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Constraints on the evolution and vertical coherency of deformation in the Northern Aegean from a comparison of geodetic, geologic and seismologic data

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Abstract

We study the 3-D strain evolution of the northern Aegean and the vertical coherency of deformation. We observe that finite strain orientations in the mantle inferred from published shear-wave (SKS) fast polarization orientations, mid- to upper-crustal stretching lineations in metamorphic core complexes of mainly Miocene age, and the gradient in regional crustal thickness variations, are subparallel to one another. This correlation suggests that the Miocene phase of extension is imprinted in the anisotropic fabric (i.e., lattice preferred orientation, LPO) of the lithospheric mantle, and that the orientation of finite strain due to extension is nearly constant with depth. The lateral variation of published seismic delay times shows a correlation with laterally varying finite strain in the crust inferred from topography and crustal thickness estimates. This correlation suggests that lateral variations in finite crustal and mantle strain are correlated and may point at a pure shear extension mechanism involving the entire lithosphere.

We also present a new strain rate model for the northern Aegean based on Global Positioning System (GPS) velocities and additional geological constraints. No-length-change orientations calculated from the model near the North Anatolian Fault (NAF) and North Aegean Trough are not consistent with anisotropy orientations at depth. Present-day extension orientations are systematically, and significantly, more N–S oriented than the stretching lineations and SKS splitting orientations. We conclude that the current shear-dominated surface deformation pattern is not (yet) reflected by significant anisotropy in the lithosphere. Based on some simple calculations, we postulate that the present-day deformation pattern

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cannot be older than ~4 Ma, which is consistent with independent arguments on the timing of the propagation of the North Anatolian Fault into the Aegean domain.

Keywords: Aegean Sea; North Anatolian Fault; lithosphere; crust; strain; Miocene; Recent; deformation; anisotropy; GPS

1. Introduction

Since the Miocene, widespread extension behind the Hellenic Arc has dominated the tectonics of the Aegean and western Anatolia [1], and it has been suggested that outward migration of the subduction zone in a land-locked basin has been the main driving mechanism [2]. At present, however, the active tectonic framework based on space-geodesy, earthquake occurrence, and active faulting (Fig. 1) appears to be rather different. The two seismically most active structures in the region are the North Anatolian Fault (NAF) and the Corinth Gulf (CG). The NAF accommodates ~24 mm year^{-1} [3] of dextral motion and has been active since 10 [4] to 5 Ma [5]. Its continuation through the Marmara Sea and connection with the Saros Trough and North Aegean Trough (NAT) is thought to have taken place not earlier than 3.5–5 Ma [6,7]. The CG is an active graben that started opening 1.0–1.7 Ma years ago [8], probably during the time when the western tip of the NAF reached continental Greece.

These major recent tectonic developments are reflected by the evolution of the (finite) strain and stress fields of the northern and central Aegean. For example, a significant difference in the orientation of extensional stresses for the Lower Pliocene–Lower Pleistocene period is observed when compared to the period between Middle Pleistocene–Recent, with a short phase of compressional stress in between both periods [9]. Also, the change from NE–SW to a more N–S-oriented extension is corroborated by NW–SE-trending normal faults in the northern Aegean that are inactive at present, but are believed to have taken up the bulk of extension in the past [9–12] (Fig. 1A). Despite the fact that the changes in stress and strain are well documented, these changes have often not been incorporated in studies that interpret finite strain, such as lattice preferred orientation (LPO). In one study, the present-day geodetic strain orientations were compared with finite strain orientations in the middle-upper crust inferred from lineations in Oligo-Miocene metamorphic core complexes [13]. This study concluded that, although extension may have become more localised upon the prolongation of the NAF into the Aegean domain, the regional deformation pattern for the inner Aegean has remained remarkably intact over the last ~25 My. It has been argued [13,14] that the temporal coherency in the orientations and rate of extension can be explained by ongoing gravitational collapse of the overriding plate. Another study [15] compared geodetic extension orientations with fast polarization orientations of SKS shear waves and concluded that they agree well. To the extent that the SKS splitting orientations register anisotropy related to finite strain at depth, the observations of [15] would suggest a vertical coherency (i.e., a constant orientation with depth) in deformation pattern between crust and mantle underneath the northern Aegean Sea. Moreover, the conclusion drawn by [15] implies a temporal coherency in deformation pattern over at least the time period needed to create a preferred finite strain orientation in the lithosphere that is large enough to be clearly detected by the splitting of SKS waves.

Much can be learned about the vertical coherency of deformation when deformation patterns from the surface (from Global Positioning System (GPS) velocity measurements and active faulting), middle-upper crust (from metamorphic stretching lineations) and lithospheric mantle (from SKS shear-wave-splitting observations) are compared (e.g., [16]). To date a careful comparison between all three different data sets is still lacking in the Aegean. Such comparisons could also provide insight into the timing of possible changes of the regional deformation field, because the different strain indicators reflect deformation over different time periods.

