Nappe stacking resulting from subduction of oceanic and continental lithosphere below Greece

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ABSTRACT

We quantitatively investigate the relation between nappe stacking and subduction in the Aegean region. If nappe stacking is the result of the decoupling of upper-crustal parts (5–10 km thick) from subducting lithosphere, then the amount of convergence estimated from balancing the nappe stack provides a lower limit to the amount of convergence accommodated by subduction. The balanced nappe stack combined with the estimated amount of completely subducted lithosphere indicates 700 km of Jurassic and 2400 km of post-Jurassic convergence. From seismic tomographic images of the underlying mantle, we estimate 2100–2500 km of post-Jurassic convergence. We conclude that (1) the imaged slab represents the subducted lithosphere that originally underlay the nappes, (2) since the Early Cretaceous, subduction in the Aegean has occurred in one single subduction zone, and (3) the composition of the original basement of the nappes indicates that at least 900 km of sub-upper-crust continental lithosphere subducted in the Aegean.

INTRODUCTION

Africa-Europe convergence since the late Mesozoic has led to the formation of an accretionary wedge of stacked nappes in the Aegean region (Aubouin, 1957; Jacobshagen, 1986). According to various models, such nappes represent the upper crustal portions that decoupled from the underthrusting continental or oceanic plate (Faccenna et al. [2003] and Ricou et al. [1998] for the Aegean, and Schmid and Kissling [2000] for the Alps). If true, the amount of convergence calculated from the balanced nappe stack combined with estimates of completely subducted portions of the lithosphere (i.e., including the upper crust) should correspond to the original length of the subducted slab estimated from seismic tomographic images. The availability of well-resolved seismic tomographic images of the Aegean mantle (Bijwaard et al., 1998) allows us to validate the model of nappes being the decoupled upper-crustal portion of the subducted continental and oceanic lithosphere.

The Aegean nappe stack was crosscut by late Cenozoic metamorphic core complexes. These expose underthrusted, metamorphosed parts of the nappes (Fig. 1) that can be correlated to the nonmetamorphosed external Hellenides of northwestern Greece. The basement originally underlying the nappes is in places included as fragments. Elsewhere, its nature can be inferred from the sedimentary facies in the nappe. This allows us to assess the role of the composition of the underthrusting lithosphere in the process of nappe stacking.

Alpine Paleogeographic Evolution and Nappe Stacking of the Hellenides

A schematic reconstruction of the nappe stack and subduction in the Aegean is shown in Figure 2. We balance a cross section in western Greece, where late orogenic extension had little influence. Originally this section was parallel to the Africa-Europe convergence direction (parallel to the tomographic cross section in Fig. 3), but has rotated by 50° in the Neogene (van Hinsbergen et al., 2005a, and references therein). The oldest nappe, formed by an ophiolite as much as 10 km thick and 100 km wide, was emplaced on top of the Pelagonian unit in the Jurassic (Ricou et al., 1998; Robertson and Shallo, 2000). The ophiolite probably originated from the Vardar ocean in the north, as suggested by evidence for a southern foreland and a northern volcanic arc (Ricou et al., 1998). Although Ricou et al. (1998) suggested that the ophiolite originated from the (northern) hanging wall of the inverted Vardar ridge, we choose to envisage the ophiolite as the upper part of the lithosphere of the (southern) footwall, with regular subduction of the rest of its lithosphere (Fig. 2). In the Late Cretaceous, the remaining northern half of Vardar closed, leading to a currently 100-km-wide Vardar-Axios nappe (Ricou et al., 1998). The original north-south width of Vardar was estimated as 1000 km by Stampfli and Borel (2004), who estimated 700 km of Jurassic and 300 km of Late Cretaceous contraction of Vardar. In the Early Cretaceous, convergence was accommodated more to the north at the former passive margin of Moesia (Ricou et al., 1998). We suggest that the subducted southern part of Vardar detached in the Jurassic along the northern margin of Pelagonia.

In the Cretaceous, the complex north-dipping Rhodope nappe stack developed: Ricou et al. (1998) subdivided the nappe into (1) a lower nappe of continental basement, overlain by a sedimentary cover (Drama nappe), and (2) an overlying mixed unit of continental and oceanic origin. Ricou et al. (1998) suggested that the two continental units were separated by a narrow oceanic rift, and that Cretaceous shortening in the Rhodope was 500 km.

