions today: (1) rifting of a continent; (2) continental drift, sea-floor spreading and formation of ocean basins; (3) subduction initiation and progressive closure of ocean basins by subduction of oceanic lithosphere; and (4) continent–continent collision and final closure of an ocean basin. The Mediterranean basin constitutes the westernmost extremity of the Tethyan domain (e.g. Stampfli & Borel 2002). Here, the last remains of this former oceanic basin have nearly disappeared, thus representing stage (4). This final closure phase is associated with rifting and drifting in the Western Mediterranean (Dercourt *et al.* 1986), and with initiation of the Tyrrhenian–Calabrian and Alboran subduction zones, i.e. all of Wilson's phases are occurring concurrently.

Imprints of previous Wilson stages are preserved in the geological record. Detailed geochemical and metamorphic-petrological study of ophiolites – on-land relics of oceanic crust in mountain belts – (Spadea & D'Antonio 2006; Barth *et al.* 2008), paleogeographic reconstructions (Hall & Spakman 2003), as well as numerical and analogue modeling experiments (Chemenda *et al.* 2001; Toth & Gurnis 1998) have revealed that initiation of oceanic subduction, as the first part of Wilson's phase 3, may start in various ways, e.g. by inversion of a mid-oceanic ridge or fracture zone, or subduction polarity reversal. The subsequent oceanic subduction stage closes the oceanic basin, eventually resulting in the arrival of a continental margin at the trench (Dewey & Bird 1970; Robertson *et al.* 2009). Small continental fragments may subduct entirely (van Hinsbergen *et al.* 2005; Gerya *et al.* 2002, De Franco *et al.* 2008). Subduction of substantially large quantities of continental lithosphere will inevitably lead to break-off of the subducted slab (Wortel & Spakman 2000), relocation of the trench, and possibly a reversal in subduction polarity (Chemenda *et al.* 2001; Kaymakci *et al.* 2009).

Wilson's phase 4 – continent–continent collision – eventually leads to the final arrest of plate convergence. The orogen that formed near the suture zone will be eroded and may experience gravitational orogenic collapse (Dewey 1988; Gautier *et al.* 1999) and the cycle may start again. However, the opposing continental margins are frequently not parallel and irregular, and continent–continent collision may start in one place, while remaining oceanic crust still present laterally along the active margin, forming land-locked oceanic basins (Le Pichon 1982). It is this situation that is presently characterizing the Africa–Arabia–Eurasia subduction zone(s). Whereas continent–continent collision between Arabia and Eurasia was already followed by break-off of the subducted Arabian slab in the Miocene (Keskin 2003; Faccenna *et al.* 2006; Hafkenscheid *et al.* 2006; Hüsing *et al.* 2009), the geodynamic situation in the land-locked oceanic basin of the Mediterranean region yielded is much more complicated. A decrease in convergence rate or a change in the plate motion direction may lead to readjustment in the orientation of the subducted slab with roll-back as a logical consequence (Malinverno & Ryan 1986; Carminati *et al.* 1998; Jolivet & Faccenna 2000; Faccenna *et al.* 2001*a*, *b*). In the Tyrrhenian, Carpathian and Aegean regions, roll-back, slab break-off and activity of Subduction Transform Edge Propagating faults (STEPs; Govers & Wortel 2005) occurred (Le Pichon *et al.* 1979; 1982; van der Meulen 1999; Wortel & Spakman 2000; Faccenna *et al.* 2001*a*; van de Zedde & Wortel

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2001; Argnani 2009), as well as lateral extrusion processes, that translate Anatolia westward parallel to the subduction zone along major strike-slip faults, notably the North Anatolian Fault as a result of the Arabia–Eurasia collision (Dewey & Sengör 1979; Sengör *et al.* 1985, 2005; Hubert-Ferrari *et al.* 2002; 2009) These processes, which may be specific for land-locked basins (Edwards & Grasemann 2009) have led to, or were associated with, a complex mosaic of geological terranes, frequently with distinct geological histories of exhumation, deformation, rotation and sedimentation.