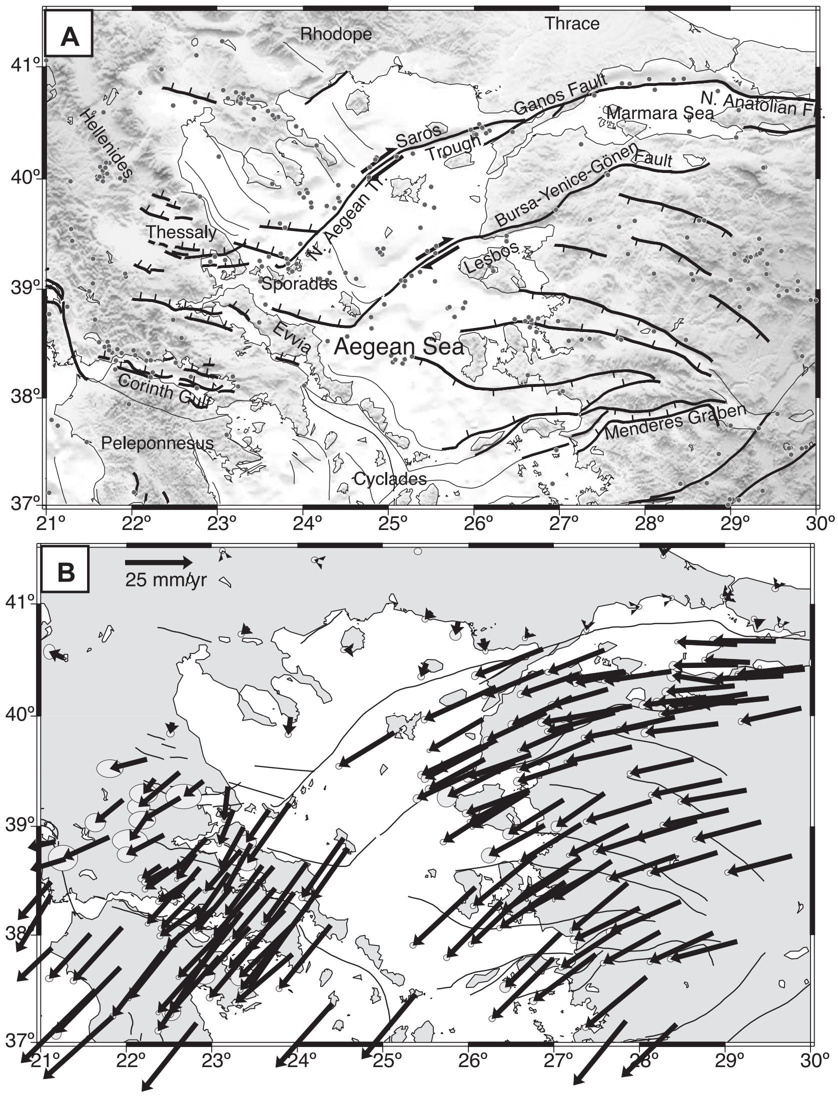

Fig. 1. (A) Thick lines indicate active faults and thin lines recently active faults [70]. Both fault sets have been used to place constraints on the style, direction and distribution of the strain rate field that is obtained through an interpolation of model velocities that have been fitted in a least-squares sense to the GPS velocities. Circles indicate epicenters of shallow (≤20 km) events [38]. (B) GPS velocities relative to a reference frame in which velocities in the Rhodope-Thrace region are minimized. GPS velocity vectors are taken from [3,34–37] and error ellipses represent $1-\sigma$ formal uncertainty (see also [41] for more details).

In this paper, we compare the finite strain indicators in the middle-upper crust with those inferred from fast polarization orientations in the lithosphere/asthenosphere. We specifically address systematic discrepancies between splitting orientations and geodetic extension orientations that were already noticed in some of the previous work [15] but not discussed. For our study, we recalculated a geodetic strain rate model, based on many geodetic studies and additional geological constraints. Because of the use of additional kinematic constraints, our model result indicates more localised and heterogeneous (i.e., partitioned) deformation in the northern Aegean, compared to previous models that indicated a more diffuse and uniform style of deformation [17–20].

2. Finite strain orientations at depth

Fast polarization orientations observed through the splitting of shear waves are generally accepted to be due to fabric or anisotropy in the lithospheric mantle or asthenosphere. This fabric is created by the LPO of the major constituent minerals (see, for example, [21] for a review). While numerous observations, laboratory experiments, and models have shown that LPO is generally closely related to the finite strain ellipse (e.g., [22,23]), it is still debated whether anisotropy orientations are associated with vertical planes of shear (e.g., [16]) or with orientations of maximum horizontal elongation (e.g., [24]). As to the delay times, typically observed delay times of 0.5–2.0 s are believed to indicate anisotropy within a 100–200-km-thick layer, with most of the delay caused in the upper mantle (e.g., [21]).

The shear-wave-splitting orientations and delay times presented by [15] are shown in Fig. 2 (we show the weighted averages at each station). The strongest characteristic of the SKS splitting results by [15] is the uniform NE–NNE orientation (N30°E–N42°E) and large delay times found at stations throughout the northern Aegean Sea and western Anatolia. The observed pattern has been interpreted as widespread

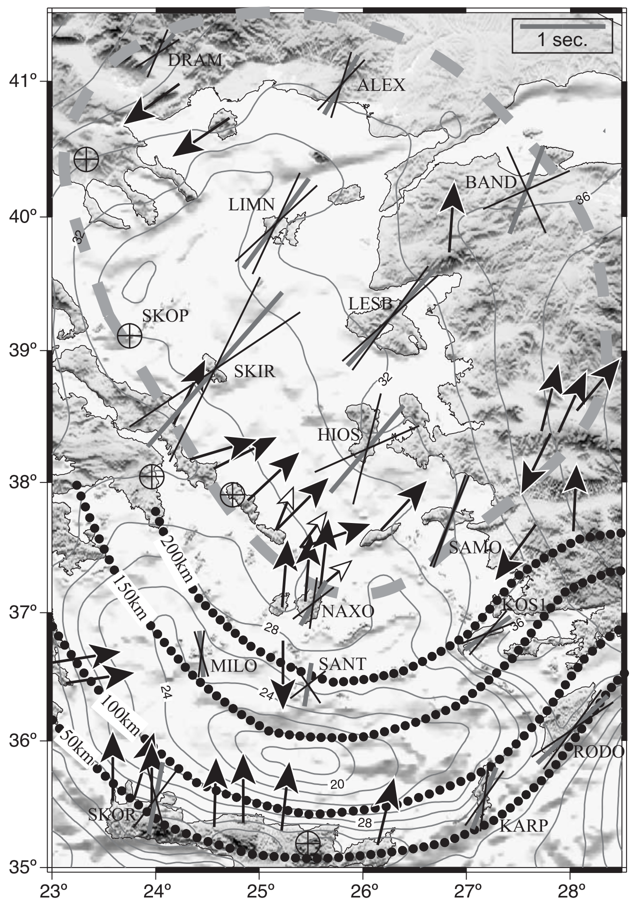

Fig. 2. Shear-wave-splitting results from [15] are shown by grey bars. Relative lengths indicate relative delay times. Station names and 1−σ uncertainties in splitting orientation are shown as well. Stations with a 'null' measurements are indicated by circled crosses. Black arrows show Oligo-Miocene stretching lineations in metamorphic core complexes [13], and white arrows show, where known, the stretching lineations before the rotations of crustal blocks [13,28,29]. In this study, we focus on the region outlined by grey dashed line. Also shown are the dotted contours of the top of the subducting slab, as inferred by [71] based on relocated hypocenters [38], and crustal thickness contour lines of [51] with a 2-km interval.

uniform deformation within the lithospheric mantle and probably deeper in the mantle [15]. We will use these splitting results as if they are the result of anisotropy present in the lithospheric mantle and not within the asthenosphere. We argue that the asthenosphere cannot be the source of the presently observed mantle anisotropy, because of two reasons. First, directions are not aligned with absolute plate motions [15] as observed under some cratons as evidence of asthenospheric flow [21]. Second, slab retreat of the Hellenic subduction slab, as evidenced by southward migrating volcanism [25], may have changed the asthenospheric flow beneath the Aegean over a considerable amount of time in such a way that no detectable anisotropic may have had the chance to develop.

Stretching lineation directions observed in metamorphic core complexes have registered the evolution and distribution of finite strain (i.e., extension) orientation within the middle-upper crust in the region (see, for example, [14,26] for recent overviews) (Fig. 2). The age of the oldest studied stretching lineations is Late Oligocene–Early Miocene, consistent with the onset of post-orogenic extension [27], and the most recent lineations date from the Late Miocene. Unfortunately, a straightforward interpretation of the stretching lineations may be obscured by the fact that lineations (as well as other markers) may have been significantly rotated around a vertical axis since the time they were formed [26,28]. We show the pre-rotated lineations only for those locations where paleomagnetic measurements have been obtained at the same localities as the stretching lineations [13,28,29] (Fig. 2).

