45 m.y. of Aegean crust and mantle flow driven by trench retreat

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ABSTRACT

The available seismic anisotropy data in the Aegean shallow mantle and their relationship with crustal deformation are used for deciphering the lithosphere-scale flow pattern driven by rollback of the Hellenic subduction slab. In the north and central Aegean, the directions of mantle seismic anisotropy trend parallel to stretching lineations in core complexes of the overlying crust, suggesting that crust and mantle have undergone the same direction of flow. At the scale of the entire Aegean, crustal extension is controlled by dextral rotation around a pole located at Scutary-Pec, Albania, that is related to the Hellenic trench retreat. The intensity of mantle anisotropy increases as a function of distance from the pole and of amount of rotation. Surface geology reveals that this rotating flow pattern resulted in strains accumulated since 45 Ma. A slab tear model is suggested to integrate the observed variations of geological events in time and space to subduction dynamics.

INTRODUCTION

Aegean extension results from the southward retreat of the Hellenic trench (McKenzie, 1978; Le Pichon and Angelier, 1981). Trench retreat that was recorded by the southward migration of volcanism (Fytikas et al., 1984) likely started in Middle Eocene time, as shown by extension in the Rhodope (Fig. 1) (Burchfiel et al., 2003; Kounov et al., 2004; Brun and Sokoutis, 2007). Trench retreat reached ~700 km, dominantly accommodated by the exhumation of metamorphic rocks in high-pressure (P) metamorphic belts and high-temperature (T) core complexes (Brun and Faccenna, 2008) occurring in the two first stages shown in Figure 2. From Late Miocene time onward, extensional basins developed in the entire Aegean (Mascle and Martin, 1990), combined with the propagation of the North Anatolian fault into the Aegean region ca. 5 Ma (Armijo et al., 1999) (late stage, Fig. 2). Paleomagnetic data (Van Hinsbergen et al., 2005) show that the extending domain has undergone as much as 50°–60° clockwise rotation around an axis located in the vicinity of Scutary-Pec (Albania) (Fig. 1). In such a kinematic setting the amount of extension increases as a function of the distance from the rotation axis.

Seismic anisotropy (i.e., SKS splitting measurements) of the shallow mantle (Hatzfeld et al., 2001) displays two main directions of fast shear wave polarization vectors (FSWPV) (Fig. 1). In the north and central Aegean, they trend northeast-southwest, almost parallel to stretching lineations in core complexes with large delay times (i.e., δ > 1.0 s), whereas in continental Greece and Peloponnesos they trend northwest-southeast with small delay times. Hatzfeld et al. (2001, p. 30,737) concluded: "Our results, both in fast polarization directions and in values of delay time, do not support the idea that anisotropy is associated with inherited tectonic fabric nor are they consistent with the present-day Aegean motion relative to an absolute frame. In contrast, the direction of fast polarization and the magnitude of delay times correlate well with the present-day strain rates observed at the surface deduced from both geodetic measurements and seismicity." Kreemer et al. (2004) suggested that parallelism between stretching lineations in core complexes and directions of anisotropy in the underlying mantle (Fig. 1) is in favor of a coeval flow of the ductile crust and mantle.