The present-day tectonic setting reveals that from east to west along the Africa–Arabia–Eurasia collision zone, a more or less gradual transition exists between two extremities: in the east, continent–continent collision is a fact between Arabia and Eurasia, and Anatolia is still being extruded eastward (McClusky *et al.* 2000; Reilinger *et al.* 2006), whereas in the west, roll-back of the subducted slab below the Tyrrhenian basin has led to oceanization in the backarc. The Aegean and western Anatolian regions form a mid-stage between these two extremes and experience continental extension associated with exhumation of metamorphic core complexes (Lister *et al.* 1984; Gautier *et al.* 1993; Gautier & Brun 1994; Bozkurt & Oberhänsli 2001; Gessner *et al.* 2001; Jolivet 2001; Ring & Reishmann 2002; Jolivet *et al.* 2003; Edwards & Grasemann 2009; Papanikolaou *et al.* 2009; Sen & Seyitoğlu 2009; Tirel *et al.* 2009; van Hinsbergen & Boekhout 2009) and migration and compositional evolution of the associated magmatic/volcanic response (Pe-Piper & Piper 2002; Dilek & Altunkaynak 2009). The exhumation during extension of the overriding plate associated with these retreating subduction zones provides a unique opportunity to study the subduction and exhumation processes within the subduction channel prior to the onset of wide-spread roll-back and stretching of the overriding plate. Jolivet *et al.* (2003) subdivided the exhumation processes of the Mediterranean metamorphic belts into two stages: the syn-orogenic extension phase, in which slices of HP/LT metamorphic rocks travel upward along the subducting slab, either by buoyancy-driven upward flow, or by tectonic extrusion (see e.g. Ring *et al.* 2007), a subject further studied by Vignaroli *et al.* (2009) and the post-orogenic extension phase, which is related to stretching of the lithosphere and exhumation of metamorphic core complexes (see also Tirel *et al.* 2009) upon roll-back or collapse.

To determine the causes and consequences of collision, extrusion and collapse at the Africa–Arabia–Eurasia subduction zone, it is most essential to place all geological elements and processes in time. The contributions in this volume provide essential new time constraints, and further constrain and define the fundamental, and regional processes related to collision and collapse in the Mediterranean and northern Arabian regions.

Research themes

We subdivide this volume into two main parts: collision and collapse. The contributions in these parts (Fig. 1) span a wide range of techniques and processes, and cover a time span from the Cretaceous to the Present, but all contribute to the further detailed understanding and identification of stages 3 and 4 in Wilson's cycle.

Collision

Four papers in this volume provide essential new data that constrain the temporal and spatial evolution of arc–continent and continent–continent collision processes from the Cretaceous to the Present in the Arabia–Anatolia segment of the subduction zone.

Robertson *et al.* document the earliest collision phase in the Anatolian collage, represented by arc–continent collision between the Anatolide–Tauride block and supra-subduction zone ophiolites and volcanic arc-related rocks of the northern part of the Neotethyan ocean, following intra-oceanic subduction. Arc–continent collision in Turkey occurred in the late Cretaceous, with widespread ophiolite emplacement and high-pressure metamorphism. Following this phase of arc–continent collision, the authors suggest that the trench migrated northward, with final continent–continent collision between the Taurides (and overlying ophiolites) and the Eurasia-related Pontides in the Paleocene–Eocene.

Kaymakci *et al.* studied the late Cretaceous to Neogene history of the Çankırı Basin, which nicely documented the post-arc continent collision history described by Robertson *et al.* The authors show that the Çankırı Basin, located on the southern part of the Pontides and straddling the northern part of the Taurides in the Paleogene part of its stratigraphy, has a history that can be subdivided in a late Cretaceous to Paleogene forearc basin stage, and a Paleocene–Eocene foreland basin history. The conclusion of these authors is in line with the conclusions of Robertson *et al.* and shows that arc–continent collision between the Anatolide–Tauride block and the Pontides was followed by relocation of the subduction thrust to the southern margin of the Pontides, leading in the late Paleocene to early Eocene to continent–continent collision between Taurides and Pontides.

Hüsing *et al.* focused their paper on the final continent–continent collision phase that characterizes the Africa–Arabia–Eurasia collision zone, concerning the collision of Arabia with the Anatolide–Tauride block, upon demise of the southern branch of the Neotethys (which is still represented by the eastern Mediterranean basin and for example, the Troodos ophiolite on Cyprus). They studied the foreland basin evolution on northern Arabia and around the Bitlis–Pötürge massif, and found that the youngest foreland basin deposits on Arabia below the southernmost thrust of the Bitlis–Pötürge massif has an age of 11 Ma. They interpret this as the end of regular subduction of the Arabian plate, coinciding with slab break-off and the onset of northward penetration of the Arabian continent into Anatolia, leading to its extrusion, in line with earlier suggestions of Keskin (2003), Sengör *et al.* (2003) and Faccenna *et al.* (2006).