After the accretion of the Vardar-Axios unit in the Late Cretaceous, the Pelagonian unit and overlying Jurassic ophiolites were underthrusted in the Paleogene. The Pelagonian unit consists of Variscan continental basement overlain by Paleozoic and Mesozoic carbonates (Jacobshagen, 1986). The minimum width of the Pelagonian zone is ~200 km, measured from its westernmost exposure on the Pindos unit to its easternmost exposure in the Païkon window (Bornovas and Rontogianni-Tsiabaou, 1983). The original width was probably larger, because the nappe was internally shortened. The thickness of the total sequence is ~10 km (Jacobshagen, 1986; Schermer, 1990).

The Pindos unit underthrusted the Pelagonian unit in the Eocene. The subducted portion of the Pindos unit was metamorphosed at depth into the Cycladic blueschist, exposed today on the Cyclades and Evia. Toward Mount Ossa, Mount Olympos, and the Païkon win-

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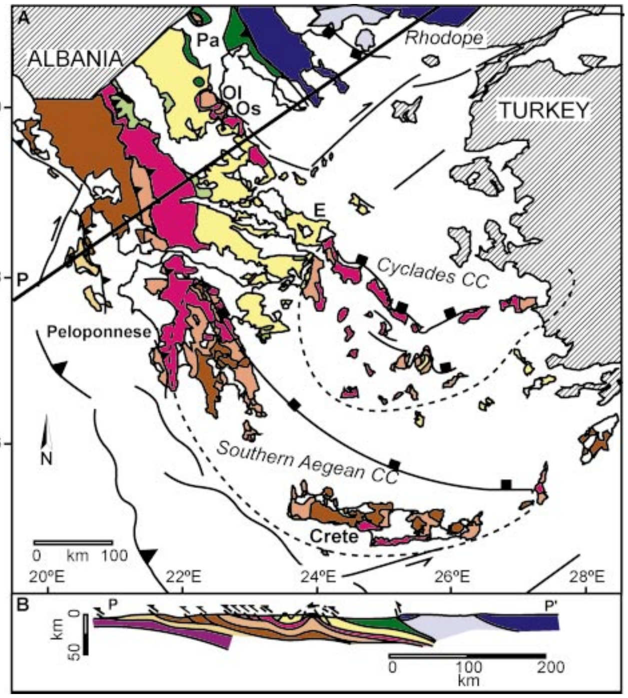

Figure 1. A: Geological map of Aegean, modified after Bornovas and Rontogianni-Tsiabaou (1983) and Jolivet et al. (2004). E—Evia; Ol—Mount Olympos; Os—Mount Ossa; Pa—Païkon window; CC—core complex. B: Schematic cross section of Aegean nappe stack along profile P-P′. See Figure 2 for key.

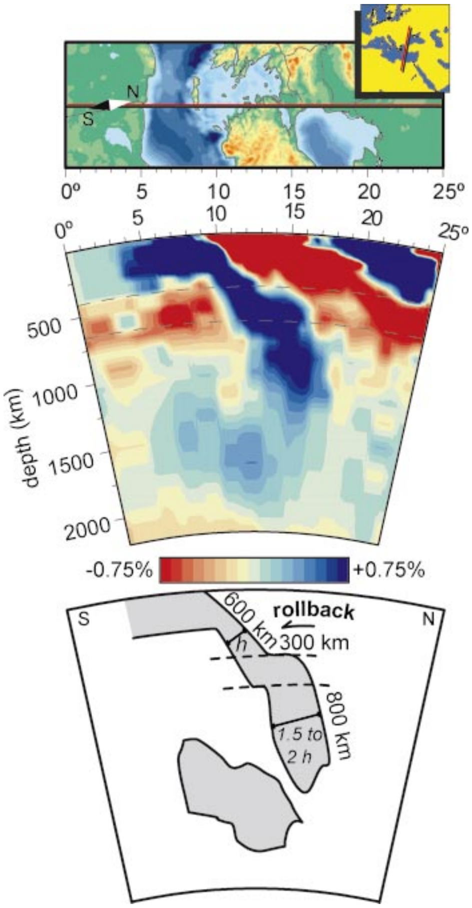

Figure 3. Cross section through Aegean from seismic tomography model of Bijwaard et al. (1998). Distance along surface is given in degrees from starting point of transect (24.14°E, 26.58°N). Slab presence is indicated by positive wave speed anomalies (blue) relative to reference model ak135 (Kennett et al., 1995); *h* is thickness.

