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New geodetic constraints on the role of faults and blocks versus distributed strain in the Nubia-Arabia-Eurasia zone of active plate interactions

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Abstract: We present a broad view of present-day motions and deformations derived from uniform processing of GNSS observations within the Nubia-Arabia-Eurasia zone of plate interaction. The new observations we present provide a ~29% increase in the number of velocity determinations, a reduction in average station spacing from ~76 km to ~39 km, and an improvement in velocity uncertainties (for <1 mm/year), from 180 to 578 sites compared to our prior published solution (Reilinger et al., 2006). We use these new constraints to better evaluate the role of faults and blocks in controlling the character of continental deformation within the zone of plate interactions. Simple elastic block models show that internal deformation of the region occurs in large part on mapped, seismically active fault systems, indicating elastic behavior of the seismogenic crust (above ~15 km). For example, eastern central Anatolia, an area of > ~126,000 km^2, bounded by the North and East Anatolian Faults exhibits internal velocity differences of <0.5 mm/year, indicating strain rates of < ~1.5 nanostrain/year. Geodetically constrained fault slip rates obtained from this simplified approach are comparable to geologic rates, indicating that major faults have controlled the recent geologic evolution of the region (i.e. 5–10 Myr). The pattern of present-day deformation, including increasingly fast motions towards the Hellenic trench, and the roughly simultaneous opening of all the major Mediterranean basins in the early Miocene with the slowing of the Nubia-Eurasia convergence, support conceptual models that foundering and rollback of the subducted Nubian slab beneath the Aegean is the primary mechanism responsible for present-day motion and internal deformation of the Anatolian-Aegean region.

Key words: Anatolia, Aegean, GNSS deformation, subduction, geodynamics, Mediterranean

1. Introduction

(Note: In this paper we use "Anatolia" to refer to all of Turkey between the North and East Anatolian faults and the Aegean coast; "Aegean region" refers to the Aegean Sea and adjacent Peloponnese; "East Anatolia (E Anatolia)" refers to the eastern section of the deforming Anatolia plate, not to the geographical definition of eastern Anatolia.)

The geology of the Anatolian-Aegean region, and indeed the Eastern Mediterranean, has been the focus of numerous early studies (see Dixon and Robertson, 1984, for overview), leading to the region becoming a "laboratory" for developing the principles of Plate Tectonics (e.g., McKenzie, 1972; Le Pichon and Angelier, 1979; Şengör and Yılmaz, 1981; Royden, 1993; Jackson, 1994). Subduction of the Tethys Ocean has dominated tectonic processes along the southern margin of Eurasia for the past >200 Myr (e.g., Agard et al., 2011). Since the early Miocene (~20 Myr), the active tectonics of the region has resulted from the interaction between the late stages of subduction of the Nubian oceanic lithosphere along the Hellenic-Cyprus subduction system, and the early stages of continental collision between Arabia and Eurasia, that at present involves an ~600 km-wide deformation zone (Jolivet and Faccenna, 2000; McQuarrie et al., 2003; McQuarrie and van Hinsbergen, 2013). Geological, seismological, and plate tectonic observations

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have provided important constraints on the evolution of the Anatolian-Aegean region including the decoupling of Anatolia and the Aegean from Eurasia and Arabia with the development of the North and the East Anatolian Faults (~11 and 5 Myr, respectively; e.g., Şengör et al., 2004; Yılmaz et al., 2006; Şengör and Yazıcı, 2020), back-arc extension of the Aegean and Corinth Gulf (Jackson, 1994; Armijo et al., 1996), and the ~north-south extension in western Anatolia (e.g., Şengör et al., 1984; Bozkurt and Satır, 2000). Furthermore, plate tectonic reconstructions and geologic investigations of paleo-fault slip rates suggest relatively steady rates of motions for Nubia (since ~11 Myr) and Arabia (since > 30 Myr) with respect to Eurasia, providing a roughly uniform temporal context in which to investigate relationships between plate interactions and lithospheric tectonics (McQuarrie et al., 2003; Hatzfeld and Molnar, 2010).