We focus our comparative investigations on the northern Aegean, defined by northwestern Anatolia, Thrace, Rhodope and the northern Aegean Sea north of the Cyclades/volcanic arc. Consequently, only the (non-null) measurements at the following seismic stations deserve our attention; DRAM, ALEX, BAND, LIMN, LESB, SKIR, HIOS and SAMO. We have two reasons to geographically constrain this study. First, it is generally argued that this entire region has been subject to the same large-scale extensional process during the Miocene [30]. Consequently we exclude most of continental Greece where the presence of the Hellenides has provided a rather different tectonic setting. Secondly, splitting measurements south of the volcanic arc are excluded because they are arguably affected by the imposed complexities of the subducting slab underneath (Fig. 2). Additional complexities due to asthenospheric flow in the mantle wedge could render inferences on finite strain in the mantle from splitting observations even more complicated [31].

A systematic direct comparison between anisotropy and stretching directions is not possible in the northern Aegean Sea because the only stretching lineations observed there are in southern Rhodope, but we note that the NE–SW fast anisotropy orientations in the northern Aegean Sea are generally consistent with (post- or pre-rotation) stretching lineations in surrounding areas (e.g., Rhodope, Evvia and the Cyclades) (Fig. 2).

3. A new surface strain rate field model

The general method used by us to obtain a horizontal velocity gradient tensor field was first explored by [32], and [33] summarized the methodology when incorporating geodetic and geologic data. The reader is referred to these papers for details on the methodology. We determine a 'GPS-alone' strain rate field solution (Fig. 3A) obtained from an interpolation of model velocities that are fitted in a least-squares sense to available GPS velocities [3,34–37] (Fig. 1B). We show average strain rate model results at the midpoints of each grid cell outlined in Fig. 4. In the GPS-alone model, we apply a uniform a priori weighting to the model strain rate values in each grid cell and we do not place a priori constraints on the expected style of strain rate within any one cell; e.g., the model strain rate field is entirely constrained by the fit to the GPS velocities alone. This solution is much like the one presented by [19].

For a region such as the northern Aegean Sea, where GPS velocities are relatively sparse, the strain rate field model is nonunique. That is, based on the GPS data alone, a multiplicity of strain rate models will be able to satisfy the accommodation of relative motion between two (or more) sites that are relatively far apart. In such a case, with no further constraints, the model will return a nearly constant velocity gradient tensor, compatible with an evenly distributed

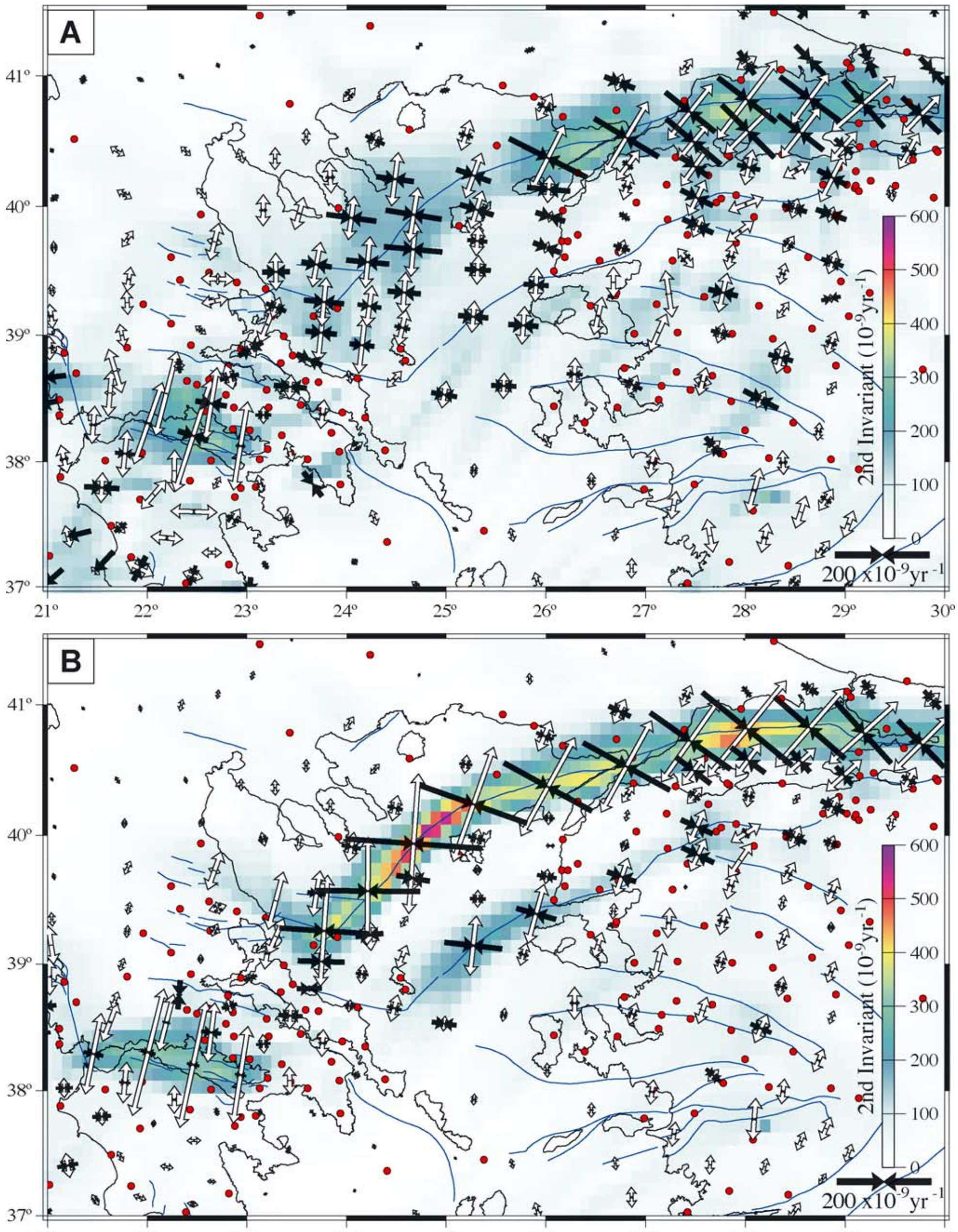

Fig. 3. (A) Contour plot of the second invariant of the model strain rate field. Also shown are principal axes of the model strain rate field; white is extensional and black is compressional. This model is referred to as the GPS-alone model, because it is based solely on the interpolation of GPS velocities. Positions of used GPS velocities are shown by red dots, and major active faults are given as reference in blue. (B) Same as in (A), but these results are for our preferred model. In this model, we have interpolated the GPS velocities but we have also used a priori constraints from active faulting (Fig. 1A). See the text for details.