We present a kinematic interpretation that accounts for crustal deformation at a regional scale, including rotations around a vertical axis as
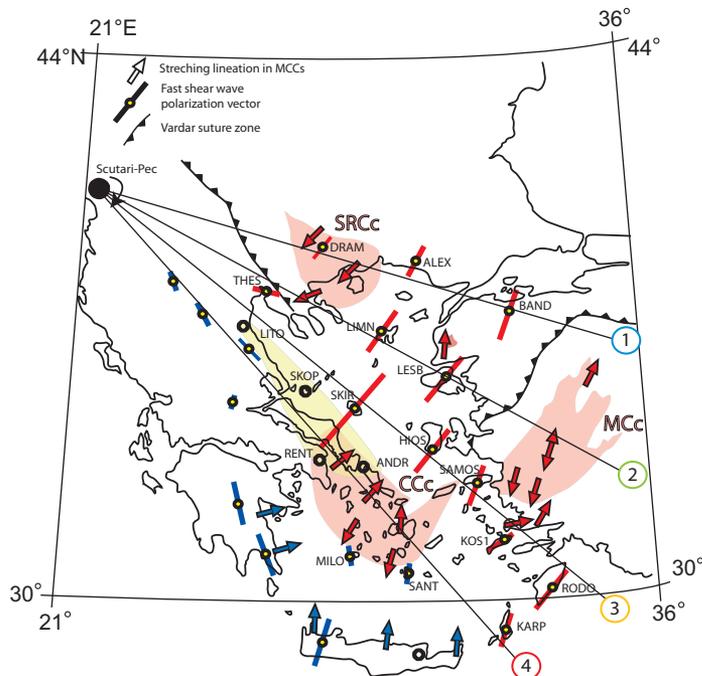

Figure 1. Relation between directions of stretching in core complexes and of seismic anisotropy in mantle. Fast shear wave polarization vectors (after Hatzfeld et al., 2001) are shown in red in north Aegean and in blue in external domains. Length of bars is proportional to delay of shear wave arrival times. Names of seismic stations are indicated. Yellow domain corresponds to four stations with no significant anisotropy. Straight lines 1–4 are those used for analysis of spatial variations of delay of shear wave arrival times. Arrows indicate stretching lineations and associated senses of shear, in red in core complexes (Southern Rhodope—SRCc; Cyclades—CCc; Menderes—MCc) and in blue in external domains of blueschist exhumation not overprinted by a high-temperature event (after Gautier and Brun, 1994; Bozkurt and Oberhänsli, 2001; Jolivet et al., 2004; Brun and Sokoutis, 2007).

documented by paleomagnetism. Subsequently, the coeval flow of crust and mantle is examined under two complementary aspects: (1) the mechanics of core complex development that favors coupling between ductile crust and mantle, and (2) the regional-scale variations of mantle anisotropy intensity.

45 M.Y. OF AEGEAN EXTENSION

On the bases described above, the evolution of the Aegean extension since Middle Eocene time can be summarized in three main stages (Fig. 2). Subduction of the Pindus oceanic lithosphere triggered the first stage with exhumation of the previously subducted Pelagonian block together with the Cycladic blueschists and the Southern Rhodope core complex to the north of the Vardar suture zone. Extension was then temporarily decreased with the arrival of the Adria block into the subduction, leading to the piling up of the Hellenic nappes. The second stage started in Early
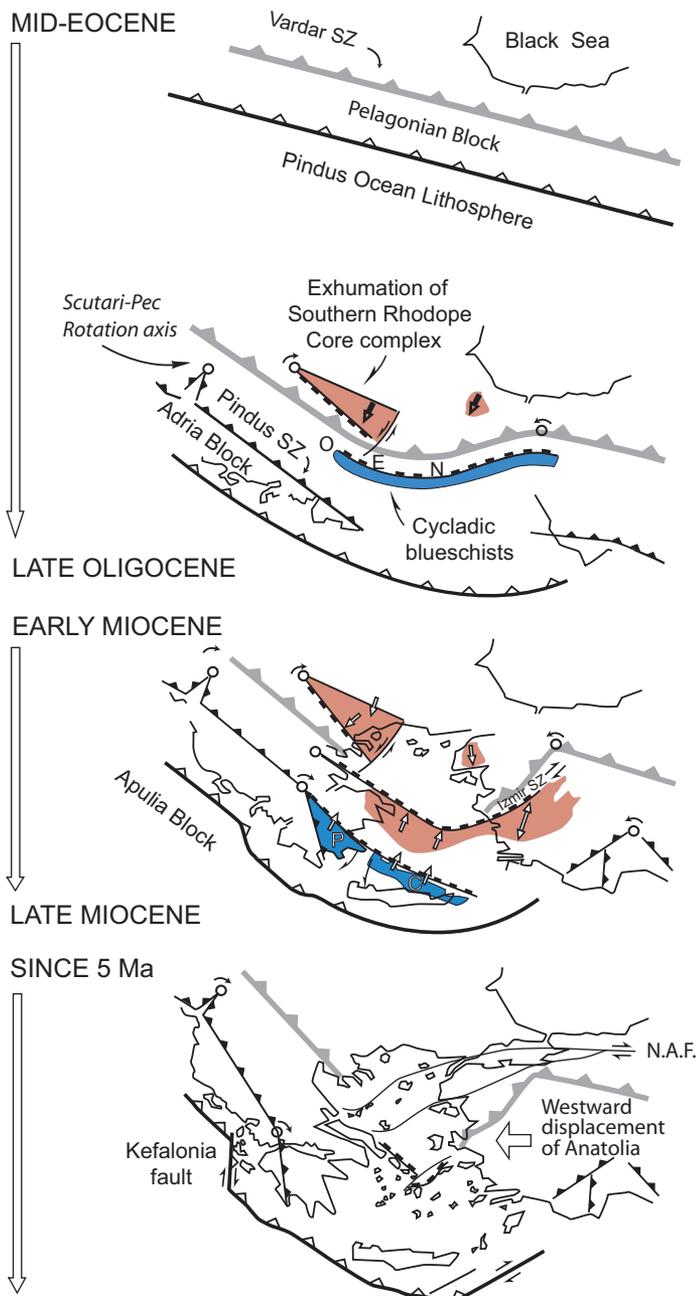
Figure 2. Three-stage evolution of Aegean deformation associated with progressive south-southwestward retreat of Hellenic subduction. For more details about geological units, see Jolivet and Brun (2008). C—Crete; P— Peloponnesos; SZ—shear zone; N.A.F.—North Anatolian fault.