Hubert-Ferrari *et al.* provide essential new $^{40}Ar/^{39}Ar$ age constraints on an offset volcano crosscut by the North Anatolian Fault Zone, and show that the majority of motion along the fault zone occurred after *c.* 2.5 Ma, with a slip rate of approximately 20 mm/a. They argue that the first phase of deformation, which established the present-day 1300 km long fault trace following the onset of its activity around 12–10 Ma ago (in line with the conclusions of Hüsing *et al.*), was associated with a much smaller slip rate of 3 mm/a.

Collapse

Nine papers provide a detailed insight in the geodynamic evolution and the tectonic responses of the Anatolian, Aegean, Carpathian and Tyrrhenian segments of the subduction zone.

Edwards & Grasemann review the geophysical and geological data concerning the evolution of the subducted Tyrrhenian, Carpathian and Aegean slabs and their Neogene history of roll-back. They conclude that upon decrease of the width of a slab as a result of its progressive decoupling, the slab retreat velocity increases and the tectonic response in the overriding plate in terms of extension and exhumation intensify. Their paper provides a new overview of the present-day state of the art of the evolution of the Mediterranean land-locked basin since the Neogene.

Argnani connects the final demise of the Calabrian slab to surface manifestations of these deeper processes in the southern central Mediterranean. He identifies periods of slab break-off and STEP fault activity (Govers & Wortel 2005) that are modulated by the older structural grain in the subducting African lithosphere.

Dilek & Altunkaynak review the post-collisional magmatic response in western Anatolia and propose an elegant scenario placing the migration and compositional variation in post-Eocene magmatism in a timely geodynamic and tectonic scenario. They show that through time since the Eocene, just after continent–continent collision between the Taurides and Pontides (see Robertson *et al.* and Kaymakci *et al.*) volcanism and magmatism in western Turkey has migrated southward, with changing compositions. They suggest that volcanism was initially caused by slab break-off after continent–continent collision, followed by southward migrating volcanism associated with asthenospheric flow due to lithospheric delamination. Middle Miocene volcanism is proposed to result to a large extent from lithospheric extension and formation of the Menderes metamorphic core complex. Finally, Quarternary alkaline volcanism near Kula in central western Anatolia is explained as the result of uncontaminated mantle, which flowed in beneath the attenuated continental lithosphere in the Aegean extensional province.

Vignaroli *et al.* integrate structural, metamorphic and geochronological data into their reconstruction of the Apennine belt of the Central Mediterranean. Tying the plate-tectonic evolution of the region to the geological observations, they track the evolution from oceanic subduction to collision. Principal constraints involve stages when HP rocks were exhumed, followed by continental collision that the authors infer to have occurred simultaneously with orogenic extension in the backarc. Their geodynamic scenario involves a principal role for slab rollback and mantle delamination processes.

Tirel *et al.* provide a new numerical model for the evolution of sequential development of metamorphic core complexes, and a thorough review of the Cycladic metamorphic core complexes as a test case. They conclude that provided the original lithosphere is thick and very hot, a sequence of metamorphic core complexes may develop. The core complexes are characterized by a two-stage development: first a symmetric stage, with graben development at the surface and lower crustal flow in the attenuating crust, followed by an asymmetric stage where one of the graben-bounding faults links up with the opposite lower-crustal flow accommodating shear zone to form an extensional detachment. If, upon cooling of the exhumed metamorphic dome, the crust is still hot and thick enough then a second (or even third) dome may form above the remaining shear zone that accommodated lower crustal flow in the first dome. This scenario is successfully tested in the Cyclades, where such paired belts are formed by e.g. Naxos and Ios, and Syros and Tinos. Tirel *et al.* postulate that the timing of