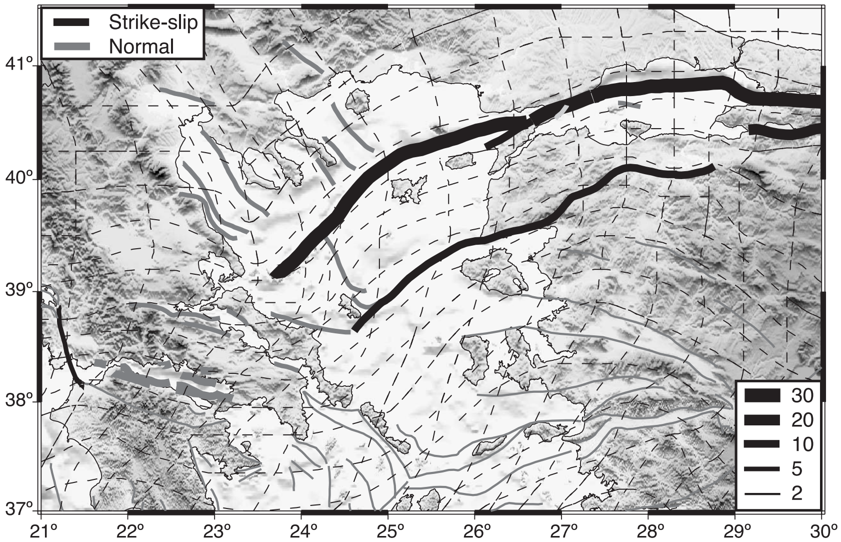

Fig. 4. Grid used in modelling is outlined by dashed lines. Fault information used in our preferred model (Fig. 3B) is indicated by means of colours and line width. Numbers are analogous to mm year^{-1}. That is, for example for the North Aegean Trough, the a priori strain rate covariance matrix for the grid areas covering this feature is constructed such that, if not in conflict with what the GPS velocities dictate, a model strain rate for these areas *could* be solved for that reflects pure strike slip deformation corresponding to 30 mm year^{-1}. This does not mean that we impose a physical fault in the model or that we *fix* the strain rate field for those areas a priori to an equivalent of 30 mm year^{-1} strike slip motion, but simply that we introduce an a priori weighting between grid areas and between the relative magnitude of the expected principal strain rate axes for each area. For grid areas that contain no faults, the a priori strain rate covariance matrix is set be analogous to 1 mm year^{-1} with no particular preferred style.

model strain rate field. Yet, for this region the bathymetry (Fig. 1A) and seismicity (in terms of concentration (e.g., [38]) (Fig. 1A) and seismic moment release (e.g., [20,39]) seem to suggest that deformation in the northern Aegean Sea is mostly localised in one or two principal shear zones, in variance with the strain rate field in Fig. 3A. Moreover, when corrected for elastic loading, GPS velocities in northwestern Turkey are consistent with having all long-term relative motion being accommodated on the NAF (including Ganos Fault) and along the Bursa-Yenice-Gönen fault system south of the Marmara Sea, with the area in between behaving more block-like [37,40]. Considering the continuation of the NAF into the North Aegean Sea, it would not be sensible if this inferred distribution of long-term strain in northwestern Turkey (i.e., a quasi rigid-block bounded by a major and minor shear zone north and south of it, respectively) would change drastically into a distributed strain rate field in the North Aegean Sea. Particularly, there is no argument why the localised 23–24 mm year^{-1} of concentrated long-term slip on the Ganos Fault [37,40] would not be maintained along its offshore continuation into the deep Saros Trough.

The model that we will name 'preferred model' (Fig. 3B), which is part of a study covering most of the eastern Mediterranean [41], uses the regional active fault map (Figs. 1A and 4) to place a priori constraints on the style and direction of the model strain rate field. In addition, fault zones were made relatively weak compared to the regions between them, with a higher 'weakness' given to larger, and seismically more active faults. What style and relative weakness has been assigned to each fault is shown in Fig. 4. It deserves repetition that we do not introduce faults in the model, but merely that the faults are used to place a priori constraints on the strain rate covariance matrix for each grid area such that it is used as a 'guide' in the accommodation of relative motions constrained by GPS. Of particular importance for this study, we assign an a priori strain rate variance to the areas covering the NAT and Saros Trough that is three times larger than for the secondary shear zone south of the NAT (Fig. 4), reflecting the distribution of historic seismic moment release (e.g., [20,39]), and the difference in inferred onshore (strike-slip) slip rates along the NAF (~23–24 mm $year^{-1}$) and the Bursa-Yenice-Gönen fault zone (~7 mm $year^{-1}$) [37,40]. For regions densely covered with geodetic velocity measurements, these a priori constraints are of minor importance, because the strain rate model is well constrained through the fit to the GPS velocities. However, for regions where GPS velocities are relatively sparse, such as the northern Aegean Sea, additional constraints become important (and indeed partially control the model results). We show the effect of including additional geologic constraints on the fit between model and observed velocities (Fig. 5). The weighted RMS between model velocities and observed velocities for our preferred model increases from 0.99 to 1.26 compared to the GPS-alone model. For our region of interest, the residual velocities are for both models within the 95% confidence intervals of the published velocities. Therefore, both models are statistically consistent with the GPS data, but our preferred model better mimics other discussed kinematic indicators present in the northern Aegean Sea.