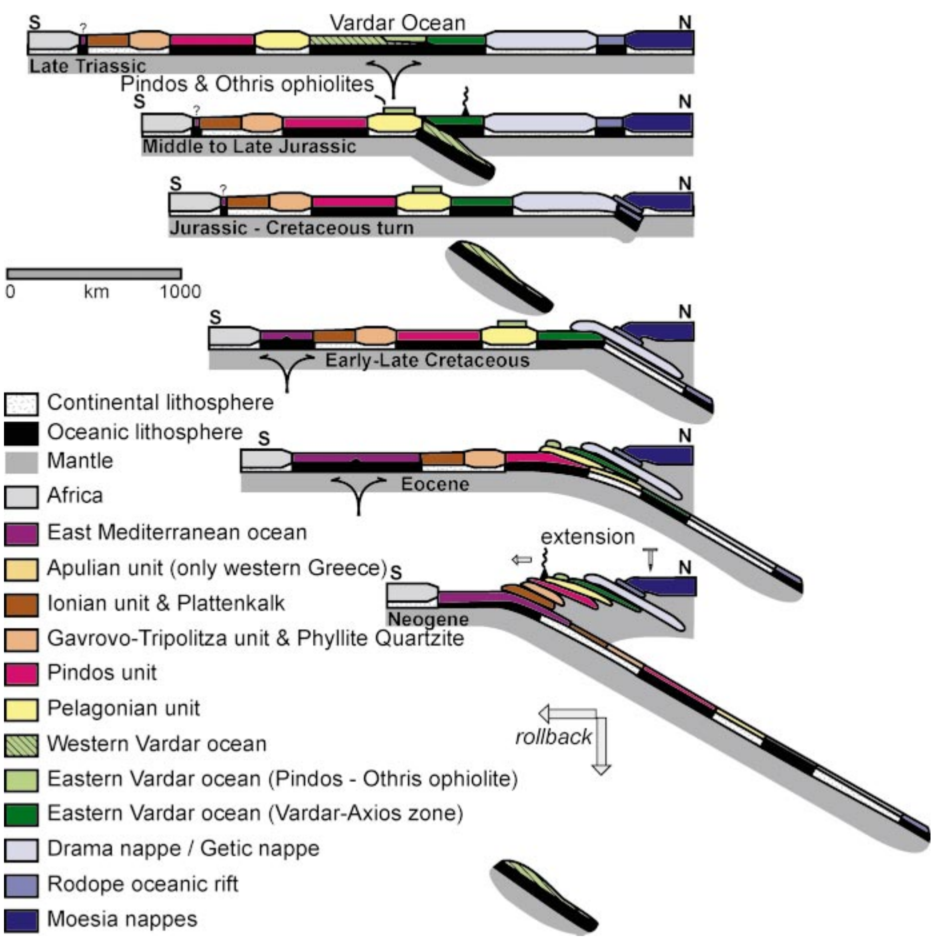

Figure 2. Schematic overview of development of nappe stack and subduction during Alpine orogeny in Greece.

dow in northern Greece, the Pindos has a lower grade greenschist to prehnite metamorphic facies (e.g., Jolivet et al., 2004; Kisch, 1981; Ricou et al., 1998; Fig. 1). The Pindos unit contains radiolarites, showing below calcium compensation depth deposition, thus suggesting an original oceanic basement (Robertson and Shallo, 2000). The Cycladic blueschist unit, however, is underlain by continental basement, which may represent the passive margin of the Pindos basin (Ring et al., 1999). Skourlis and Doutsos (2003) restored sections across the Pindos unit, showing an original width of 160 km for the parts exposed in western Greece. The present-day distance between the Pindos unit and the Païkon window is ~140 km, leading to a total original width of at least 300 km. Stampfli and Borel (2004) estimated the original width of the Pindos ocean as 500 km. The thickness of the Pindos nappe is ~5 km in western Greece (Jacobshagen, 1986).