Beginning in the late 1980s, geodetic observations, most notably from Global Navigation Satellite Systems (GNSS), have allowed quantification of the spatial and temporal behavior of active deformation within the zone of interaction of the Arabia, Nubia and Eurasia plates, providing precise constraints on plate motions and broad-scale continental deformation (e.g., Oral et al., 1993; Smith et al., 1994; Le Pichon et al., 1995; Barka and Reilinger 1997; McClusky et al., 2000; Briole et al., 2000; Reilinger et al., 2006; Floyd et al., 2010; Nocquet, 2012). In this study, we present an updated GNSS velocity field for the Anatolia-Aegean region and surrounding areas (Figure 1). We take the approach of developing local reference frames for the Aegean and east Anatolia to better resolve subtle variation of motions within rapidly moving (i.e., with respect to Eurasia) regions. We use this broad view of plate motions and deformations to investigate the role of Nubian lithosphere subduction along the Hellenic-Cyprus subduction zone, and continental collision between Arabia and eastern Anatolia, in the active deformation of the Anatolia-Aegean region. Furthermore, to investigate the distribution of the deformations within the Anatolian plate, we developed a simplified block model. Two key results of this study are, within the resolution of present geodetic observations (~ <0.5 mm/year): firstly, the seismogenic crust (above ~ 15 km depth) deforms elastically, with a very broad area bounded by the North Anatolian Fault (NAF) and East Anatolian Fault (EAF) rotating with negligible internal strain; secondly, increasing rates of motion directed towards the Hellenic trench supports models in which foundering of the subducting Nubian slab along the Hellenic subduction zone is the principal driver of western Anatolia-Aegean motion and internal deformation (Le Pichon and Kreemer, 2010; Özeren and Holt, 2010; Reilinger and McClusky, 2011; Royden and Facenna, 2018). In support of this interpretation, our new observations demonstrate a close relationship between surface deformation and slab breaks/contortions along the Hellenic and Cyprus subduction zone system (Karabulut and Özbakır, 2018; Karabulut et al., 2019a).