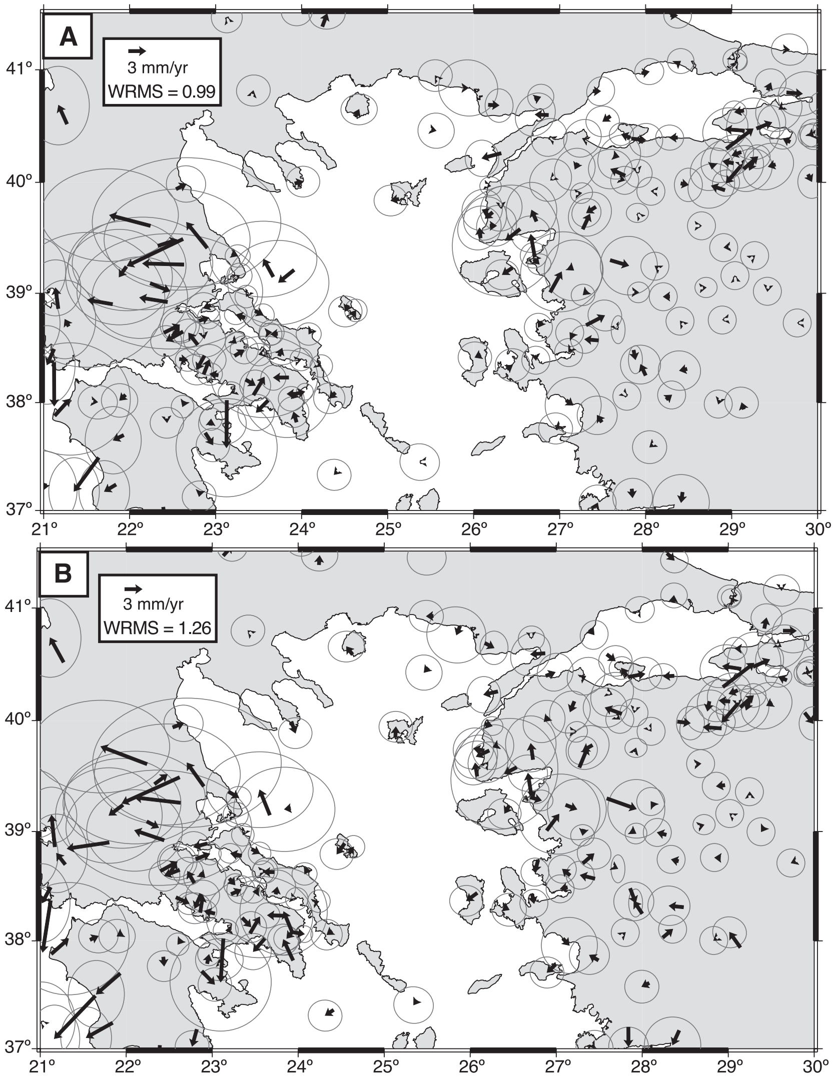

Fig. 5. (A) Residuals between GPS velocities and the fitted model velocities for the GPS-alone model (Fig. 3A). Error ellipses represent 95% confidence intervals. WRMS is weighted root-mean-square. (B) Same as in (A) but for our preferred solution (Fig. 3B).

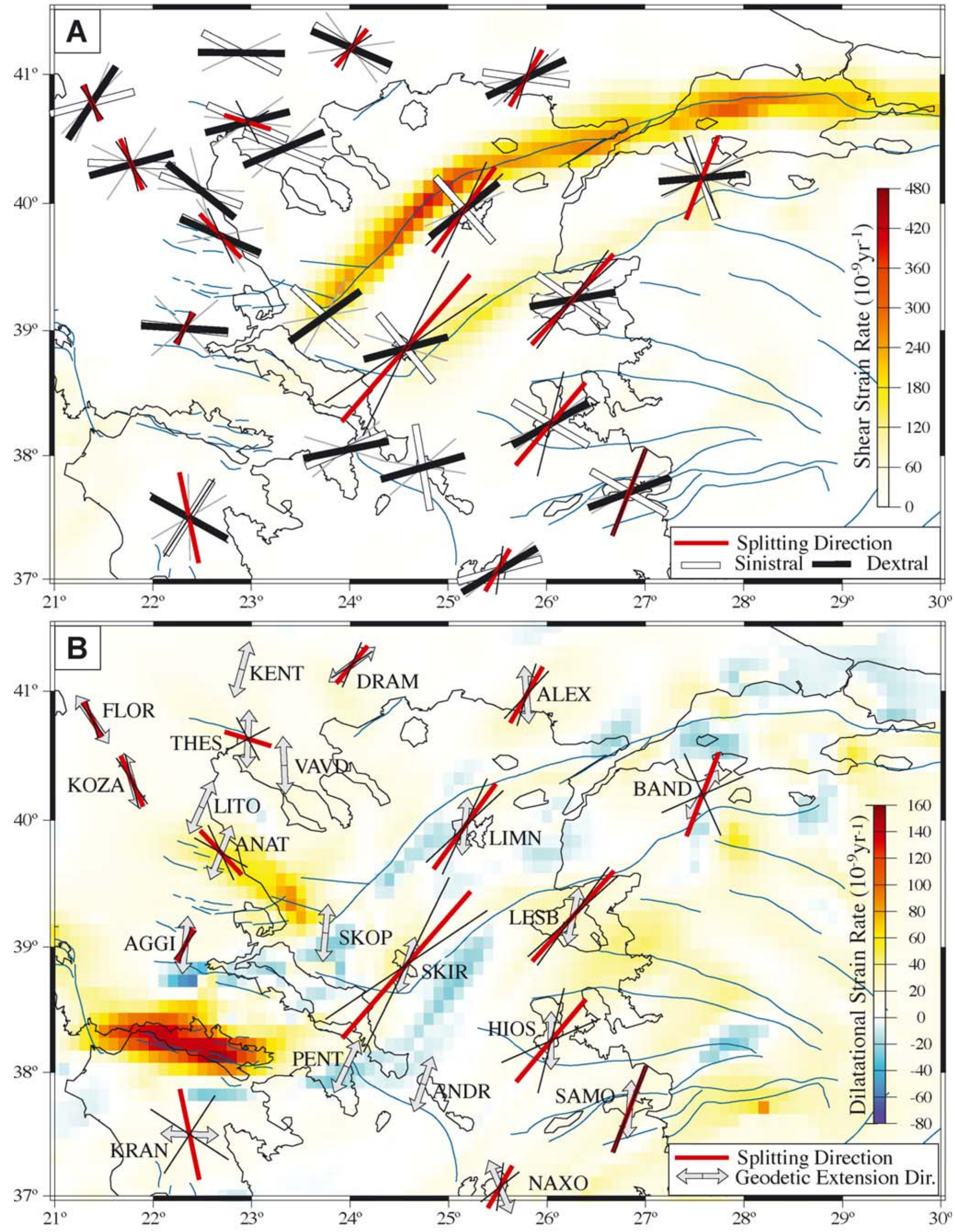

Fig. 6. (A) Contour plot of the shear strain rates associated with strain rate model in Fig. 3B. Shear-wave-splitting results [15] are shown by red bars ($1-\sigma$ angular uncertainties outlined by thin black lines). Also shown at all seismic stations are the orientations of no-length-change predicted by the model strain rate field; white and black bars reflect sinistral and dextral planes of shear, respectively. If the two bars are perpendicular, the planes of no-length-change are vertical and pure strike-slip is predicted. If the two bars overlap then the style of deformation is pure compressional or extensional and the no-length-change orientations are normal to the largest principal strain orientation. Thin grey lines outline $1-\sigma$ angular uncertainty in no-length-change directions (for clarity, we only show uncertainties for the dextral direction). For reference, major active faults are shown in blue. (B) Contour plot of the dilatational strain rate (positive is extensional) associated with strain rate model in Fig. 3B. The shear-wave-splitting results are repeated as in (A) and we also show in grey the (averaged) predicted extension orientations at all seismic stations. Station names are from [15].

