Aegeis – deep structure & slab rollback in the Mediterranean
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Introduction
The Mediterranean realm has a relatively short but, a fortiori, intensive history of geologic research since the 70’s. Especially the Aegean region features numerous studies relating its development nowadays as well as discussions and modelling of the deep structure environment (JOLIVET et al. 2013). In general the Mediterranean area comprises many geologic large-scale phenomena based on different characteristic processes like “subduction, accretion, arc magmatism [& metamorphism], exhumation, [...] faulting, [...] continental extension” (RING et al. 2010) and so on.

The continental collision of Africa and Europe and its resulting subduction events define the area and indicate to “a complex evolution that started at the end of the Cretaceous with the closure of the Tethyan ocean” (JOLIVET & BRUN 2010). As illustrated in Figure 1 several plates – the African, Eurasian, Anatolian and Arabian plate – are involved in the process of continental convergence and influence the deformation of the Aegean Sea plate in rather complex ways. Consequently, deformation in the Aegean region is known to be very active since the ongoing subduction of the African-Arabian plate underneath the Eurasian major and Anatolian respectively Aegean micro plates (DOGLIONI 2002). The initial collision of the African and Eurasion continental bodies is assumed to have started in Oligocene times (JOLIVET & FACCENNA 2000).

In this meaning the Aegean Sea is considered to be one of the Mediterranean Cenozoic backarc basins – which started to form 30–35 Ma ago as per Jolivet et al. 2009 – controlled by the underlying and retreating African slab that is still sinking below Crete and the Mediterranean Ridge (JOLIVET & BRUN 2010). This process is explained by a slow initial

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**Figure 1.** A: Plate boundaries and geodynamic pattern of the Aegean Sea plate. B: Tectonic sketch of the Aegean present day situation. Modified after VÖTT (2007) and RING et al. (2010).
convergence rate of Africa and Eurasia, while the velocity of backarc extension was larger, so that the subduction rate overcame convergence rate (JOLIVET et al. 2009). The basic principles and effects of subduction plus slab rollback are shown in Figure 2.

Besides, there are commonly three models associated to a subducting slab as concluded by MAGNI et al. (2013). While slab detachment refers to a complete decoupling or so called break-off of the lithosphere, a separation between the upper section of the continental crust and lithospheric mantle is occurring during slab delamination (Figure 3).

Not all of those consequences related to the Mediterranean subduction zone are entirely understood yet, but with the seminal discoveries of the Aegean metamorphic core complexes by LISTER (1984), for example, more accurate geodynamic models – featuring subject areas like slab rollback or extensional detachment faulting – became the focus of attention (e.g. BUICK 1991, URAI et al. 1990 etc.). It has thus been possible to overcome initial models which, for example, “used several subduction zones that jumped southward through time, instead of a single migrating subduction used in most models nowadays” (JOLIVET et al. 2013).

Figure 4 represents a present day situated N-S cross-section through the Aegean realm from the northern passive margin of Africa to the Moesian platform across the main structural features Crete, the Cyclades and the Rhodope massif.
This paper focuses mainly on the research of the Aegean deep structure and slab retreat including tomographic images, while numerous studies also assess analyses of high-pressure metamorphism units or metamorphic core complexes (MCC) to derive information about geodynamic evolution.

Deep structure
In the Hellenic subduction system the Hellenic slab subducts under the Eurasian plate, including several microplates and fragments of both oceanic and continental lithosphere. The trench is to be found to the south of Crete with volcanic activity north towards the Aegean Sea, including the islands of Santorin, Nisiros, etc. The slab was first assumed to dip northward at an angle of about 35° after CAPUTO (1970) but is suggested to have been steeper in the past. The slab is known to be continuous and as evidence of tomographic images over 1500 km long. It penetrates the 660 km discontinuity and continues in the

Figure 4. Schematic N-S cross-section of the present day situation through the Aegean realm from the northern passive margin of Africa to the Moesian platform across the main structural features Crete, the Cyclades and the Rhodope massif. CD: Cretan detachment, NCDS: North Cycladic Detachment System. Modified after JOLIVET et al. (2013).

Figure 5. Topographic images across the Aegean realm. The dashed lines in the tomographic section indicate the 410 and 660 km discontinuities (WORTEL & SPAKMAN 2000).
lower mantle (JOLIVET et al. 2013) as seen in Figure 2.