In the Oligocene, the Pindos unit was underthrusted by the Tripolitza unit, consisting of 3 km of platform carbonates and 4–5 km of flysch (Jacobshagen, 1986). The Tripolitza unit was probably the stratigraphic continuation of the metamorphic Phyllite Quartzite unit of the Peloponnese and Crete (Van Hinsbergen et al., 2005b), which is 2 km thick (Krahl et al., 1983) and unconformably overlies slivers of continental pre-Alpine basement on eastern Crete (Finger et al., 2002). The platform carbonates exposed in the Mount Olympos window are correlated to the Tripolitza (Godfriaux, 1970), showing an original width of at least 150 km.

Simultaneously with the subduction of the Tripolitza unit, the Ionian unit underthrusted the Tripolitza unit, metamorphosing at depth into the Plattenkalk unit of the Peloponnese and Crete (Sotiropoulos et al., 2003; Thiébault, 1979; Fig. 1). The oldest part of the Ionian unit is formed by the Kastania phyllites underlying the Plattenkalk unit (Kowalczyk and Dittmar, 1991). These were interpreted as passive margin sediments, laterally equivalent to the lower part of the Phyllite Quartzite unit (van Hinsbergen et al., 2005b). The Ionian unit in western Greece has a width of 100 km, but was at least 50 km shortened, and has a thickness of 5–8 km (IGRS-IFP, 1966). It is unknown what underlies the Plattenkalk unit (Thiébault, 1979).

During the Miocene and early Pliocene, the Ionian unit overthrusted the pre-Apulian slope of the Apulian platform. This platform did not exist in the eastern part of Greece, where lithosphere of the Eastern Mediterranean basin subducted since the early or middle Miocene (Le Pichon et al., 2002; Underhill, 1989). We follow the reconstructions of Robertson et al. (1996) and Stampfli and Borel (2004) in assuming an oceanic origin of the subducted Eastern Mediterranean lithosphere. Neogene Africa-Europe platewise convergence since 20 Ma (not represented in the nappe stack) was estimated as 300 km (Müller and Roest, 1992). Finally, parallel to our tomographic cross section, 300 km of post–30 Ma Aegean trench retreat occurred (Jolivet, 2001); the retreat is not included in our balancing exercise yet, and should be added to the total amount of Africa-Europe convergence.

In summary, the nappes of the Aegean show an original minimum width of the underthrusting lithosphere of 1500 km, 900 km of which was continental in nature. In addition, the total length of entirely subducted portions of Vardar (600 + 200 km), the Pindos (200 km), and the eastern Mediterranean (300 + 300 km) lithosphere is ~1600 km. Jurassic Vardar convergence was probably 700 km (100 km in the ophiolite in the nappe stack + 600 km entirely subducted). Cretaceous convergence was thus (1500 − 100) + (1600 − 600) = 2400 km.

Subducted Slab Underneath the Aegean

We study a cross section of the Aegean mantle, taken from the tomographic model of Bijwaard et al. (1998), parallel to the convergence direction inferred from the nappe stack (Fig. 3). The image reveals a high-velocity anomaly, continuous to a depth of ~1500 km, that is spatially well resolved (see Bijwaard et al., 1998). The interpretation of slab-like anomalies as the images of subducted lithosphere is warranted, as shown by De Jonge et al. (1994) and others. The dipping upper mantle part has a length of ~600 km. The tomographic image further suggests that the slab is horizontally above the 660 km discontinuity over a length of 300 km. This geometry may correspond to 300 km of slab rollback, in agreement with the amount of late Cenozoic north-south extension in the Aegean (Jolivet, 2001). The anomaly in the lower mantle is ~800 km long, but is ~1.5 to 2 times thicker than the upper mantle slab. If we assume that the increased thickness of the anomaly is the result of slab thickening only, thus ignoring thermal effects as the cooling of the mantle surrounding the subducted slab, the entire slab anomaly would represent 2100–2500 km of convergence. An approximate two-fold thickening of the subducted lithosphere in the lower mantle is in agreement with the findings of Hafkenscheid (2004). In that study, temperature effects were included when predicting the present thermal volume of subducted Aegean lithosphere, and comparing this to the total slab volume of the tomographic anomaly in the Aegean mantle.