boundary conditions was likely responsible for the transition in the mode of extension, from core complex type to the wide rift type.

CORE COMPLEX STRETCHING AND MANTLE ANISOTROPY

During exhumation in the core complexes domains of the Aegean (i.e., the Southern Rhodope, Cycladic, and Menderes core complexes), high-T metamorphic rocks acquired a strong foliation and an often-prominent stretching lineation trending northeast-southwest, at a high angle to detachment zone traces (Fig. 1). The associated senses of shear are uniformly to the southwest in the Southern Rhodope core complex, while in the Cycladic and Menderes core complexes, senses of shear are dominantly to the northeast but also to the southwest.

The core complex mode of extension requires an initial Moho temperature >800 °C. Mantle rocks then become entirely ductile and the viscosity contrast between lower crust and mantle drops drastically, allowing the Moho to remain flat during increasing stretching (Tirel et al., 2008). The upper crust is divided in almost undeformed rafts, the progressive separation of which accommodates the exhumation of the core complex from the ductile middle-lower crust (Fig. 3). During this process, the crust undergoes extremely heterogeneous strains; however, the underlying mantle deforms rather homogeneously but with principal strain directions trending parallel to those of the crust (Fig. 3). In the Aegean region, the upper crustal blocks, between which core complexes were emplaced, rotated during extension, as indicated by paleomagnetic data (Brun and Sokoutis, 2007). This explains why block rotations about the Scutary-Pec pole increase from the Southern Rhodope core complex toward southwest Greece. Once uplifted close to the surface, the ductilely deformed metamorphic rocks become brittle. Upper crustal blocks can then be rotated around vertical axes with consequent deviation of stretching lineations from their original trends, and therefore from FSWPV in the underlying mantle. However, in the north and central Aegean, departures between stretching lineation in the crust and FSWPV in the mantle remain small (Fig. 1).
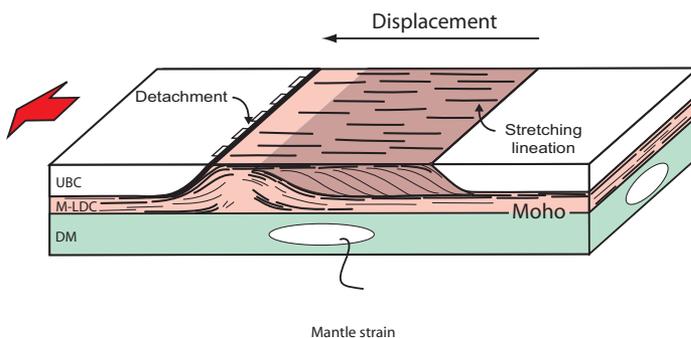