Tomographic images (Figure 5) show a 300 km part of the slab draped just above the 660 km discontinuity, this portion of the slab corresponds to the ~320 km long estimate for Cenozoic extension. Due to the phase change of spinel to perovskite and the buoyancy associated with the discontinuity the penetrating slab is slowed down (RING 2010). This leads to the rate of convergence of the overriding plate being lower than the rate of subduction which is a major parameter for the occurrence of slab rollback and retreating subduction zones.

The rollback of the Hellenic slab is further recorded by the southward migration of the volcanic arc and a steady slowdown of convergence. The 300 km of draped slab can be correlated to the estimated 320 km of subducted slab during the Cenozoic. From a subduction angle of 30-40° and a subduction rate of 30 km/Ma, the arrival of the Pindos Ocean unit – which started subducting at 60-55 Ma – at the 660 km discontinuity can be estimated to have occurred at 25-20 Ma. This coincides with the start of large-scale extension forming the Aegean Sea at 23-19 Ma. It is therefore suggested that the draping of 300 km of slab on the 660 km discontinuity triggered a period of enhanced rollback resulting in ca. 300 km of rapid extension throughout the Aegean (RING et al. 2010).

As a result of fast slab rollback, tearing and slab detachment may occur. While slab rollback is the most important process in the Aegean, slab detachment would explain observations of stress field variations, arc migration, and back-arc deformation (WORTEL & SPAKMAN 2000). A slab tear below turkey was suggested by DE BROODER et al. (1998) and newer tomographic images by JOLIVET et al. (2013) show at least two tears below Turkey and one under the Corinth Rift as indicated in Figure 6.

Geodynamic evolution
The subduction of the Hellenic slab under the Eurasian plate forms a continuous subduction zone since around 200 Ma starting of as a simple subduction during the Jurassic and Cretaceous though advancing northward as a retreating Subduction zone due to slab rollback from 55 Ma onwards. This is recorded by the southward migration of the magmatic arc and the slowdown of the plate convergence related extension in the back-arc basin (RING et al. 2010).

The Hellenides which form an arcuate orogen above the subducting Hellenic slab can be divided into several tectonic domains. These tectonic domains are visible in Figure 7, as there are, from north to south, the Rhodope-Sakarya Block, the Vardar-Izmir Oceanic Unit, the Pelagonian-Lycian Block, the Pindos Oceanic Unit (including the Cycladic Blueschist Unit), the Tripolitza as well as the Ionian Block, and the East Mediterranean

![Figure 6. Topographic images in a horizontal view of the Aegean realm (JOLIVET et al. 2013).](image-url)
Ocean (RING et al. 2010). Due to this the subduction zone has consumed both, oceanic and continental lithosphere successively the Vardar Ocean, the Pelagonian continent, the Pindos Ocean, the Apulian platform and finally the eastern Mediterranean ocean with the crustal parts being accreted and forming the Hellenic chain as well as the Mediterranean Ridge accretion complex (JOLIVET et al. 2013).

From ~200 Ma until ~125-85 Ma ago the Rhodope-Sakarya block, the Vardar-Izmir Oceanic Unit and the Pelagonian-Lycian Block were subducted in a simple fashion as interpretation of tomographic data suggests. After this a distinct time gap of at least 20 Ma, where the relative motion between Africa and Europe comes to a complete stop around (around 67-65 Ma ago according to JOLIVET (2010)), before the subduction of the Pidos oceanic unit began at ca. 50 Ma (RING et al. 2010). During this period the sinking slab is only driven by its own weight, leading to continued subduction without convergence. (JOLIVET & BRUN 2010).

The convergence then accelerates again forming a compressional regime and is quickly subducting the Pindos Oceanic Unit. The subduction and accretion of the Pindos Oceanic Unit caused a distinct switch in the dynamics of the subduction changing it from

![Geodynamic reconstruction of the retreating Hellenic subduction zone and its tectonic domains](RING et al 2010).