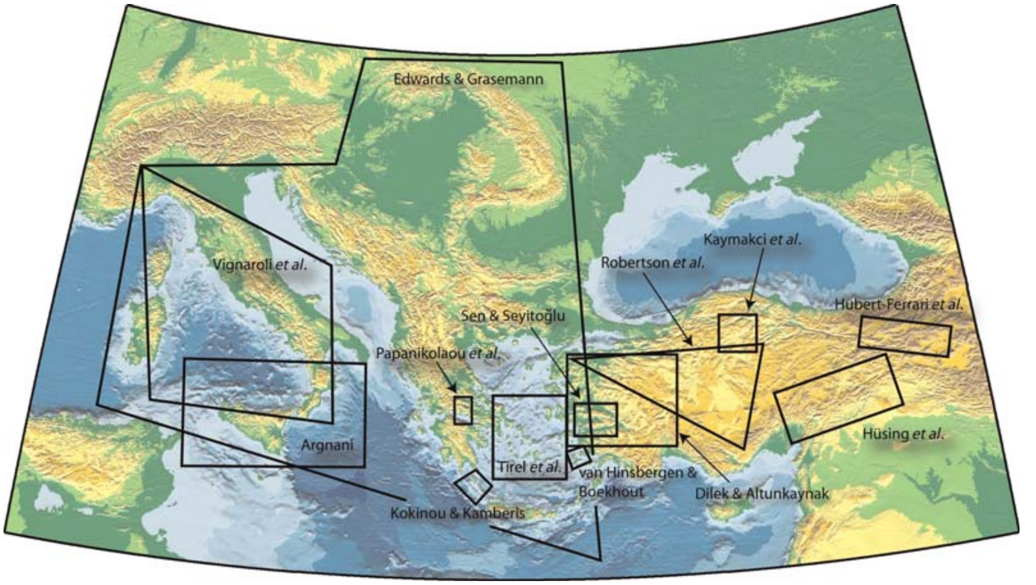

Fig. 1. Topographic and bathymetric map of the Africa–Arabia–Eurasia collision zone, with outlines of the study areas of the papers in this volume.

onset of extension that leads to the formation of a core complex can be approximated by the age of the onset of supra-detachment basin sedimentation.

Papanikolaou *et al.* document the structure of the Itea–Amfissa detachment and the stratigraphy of the lower-upper Miocene supra-detachment basin associated with its activity. They show that this detachment is older than the Gulf of Corinth, and belongs to the East Peloponnesos detachment, which exhumed HP/LT metamorphic rocks. This paper provides essential new age constraints on this detachment fault zone, which, on the Peloponnesos, lacks a well-defined supra-detachment basin stratigraphy. Their new results help to further define the extensional and exhumational history of the external Hellenides and Crete in the Miocene.

van Hinsbergen & Boekhout test a recently postulated scenario for the exhumation of the Menderes core complex. Contrary to the numerical simulations of Tirel *et al.* the Menderes core complex seems to lack an overall asymmetry, and appears to have been exhumed in two symmetric dome stages (e.g. Gessner *et al.* 2001). Recently, Seyitoğlu *et al.* (2004) postulated a southern break-away fault of the Menderes core complex, located in the Lycian nappes, with an Oligocene to early Miocene age. van Hinsbergen & Boekhout tested this postulation on the island of Kos, very close to the postulated break-away fault, and found indeed evidence for an extensional detachment related to the Aegean and Menderes extensional province, but with a much younger age (younger than 12 Ma), and no evidence for pre-12 Ma exhumation as postulated by Seyitoğlu *et al.* (2004). Hence, they conclude that the symmetric bivergent rolling-hinge model of Gessner *et al.* (2001) is a more likely scenario.

Sen & Seyitoğlu provide essential new age constraints on supra-detachment basin evolution associated with the activity of the Alaşehir and Büyük Menderes detachments, that exhumed the second dome-stage of the Menderes core complex. They magnetostratigraphically dated the deposits in these supra-detachment basins, and show an age ranging from 16.6–14.6 Ma, and 16.0–14.9 Ma for the Alaşehir and Büyük Menders supra-detachment basin stratigraphies, respectively. Following the conclusion of Tirel *et al.* this date may coincide with the onset of formation of the second dome of the Menderes, which is in line with this date coinciding with the final cooling of the first dome constrained by fission track analysis (Gessner *et al.* 2001).

Kokinou & Kamberis finally, provide five new seismic profiles of the complex and submerged Kythira Straits, a submerged segment of the external Hellenides between the island of Kythira and Crete. These new data document the complex interactions between arc-normal compression and extension, and arc-parallel extension during the late Neogene outward migration of the Hellenic arc and shed new light on the neotectonic history of the Hellenides.

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