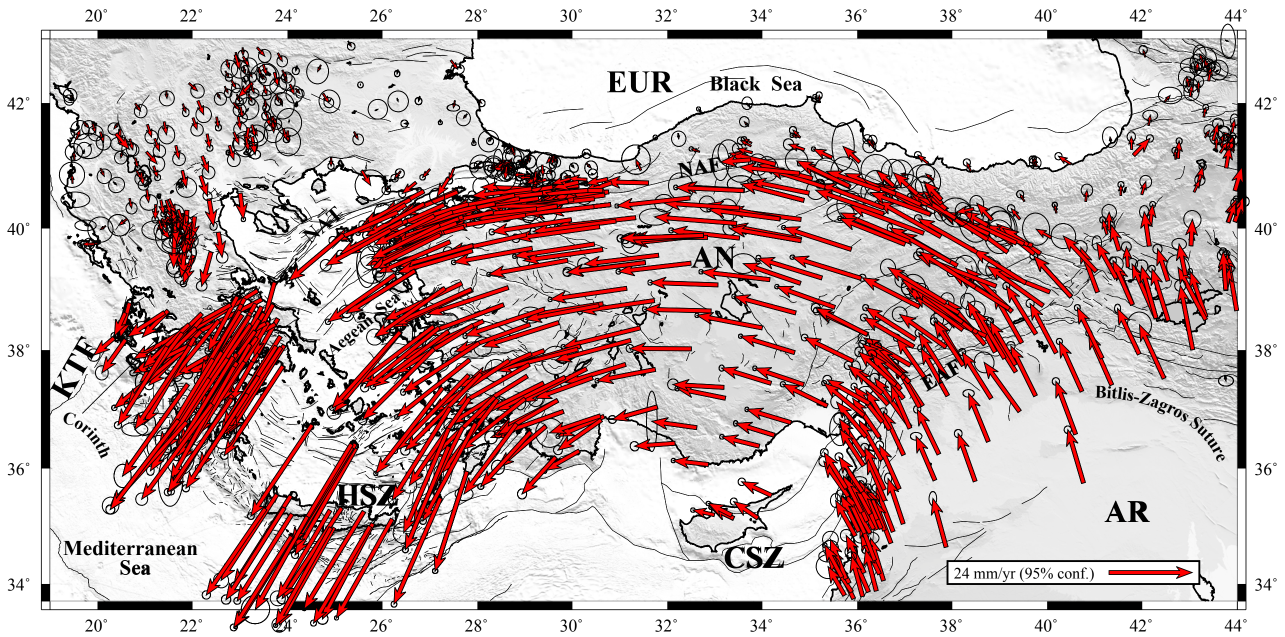

Figure 1. GNSS velocities and 95% confidence ellipses shown with respect to Eurasia (see text and Table S1 for details). Thin black lines show active faults (Ganas et al., 2013; Emre et al., 2013). Abbreviations: EUR = Eurasia, NAT = North Aegean Trough, KTF = Kephalonia Transform fault, HSZ = Hellenic subduction zone, CSZ = Cyprus subduction zone, AN = Anatolia, AR= Arabia, NAF= North Anatolian Fault, EAF = East Anatolian Fault.

2. GNSS data and analysis

GNSS velocities and associated uncertainties used in this study cover a period of 27 years from 1984 to 2018. All GNSS observations were analyzed uniformly in a single solution using the GAMIT/GLOBK software (Herring et al. 2018) as part of the updated version of a velocity solution covering the Eastern Mediterranean (Reilinger et al., 2006), following the approach described in Floyd et al., (2022). Hence, our velocity field is estimated from a uniform processing and is isolated from any effects of combined published velocity fields, obtained by the optimization of their reference frames in a common datum (e.g., Nocquet, 2012).

Daily solutions for each station were combined into position time series. All discontinuities in the time series (including coseismic displacements) were defined and estimated simultaneously with velocities, where velocities are equated before and after the discontinuity. At this stage, sites which have less than 2.4 years duration are excluded from our solution to minimize the potential bias introduced by seasonal variations (Blewitt and Lavallée, 2002; Blewitt and Lavallée, 2003). If statistically significant changes in velocity are found, multiple velocities are retained over different periods. In the case of significant postseismic motion, a few years of data after the event are excluded if the observations are sparse or otherwise fit with an additional logarithmic decay function in addition to the linear velocity (Ergintav et al., 2009; Ergintav et al., 2014). The only exception is the rupture zone of 1999 İzmit event (Mw 7.6). Within this zone, researchers reported ongoing shallow deformations (Çakır et al., 2012; Özarpacı et al., 2021) and we could not remove this local deformation anomaly from our velocity field but we isolated it during our interpretations.

To define the reference frame, a total of 14 IGS core stations included in the processing are used to estimate a consistent transformation (translation and rotation) to align our network velocity solution to the ITRF2014 (Altamimi et al., 2016). Euler pole parameters from the Altamimi et al. (2017) plate motion model were used to rotate the velocity field into a Eurasia-fixed reference frame. The weighted root-mean-square (WRMS) misfit of our velocity field to the reference frame is (e, n, u) = (0.17, 0.14, 0.38) mm/year (Floyd et al., 2022). Finally, we removed any sites whose formal (1-sigma) velocity uncertainties in either horizontal component is greater than 1.5 mm/year.

Within the frame of this study, we interpret only observations within the Anatolia- Aegean domain (Figure 1, Table S1). Table 1 summarizes the improvements in the new velocity field in our study area (longitudes 19.0°E–44.0°E, latitudes 33.7°N–43.0°N).

3. Analysis approach for the velocity field

In this study, instead of interpreting our observations with respect to Eurasia (Figure 1), we defined local reference frames to focus on subtle variations within the Anatolia-Aegean region. Figure 2 shows the same velocity field (Table S1) plotted with respect to E Anatolia, accomplished by rotating the full velocity field to minimize the relative motions between the GNSS sites circled in blue (their names are marked in Table S1). These sites were selected because of the small intersite relative velocities, and the low level of shallow seismicity in E Anatolia (Figure 3). To mark the low-level seismicity zones, we used the reviewed ISC catalog (Bondár and Storchak, 2011) (depth < 40 km, Mw > 4.5; between 1964 and 2022) that has accurate spatial resolution for this kind of classification (Figure 3).