Figure 3. At a core complex scale (redrawn from Tirel et al., 2008), strong stretching develops in exhuming middle-lower ductile crust (pale pink) between almost undeformed blocks of upper brittle crust (white). When exhumed, ductile crust becomes brittle (dark pink). In underlying mantle (green), strain is more distributed but with same direction of stretching of crust. Moho remains almost flat during stretching. UBC—upper brittle crust, M-LDC—middle-lower ductile crust, DM—ductile mantle.

REGIONAL-SCALE STRAIN PATTERN FOR THE NORTH AEGEAN MANTLE

Delays of shear wave arrival times (δ) depend on the amount of mantle anisotropy. From a physical point of view, this is attributed to the degree of preferred orientation of olivine due to mantle flow (Silver et al., 1999). As the north-central Aegean is bound by domains of intense crustal extension localized in the Southern Rhodope core complex to the north and in the Cycladic core complex to the south (Fig. 1), the underlying

Miocene time, with (1) the continuation of the Southern Rhodope core complex, (2) a high-T core complex superposed to the already exhumed high-P rocks in the Cyclades, and (3) the exhumation of high-P rocks in Crete and Peloponnesos. In the third stage, starting in Late Miocene time, the Apulia block entered into continental collision, slowing down the subduction rollback along this segment. Consequently, the trench retreat continued only to the southeast of the Kefalonia fault (Fig. 2), resulting in the clockwise rotation of the Peloponnesos and anticlockwise rotation of Crete. Since Late Miocene time, Aegean extension has been controlled by the combined effects of the continuing southward rollback of the Hellenic subduction and the westward displacement of Anatolia. This change in

ductile mantle should have undergone comparable amounts of stretching, but in a more distributed fashion (Fig. 3). In its most eastern part, the Southern Rhodope core complex has accommodated ~120 km of extensional displacement (Brun and Sokoutis, 2007). Similarly, the Cycladic core complex should have accommodated a minimum of 80 km of displacement. Such large displacements in the north and central Aegean are in agreement with large δ values measured in this area (Figs. 1 and 4).

To test the kinematic compatibility of clockwise rotations of crustal blocks separating core complexes with the underlying mantle anisotropy, δ values (weighted averages including non-null values) are plotted against the distance r from the axis of rotation along four radii (Fig. 4; see radii locations and numbe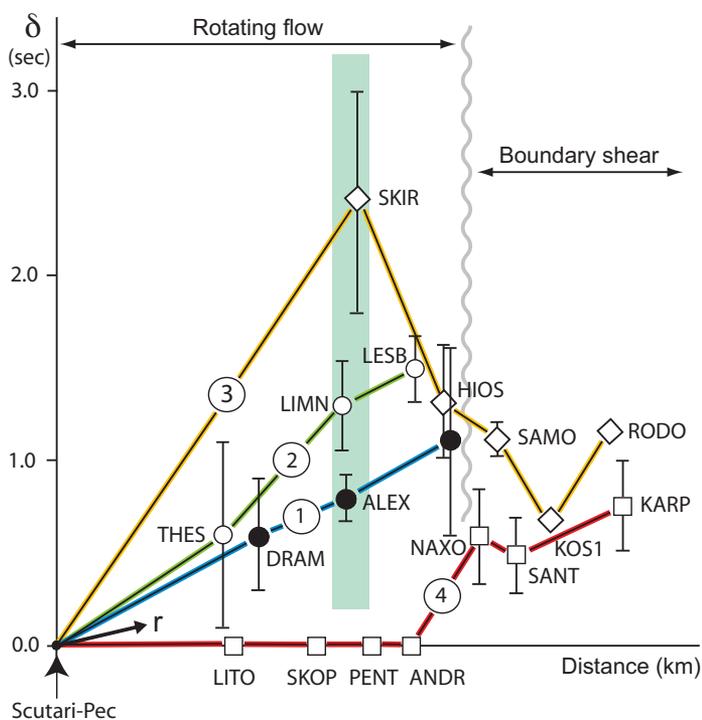rs from 1 to 4 in Fig. 1). Seismic stations located along radius 1 (DRAM, ALEX, BAND) and radius 2 (THES, LIMN, LESB) show a quasi-linear increase of δ with r. A comparable relation cannot be observed for radius 3 as there is no station available between Scutari-Pec and SKIR, after which δ decreases down to values of ~1.0 s and even lower. The first four stations of radius 4 (LITO, SKOP, PENT, ANDR) do not show any significant anisotropy. The next three stations (NAXO, SANT, KARP) have δ values ranging between 0.5 and 1.0 s. Stations ALEX, LIMN, and SKIR, located at comparable distances r from Scutari-Pec, show a strong increase of δ for increasing values of the radius azimuth θ (Fig. 1).