Faccenna et al. (2003) estimated 2000 km of convergence, but their analysis was primarily based on a tomographic model that stops at 1000 km depth. In the mid-mantle (~1500 km; Fig. 3), a second positive velocity anomaly can be seen parallel to the Aegean slab (Van der Voo et al., 1999). This anomaly in the Bijwaard et al. (1998) model was interpreted by Faccenna et al. (2003) to be the result of drag folding of the slab at the 660 km discontinuity in response to northward motion of the trench. In the present study, we prefer to alternatively interpret the second anomaly as the remnant of the southern half of the Vardar ocean, which probably subducted and detached in the Jurassic (Fig. 2). A pre-Cretaceous origin for this anomaly was also suggested by Hafkenscheid (2004). The anomaly is therefore not included in the further analysis of post-Jurassic convergence.

ANALYSIS AND DISCUSSION

For the Aegean region, the 2100–2500 km of post-Jurassic convergence that we inferred from seismic tomographic images is in agreement with the 2400 km of convergence in our geologic reconstruction. These results suggest that both the mantle part of the lithosphere and the lower crust that originally underlay the Aegean nappes subducted.

The possibility of subduction of continental crust has been investigated by numerical modeling (Toussaint et al., 2004), analyses of ultrahigh-pressure metamorphosed continental crust (Chopin, 2003; Liati et al., 2002; Van Roermund et al., 2002), and geochemical analyses of volcanics (Elburg et al., 2004). Paleogeographic reconstructions for the Aegean region agree on the presence of a number of oceanic basins separated by isolated elongated continental terrains (Ricou et al., 1998; Robertson et al., 1996; Stampfli and Borel, 2004). Our reconstruction strongly suggests that continental subduction played a significant role in the Alpine history of the Aegean: the composition of the original basement of the nappes (Fig. 2) suggests that at least 900 km of continental lower crust and upper mantle subducted. In the continental basement of the Rhodope, evidence for ultrahigh-pressure metamorphism suggests that continental upper crust was dragged down to a depth of 70–80 km (Liati et al., 2002). These values indicate that continental crust has actually subducted to depths well exceeding the thickness of the overriding plate.

The average convergence rate since the Early Cretaceous was ~2.1–2.5 cm/yr (~2100–2500 km in ~100 m.y.). According to Toussaint et al. (2004), the convergence rate should be at least twice as high to allow stable, oceanic-type subduction of continental lithosphere. In the Aegean, however, the slab consists of short (300–500 km), alternating segments of continental and oceanic lithosphere. In this case, the subduction appears to have been a continuous process, as suggested by Faccenna et al. (2003) and Hafkenscheid (2004).

Former passive margins as in the Alpine orogen tend to serve as weakness zones that lead to detachment of the lithosphere during its subduction (Van de Zedde and Wortel, 2001; Wortel and Spakman, 2000). From seismic tomography we infer that no slab detachment occurred in the Cretaceous and Tertiary history, but probably such a process occurred in the Late Jurassic along the northern margin of Pelagonia.

CONCLUSIONS

We reconstructed the original width of the Hellenic nappe pile, added to this the estimated amount of completely subducted lithosphere, and compared this with seismic tomographic images of the subducted material in the mantle below the Aegean. The nappes indicate at least 1500 km of shortening, and previous reconstructions indicate 1600 km of completely subducted lithosphere since the Middle Jurassic. With 700 km of intraoceanic Jurassic subduction, followed by a northward shift of subduction, we find 2400 km of continuous subduction with south-verging, southward-stepping nappe stacking since the Early Cretaceous. The tomographic anomalies indicate 2100–2500 km of subduction since the Cretaceous. We conclude that the imaged slab represents the subducted lithosphere that originally underlay the nappes and that since the Early Cretaceous, subduction in the Aegean has occurred in one single subduction zone. Moreover, the oceanic or continental composition of the original basement of the nappes is known, or inferred from the sedimentary facies in the nappe. We conclude that at least 900 km of continental lower crust and lithosphere subducted underneath the Aegean. We expect that our result for the Aegean will shed light on the evolution of other orogens in comparable settings.

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