The most characteristic feature of the preferred strain rate field model (Fig. 3B) is a continuous and relatively narrow zone of high shear strain rates that continues from the NAF through the Sea of Marmara, Saros Trough, and NAT, and abruptly terminates near Sporades, east of the Pilion peninsula (see also Fig. 6A). A second zone of minor shear extends between Lesbos in the east and central Evvia in the west. No significant shear rates are predicted in the remainder of the region. The CG is by far the most extensional structure in the region, as evidenced by high dilatational strain rates (Fig. 6B) (see also [19,35]). Another zone of relatively high extensional strain rates is predicted in Thessaly, west of the western-most extremity of the NAT. Furthermore, most of western Anatolia undergoes some level of diffuse extension, as found by others [3,19]. For most other areas, including the NAF–NAT system, significant dilatational strain rates are absent. In general, because of the additional constraints from active faulting, our obtained strain rate field is quite different from, for instance, the one obtained by [19], who inferred much broader zones of shear and extension. Our model with one major through-going fault zone that maintains a nearly constant slip rate from Anatolia to the Aegean Sea is more akin to the originally postulated ideas of [42] than to some more recent models (e.g., [43]). Orientations of the extensional strain axes are very similar between the GPS-alone model and our preferred model (Fig. 7), but our preferred model is better compatible with a scenario in which localised shear zones dominates the deformation regime, as constrained from the observations of localised seismicity, relatively narrow bathymetric lows, and onshore strain localisation.

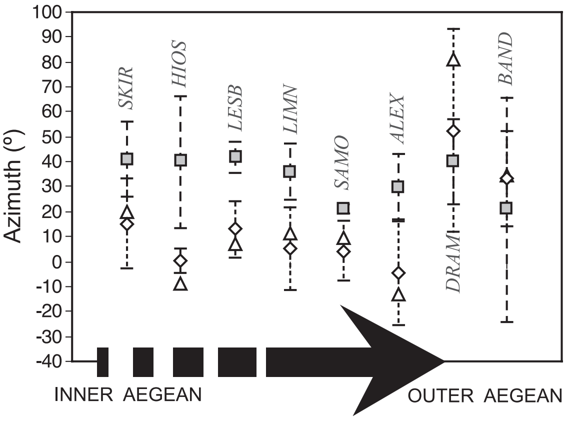

Fig. 7. Shear-wave-splitting azimuths (grey squares) [15] are plotted along with the predicted extension directions of our preferred model (Fig. 6B, open diamond) as well as for the GPS-alone model (open triangles). Long-dashed error bars are $1-\sigma$ uncertainties in shear-wave-splitting directions, and short-dashed error bars are $1-\sigma$ uncertainties in the extension directions of our preferred model.

4. Present-day crustal deformation versus fast polarization orientations

To investigate possible relationships between anisotropy in the lithospheric mantle and the present-day surface deformation field, we determine no-length-change orientations (Fig. 6A) and expected extensional strain rate orientations (Fig. 6B) from our model strain rate field at the locations for which shear-wave-splitting results are presented [15]. In addition, to facilitate this comparison we separate our strain rate model field into its shear and dilatational components (contours in Fig. 6A and B, respectively). No-length-change orientations are equivalent to the predicted planes of shear and are analogous to the nodal planes of an earthquake focal mechanism (e.g., [16]). Both the no-length-change and extension orientations are determined as averages over a 50-km radius around the seismic station, and results are also shown at stations where [15] found a null result. Note that, although we show principal extension orientations, the northern Aegean is not significantly extending at present, as discussed before and shown by the dilatational strain rates in Fig. 6B.

The anisotropy in the lithospheric mantle inferred from the splitting delay times [15] appears to be much more widespread than our model of the distribution of present-day crustal strain rates suggests. Furthermore, we find that SKS splitting orientations are at almost every station inconsistent with the orientations of predicted no-length-change (Fig. 6A). Moreover, at station SKOP on the island of Sporades, near the westernmost extremity of the active NAT, along which the model predicts high shear rates, [15] observed a ‘good null’. For most stations in the northern Aegean (ALEX, LIMN, LESB, SKIR, HIOS, and SAMO), present-day extension orientations (either associated with shear or with low-level dominant extension) are consistently 17–40° more N–S oriented than the splitting orientations (Figs. 6B and 7). The difference in extension direction is for most stations more than the $1-\sigma$ uncertainty of the observed splitting orientations and in most cases the formal errors of the observed and modelled directions do not overlap (Figs. 6B and 7). Good correlations between present-day extension orientations and splitting orientations are found at station BAND, located south of the Marmara Sea (although the splitting orientation has a large uncertainty), and DRAM in Rhodope (where strain rates are almost zero). Note that the differences between extension directions and shear-wave-splitting directions are also evident when we consider the GPS-alone model, consistent with what was presented by [15]. That is, almost all key conclusions of this study and the following discussions could have been made as well when only the GPS data were used to infer the present-day strain rate field.

5. Finite strain estimates of the crust

When the original crustal thickness of an area before the onset of extension is known and assumed to be laterally constant, crustal thickness measurements allow to quantify a β-factor, which gives insight in the amount of finite crustal strain [44]. For our area of interest (either as a whole or at one or more distinct points), many crustal thickness estimates have been presented using tomography [45], receiver functions [46–49], gravity [50], or combined refraction–gravity studies (e.g., [51]) and the results converge to 30–32 km for the northern Aegean Sea. However, seismological and gravimetrically derived crustal thickness estimates could be biased due to the fact that the often-used assumption of one single crustal layer may be an oversimplification. When the crust is multilayered, the true crustal structure and thickness may be different from the modelled estimates and a careful investigation of seismic structures or testing of alternative multilayered models to fit seismologic and gravity data is recommended. Wide-angle reflection and refraction data near the Cyclades and below the western NAT [52] and a receiver function analysis on the island of Samos [49] clearly indicate a distinct lower crust. It has been argued that a ductile lower crust in most of the Aegean domain has facilitated the large-scale extension that has governed crustal deformation in the northern Aegean during the Miocene (e.g., [53,54]). For both the Cyclades and North Aegean Trough, it has been shown that lateral variations in extension have been accommodated by large variations in the thickness of the lower crust, while the Moho has remained rather flat [52], compatible with lower crustal flow. Topography variations are thus likely to be compensated in the lower crust, suggesting a Basin and Range type of extension mechanism.

We are not greatly concerned with the question whether extension has thinned the crust as a whole or only its brittle portion, because we use crustal thickness estimates not as absolute measures but as indicators of lateral variations in finite strain. Although this assumption may not give us the desired finite strain estimates by means of a β-factor, we argue that lateral variations in gravitational or seismological-derived crustal thickness estimates probably indicate variations in extension-related crustal structure, regardless of whether the interpreted thickness estimates are biased or not. This assumption implies that before extension possible variations in crustal thickness were minor with respect to the present variations. Because our area of interest includes the deep basins of the northern Aegean, the western Anatolian margin, as well as Rhodope, Thrace and northwestern Anatolia, the lateral variation in finite strain may be significant enough to warrant a comparison between lateral variations in crustal extension and the delay times of splitted SKS phases.