Quasi-linear variations of δ with r are observed along radii 2 and 3 (Fig. 4), but also with θ, as shown by the increase of δ from ALEX toward SKIR (green band in Fig. 4). In addition, the directions of FSWPV are tangent or close to tangent to circles whose center is Scutari-Pec, in particular when the delay times are large (e.g., SKIR, LIMN, ALEX, HIOS, LESB, BAND, SAMOS and RODO). Although it is not possible to calculate amounts of strains from δ values, the observed variations in space ($d\delta/dr$ and $d\delta/d\theta$) provide evidence for a direct relationship between anisotropy and strain. Moderate to medium values of δ are observed to the east-southeast of HIOS-ANDR (Fig. 4); this indicates a lateral decrease of mantle flow in a zone trending southwest-northeast, located below the eastern part of the Aegean and western Turkey, where the Menderes core complex is located (see location in Fig. 1 and progressive evolution in Fig. 2). This rotating pattern of mantle flow is a consequence, in the Aegean region, of the African slab rollback that occurred through a clockwise rotation around the Scutari-Pec axis since Middle Eocene time (Fig. 2).

GEODYNAMIC INTERPRETATION

The overall pattern of principal FSWPVs in the mantle and stretching in core complexes portrays the resulting lithosphere-asthenosphere flow above the subducting plate (red trends in Fig. 5A). To allow this rotation around a vertical axis, the slab that was originally trending ESE-WNW must have been torn parallel to the plate convergence direction (Fig. 5B). The deformation zones trending northeast-southwest in western Turkey (i.e., the Menderes core complex and sinistral strike-slip shear along the Izmir shear zone [Fig. 2] [Bozkurt and Oberhänsli, 2001]) suggest that the slab tear is located below this area. In this region, several P-wave models (i.e., Wortel and Spakman, 2000; Piromallo and Morelli, 2003) exhibit a more or less pronounced lateral break in the continuity of the high-velocity anomaly of the Hellenic slab. This is illustrated by the plot of the vertical average of P wave velocity perturbation (from Piromallo and Morelli model) between 100 and 250 km depth (see Jolivet et al., 2009, their figure 1b).