**Figure 7.** Geodynamic reconstruction of the retreating Hellenic subduction zone and its tectonic domains (RING et al 2010).
advancing and stationary, to retreating at some time near 55–50 Ma starting the first extension to occur in the back-arc. The start of slab rollback due to the anchoring of the subduction slab and therefor retreating respective to the overriding slab, also occurs around this time (JOLIVET & BRUN 2010). The Boundary conditions change drastically with the northward motion of the African plate decreasing and continued slab rollback thrusting propagates southward where the Tripolitza and Ionian Unites are understacked (JOLIVET & BRUN 2010). With slab rollback continuing, extension reaches its peak and extensional deformation is established around 20-30 Ma ago in the back-arc forming the Aegean sea. Accretion of sediments occurs to the south which starts forming the Mediterranean ridge at approximately 15 Ma ago (JOLIVET & BRUN 2010). With a still ongoing slab retreat the slab acquires a strong curvature leading to a lateral tear in the slab west of Anatolia leading to the rotation of the western Hellenic belt. A second tear appears slightly later under the east Anatolic Block while oceanic crust of the eastern Mediterranean starts to subduct. Between 5 Ma and present day a third tear develops under the Corinth rift (JOLIVET et al. 2013). At present day the Mediterranean Ridge is being
underplated (RING 2010). This evolution of the Aegean realm is covered graphically by Figure 8.

Although both (JOLIVET & BRUN 2010) and (RING et al. 2010), based tomographic images and suggest this was a continuous subduction of one slab of 1500 km length penetrating the lower Mantle, RING et al (2010) propose and two separate subduction, one Mesozoic and a Cenozoic. RING et al. (2010) point out the difference in slab subduction style when reaching the 660 km discontinuity, with penetration in the Mesozoic part and draping of the plate along the discontinuity, most likely triggered the slab rollback, in the Cenozoic part of the subduction as shown in tomographic studies.

P-T evolution
As mentioned in the introduction other important indicators to reconstruct geodynamic evolution scenarios can be derived by analyzing the exhumation of (ultra)high-pressure rocks. In the process of metamorphosis, subducted crustal material is undergoing high pressures plus temperatures – during ongoing lithospheric convergence – and appears, when uplifted and exposed, for example at extrusion wedges close to the trench or as metamorphic core complexes within the backarc environment. Those metamorphic units are common in the Aegean basin and can be described as subsequently-formed metamorphic belts along the volcanic arc. As stated by JOLIVET et al. (2003) a changing of the geodynamic character (e.g. slab retreat) leads to non-steady P-T-t evolutions as seen in Figure 9. Significantly younger rocks in the south opposed to older material in the north indicate the southward retreat of the Hellenic subduction zone (RING et al. 2010).

According to JOLIVET et al. (2013) “the age of the first backarc extension is still a disputed point” (JOLIVET et al. 2013), where isotopic dating of metamorphic units is a commonly used tool of studies. As the earliest unconformable marine deposits date from the beginning of the Miocene (Aquitanian 23–20 Ma), RING et al. (2010) suppose this timeframe to be the earliest possible date of extension. However, JOLIVET et al. (2013) propose an earlier beginning of backarc extension based on arguments coming from P–T–t paths, in

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**Figure 9.** A: Latitude versus age diagram of magmatic events in the Aegean region featuring several tectonic structures. B: P-T-t paths of Aegean exhumation. Modified after JOLIVET & BRUN (2010).
which the evolution for high-P–low-T metamorphic rocks proceeded in three stages “corresponding to two clusters of metamorphic ages” (JOLIVET et al. 2013):

Followed by subduction, the first stage of exhumation occurred during the Eocene, where blueschists and eclogites were partly brought to the surface. In the second stage, during Oligocene and Miocene times, post-
orogenic exhumation took place and metamorphic units “were brought to the surface by core complex-type extension forming a series of metamorphic domes” (JOLIVET & BRUN 2010), for example the metamorphic core complexes of Naxos (Jolivet et al. 2013).

According to this interpretation, extension initiated in the Early Oligocene, while the Rhodpe massif was already extending, implying that backarc extension started around the same time as the initial African-Eurasian continental collision (JOLIVET et al. 2013).

Conclusion

In contrast to the model of DAVIES & VON BLANKENBURG (1995), where subduction leads – due to gravitational forces – almost inevitably to slab break-off, JOLIVET & BRUN (2010) favor slab delamination instead of slab detachment for the Aegean realm. Regarding to tomographic, tectonic, kinematic or P–T–t evolution evidence, the hypothesis of a single and retreating subduction slab is by now commonly accepted and already used in several models (e.g. VAN HINSBERGEN et al. 2005) or further investigations (e.g. JOLIVET & BRUN 2010). This supports the idea of slab delamination and thus an efficient decoupling process between the lithospheric mantle plus lower crust below the main detachment fault and the upper crust (JOLIVET et al. 2003). The thinnest parts of the lithosphere is located under the magmatic arc area, north of the Cretan island. Figure 10 gives a final and composed overview about the deep structure environment underneath the Aegean realm.

References