6. Variations in finite crustal strain versus SKS splitting delay-time variations

In Fig. 8A, we have plotted lateral variations of shear-wave-splitting delay times [15] against crustal thickness estimates of [51]. The crustal models of Makris are generally determined on the basis of gravity and seismic data. Because the crustal thickness map of [51] is already presented as an interpolation, we have

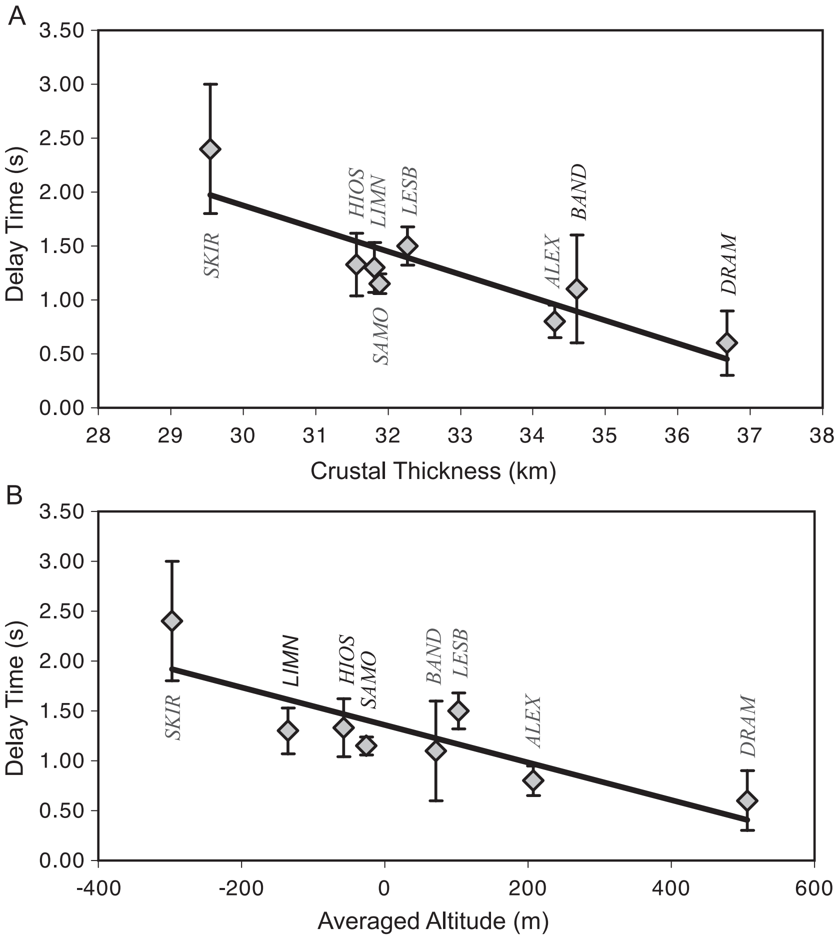

Fig. 8. (A) SKS splitting delay times [15] are plotted against crustal thickness estimates [51] at seismic station in northern Aegean that did not show a "null" measurement. (B) Delay times of stations versus altitude at seismic station from ETOPO5 database, with the altitude averaged over a region with ~20-km radius.

simply taken the predicted value at the station locations without averaging. We find a Pearson correlation coefficient R of -0.88 given eight observation points. Using Pearson's probability statistics, this value implies that there is a more than 99% chance that the found correlation is clinically negative (i.e., <-0.10). Although it may appear that the correlation is to a large extent determined by the fast delay time and small thickness for station SKIR, R is still -0.87 without this station. If the used crustal thickness estimates [51] prove to be erroneous, and if we assume that the crust is isostatically compensated (compatible with the inferred presence of ductile lower crust [52–54]), we can use variations in altitude as a measure of lateral variations in crustal extension. That is, unlike crustal thickness estimates, altitudes are unaffected by potential modelling biases and can give a valuable proxy of the relative amount of extension. We have calculated the altitude or water depth as average over a region around the station with a ~20-km radius and plotted it versus seismic delay time (Fig. 8B). We find that R is -0.84 for the linear relationship between delay times and altitude. Our results indicate that, taken into account that there are a limited number of data points, there is a strong negative correlation between the delay times observed in the shear-wave-splitting experiments [15] and altitude and crustal thickness variations. This observation suggests that delay-time variations in the mantle are positively correlated with finite crustal extension.

7. Discussion

7.1. How to reconcile crustal finite strain and seismic delay-time observations?

Lateral variations in seismic delay times reflect variation in either the path-length that the seismic wave travelled through the anisotropic layer (which for SKS waves is nearly analogous to the thickness of the layer) or the amount (and orientation variation) of in situ anisotropy, or both. In case the delay times reflect the thickness of the anisotropic layer, and if the in situ anisotropy is laterally and vertically constant, then the delay-time observations in the northern Aegean would suggest an anisotropic layer whose thickness varies laterally with a factor of 2–3. There are no reasons to believe that such variations are plausible, because tomographic studies [55–57] do not hint at strong lateral variations (with the exception of the presence of the Aegean slab to the south). Moreover, it is difficult to explain how the possibly thickest anisotropic layer would be placed underneath the places where the crust has thinned the most.

Thus, the delay-time variations are more likely the result of lateral varying in situ anisotropy. This would imply that the observed delay-time variation and its correlation with finite crustal extension hint at a positive correlation between the lateral variation in the amount of crustal and mantle strain, i.e., a relative large in situ anisotropy in the mantle can be found underneath the stations where crustal thinning appears to be the largest.

7.2. Vertical coherency

We show that anisotropy orientations in the lithospheric mantle underneath the northern Aegean are in relatively good agreement with extension orientations from the Late Oligocene–Late Miocene period as indicated by the stretching lineations (Fig. 2). Moreover, anisotropy orientations are generally subparallel to the crustal thickness gradient (Fig. 2). We thus argue for a vertical coherency in the finite strain orientation of the upper- to middle crust and lithospheric mantle.

Although directions of deformation appear to be vertically consistent, deformation rates may not be. Yet, the observed correlation between seismic delay time and indicators of crustal extension indicates that the lateral variations of crustal and mantle strain are consistent with one another. This correlation hints at a pure shear extension mechanism for the Miocene extension, affecting both crust and lithospheric mantle.

The consistency between the direction of and lateral variation in finite strain between the crust and mantle implies that the Miocene stretching is imprinted in the lithospheric mantle. The observed stretching lineations, crustal structure, and SKS splitting observations are thus all the result of the same Miocene extension. The fact that the mantle must have played an important part in the Miocene extensional phase is perhaps more clearly manifested in the southern Aegean. That is, for the Sea of Crete the high heat flow, thin crust, and large subsidence all indicate that the mantle has stretched there (e.g., [1]). Also, for some sites in western Anatolia (~100 km south of BAND) it has been argued that the β-factor has been the same for the crust as for the mantle lithosphere as a whole [48], implying that the whole lithosphere has been affected by the same amount of extension there.