Figure 4. Variations of delay times of shear wave velocities, δ ± 1σ, in north-central Aegean mantle as function of distance (r) from Scutary-Pec (Albania) along four radii shown in Figure 1A and in a perpendicular direction (green band). For further details on data used for this diagram, see Hatzfeld et al. (2001).
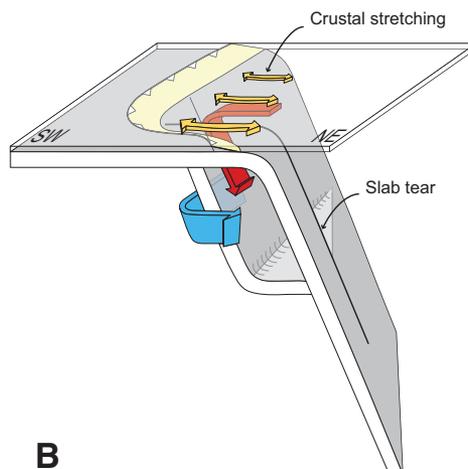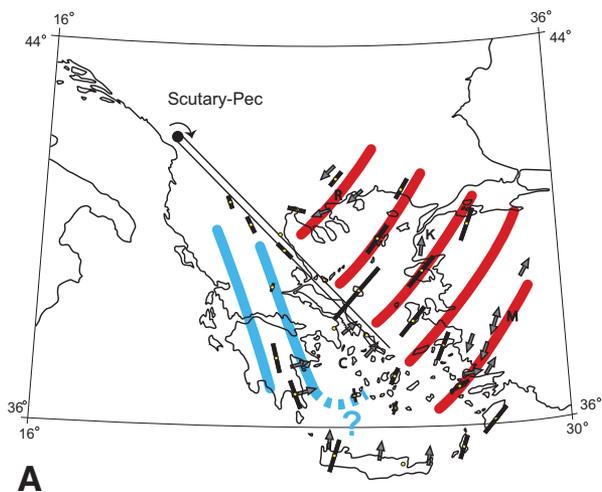

Figure 5. Mantle flow pattern at Aegean scale powered by slab rollback in rotation around vertical axis located at Scutary-Pec (Albania). A: Map view of flow lines above (red) and below (blue) slab. B: Three-dimensional sketch showing how slab tear may accommodate slab rotation. Mantle flow above and below slab in red and blue, respectively. Yellow arrows show crustal stretching.

In such a three-dimensional subduction model, the southern domain of mantle anisotropy (i.e., where the FSWPVs trend parallel to the orogenic belt; Fig. 1) likely represents a southeast-directed mantle flow, laterally expelled from below the rotating slab, so-called toroidal flow (blue trends in Fig. 5A), as observed in numerical and laboratory experiments (Funiciello et al., 2006; Piromallo et al., 2006). This is in agreement with the discussion in Jolivet et al. (2009) concerning the orientation of streamlines in the mantle above a retreating slab that are expected to trend perpendicular to trenches, rather than parallel.

The Middle Eocene age for the onset of extension in the Southern Rhodope core complex indicates that extension- and/or rotation-related mantle anisotropy results from a long deformation history, likely ~45 m.y. The minimum extensional displacement of 700 km over this period implies a mean displacement rate of 1.7 cm yr^{-1}. This displacement rate has likely varied through time with acceleration since the Early Miocene to reach present-day values close to 2.5 cm yr^{-1} in Crete (McClusky et al., 2000). In counterbalance, early displacement rates were likely rather low in Eocene–Oligocene time, i.e., significantly less than 1.0 cm yr^{-1}.

CONCLUSIONS

Aegean extension since Middle Eocene time has been driven by rollback of the Hellenic subduction through clockwise rotation around a pole located at Scutary-Pec in Albania. In the north and central Aegean, the directions of mantle seismic anisotropy trend parallel to stretching lineations in core complexes in the overlying crust, indicating that crust and mantle have undergone flow in the same direction. The spatial variations of shear wave arrival time delays show that intensity of mantle anisotropy increases as a function of distance from the pole and of amount of rotation. This provides evidence for a direct relationship between anisotropy and strain. The corresponding rotating flow pattern likely resulted from the slab rollback of the African lithosphere through rotation around the Scutari-Pec axis since ca. 45 Ma, as recorded in surface geology. To facilitate this rotation around a vertical axis, the slab that was originally trending ESE-WNW must have been torn parallel to the plate convergence direction, leading to the clockwise strike-slip shear zones trending northeast-southwest in western Turkey and the eastern and southeastern Aegean.

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