7.3. Contributions of the lower crust to anisotropy

We would like to point out that the scenario described above could be somewhat different (but not enough to change its main gist) if a small part of the observed total delay time reflects anisotropy in the ductile lower crust. Crustal anisotropy has been observed in the Basin and Range province, which is in many ways similar to the Aegean extensional domain (e.g., [27,58]). For the Basin and Range province, splitting delay times due to crustal anisotropy (obtained from converted P_s waves at the Moho) are 0.2–0.3 s [59] and it is argued that the crustal anisotropy must reside in the lower ductile portion. These delay times caused by crustal anisotropy are small compared to the observed delay times in the northern Aegean. However, the possibility that we can expect a similar (or larger) amount of crustal anisotropy in the Aegean as is observed in the Basin and

Range needs to be kept open and, indeed, explored in future studies. Particularly, combined receiver function and P_s anisotropy measurements need to be carried out at a variety of locations in the northern Aegean. Such study would also address the trade-off between the amount of anisotropy of the lower ductile crust and its thickness.

If the extension in the Aegean is accommodated in similar ways as in Basin and Range, as suggested by observations of a flat Moho and large lateral variations in lower crustal thickness in the central Aegean [52], lower crustal flow may act as an important mechanism in accommodating part of the far-field extension. These observations suggest that finite strain can be different for the upper-, lower crust, and the mantle underneath. Other proposed extension mechanisms such as boudinage [60,61] or simple shear (core complex) mode (e.g., [53]) could also give different aspect ratios of crustal and mantle strain.

7.4. Change of the strain rate field since Plio-Pleistocene

As evidenced already by [15], we observe no correlation between splitting orientations and recognised planes of shear, even though at present the northern Aegean is dominated by shear (Fig. 6A). As to the agreement between fast polarization orientations and present-day extension orientations, we report a systematic misfit between the two for a large portion of the northern Aegean (Fig. 6B). The inconsistency between present-day strain rate orientations at the surface and the finite strain orientations at depth could imply either that deformation in most of the northern Aegean lithosphere is vertically incoherent or that there is an incoherency between the finite and infinitesimal strain field, or both. We show in this paper that at least for the Miocene the orientation and lateral variation of strain in the northern Aegean was probably vertically coherent. We therefore suggest that the cause of the observed discrepancies between the instantaneous surface deformation field and the finite deformation pattern at depth is a temporal evolution effect. The possibility that the brittle crust accommodates deformation in a different style than the lower crust and deeper (e.g., [29,54]) cannot yet be tested because that would require the knowledge of the present-day strain pattern at depth.

We propose that the deformation pattern has changed because of the recent prolongation of NAF into the Aegean domain. This is a very different interpretation than the one of [15] based on most of the same data. The prolongation of NAF has changed the dominating deformation mechanism in the northern Aegean from extension to shear. It is to be expected that the current presence of a major shear zone in the northern Aegean will, if enough time passes, align anisotropy in the lithospheric mantle parallel to the shear plane. For many other major shear zones, anisotropy in the lithospheric mantle has been shown to be oriented roughly parallel to the shear orientation over a 50–100 km (or perhaps more) wide zone normal to the major fault (e.g., [62]). At present, we observe that seismic anisotropy orientations are not clearly aligned with the optimal shear plane. Ultimately, with these observations in mind, we would like to place bounds on the amount of expected finite shear, and thus roughly on the time of initiation of the shear zone, that is required for anisotropy in the lithospheric mantle to be aligned with the orientation of shear. However, complexities dealing with the mechanisms creating LPO (particularly in a changing strain regime), the mineral composition, the vertical distribution of anisotropy, and the fact that for large strains the seismic anisotropy can be related to either elongation or shear orientations [22,63] make such calculations difficult at best. Nevertheless, regardless whether the shear strain in the northern Aegean is distributed (Fig. 3A) or localised as we propose (Figs. 3B and 6B), we do know with some certainty that the total shear strain rate is about 0.2–0.25 μstrain year^{-1} if we consider the shear zone to be a 100-km-wide zone. This chosen width is consistent with the observations (e.g., [62]) that for most strike-slip fault systems the horizontal transcurrent motion at depth is confined to a region narrower than 100 km. It is reasonable to assume that our inferred strain rate is the upper limit since the time the shear zone established itself. Estimates on the amount of required shear strain to rotate LPO in the shear plane are much more difficult to asses and vary dramatically based on experimental [64], numerical [22], or 'natural laboratory' (i.e., New Zealand's South Island) studies [65]. However, minimum values, when dynamic recrystallization is taken into account, are on the order of 100%. For smaller values of finite strain, LPO is expected to be at an angle with the shear plane. Thus, although uncertainties in both the parameters and general conceptions of strain–anisotropy relationships are large, we would expect at least ~4 My (and possible much longer) to pass before seismic anisotropy in the diffuse zone of shear underneath the northern Aegean would be aligned with the shear orientation.

Our calculations and postulated scenario are simple and ignore the many mentioned complexities. Yet, our obtained result can provide some constraints on which future studies can be build. Our result suggests that shearing in the northern Aegean is younger than ~4 Ma. This timing agrees well with geological indications that the kinematics have probably changed during the Pleistocene. Our result is also consistent with the timing of the origin of the CG and Kephalonia Fault (1.0–1.5 Ma) [66,67]. The origin of the CG has been argued to have originated as a result of the westward prolongation of the NAF [43,68]. Indeed, the proposed origin time of the CG would be after or concurrent with the time the NAF had captured the NAT and established the present shear zone in the northern Aegean. We thus conclude that the inconsistency between surface strain rate pattern and finite strain at depth can be explained by the change from an extensional to a shear regime in the northern Aegean during the Pleistocene.

8. Conclusions

For the northern Aegean, we observe an agreement between finite strain orientations in the middle-upper crust, inferred from Miocene stretching lineations in metamorphic core complexes, and anisotropy orientations in the lithospheric mantle, inferred from seismic polarization observations. Moreover, the finite strain orientations are subparallel with the regional crustal thickness gradient. In addition, lateral variations in SKS splitting delay times are negatively correlated with variations in crustal thickness estimates and altitude, which have both been used as an inverse proxy of lateral variations in extension-related finite strain. These correlations suggest that the anisotropy in the lithospheric mantle is the result of the long period of extension during the Miocene. To reconcile the fact that large delay times are observed there where the crust has thinned the most, it is likely that there is positive correlation between mantle and crustal finite strain, consistent with a pure shear extension mechanism for the lithosphere as whole. However, the possibility that part (i.e., a few tenths of a second) of the observed delay time at stations in the northern Aegean Sea proper originates in the ductile lower crust should not be excluded. Future studies are necessary, particularly to explore the presence and extent of crustal anisotropy.

In the northern Aegean, present-day crustal strain orientations, inferred from a new strain rate field model determined from GPS velocities and geological constraints, are not in agreement with the finite strain orientations at depth. We postulate that the present-day crustal strain rate field is associated with a recent kinematic framework that is dominated by shear in the northern Aegean, whereas the finite strain pattern at depth corresponds to the preceding period of extension. Simple calculations would predict that at least 4 Ma are needed to reorient (or establish) LPO in the shear-plane orientation. This result is consistent with the other arguments that the NAF propagated into the Aegean during the Pleistocene.

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