Following Floyd et al. (2022), we use the same approach to better illustrate the deformation of the Aegean, using the same sites of Floyd et al. (2022) to minimize velocities and define a local Aegean reference frame (Figure 4, Table S1); as for E Anatolia, these sites are located in the area of low shallow seismicity in southwest Anatolia (Figure 3). Site names are marked in Table S1. Table 2 shows estimated Euler poles within these reference frames, relative to ITRF2014. The predicted internal motions (<1 mm/year) are around the upper bound for stable plate interiors (e.g., Argus and Gordon, 1996; Gordon, 1998), confirming the high degree of coherence of the selected zones.

Table 1. Improvements in the new velocity field compared with Reilinger et al. (2006).

Velocity field	# sites	Velocity uncertainties in both horizontal components	Minimum station distance
Reilinger et al., 2006	223	220 sites (98.7%) ≤ 2.0 mm/year 180 sites (80.7%) ≤ 1.0 mm/year 16 sites (7.2%) ≤ 0.5 mm/year	75.8 km
This study	783	726 sites (92.7%) ≤ 2.0 mm/year 578 sites (73.8%) ≤ 1.0 mm/year 298 sites (38.1%) ≤ 0.5 mm/year	39.3 km

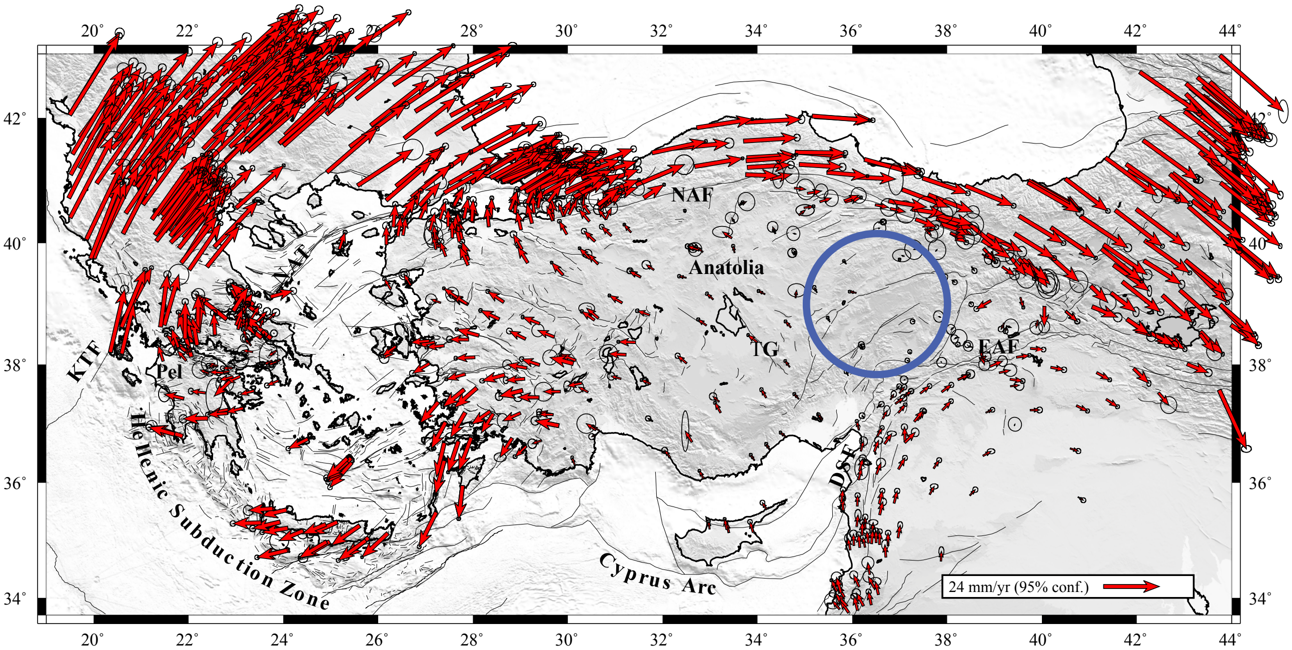

Figure 2. GNSS velocities and 95% confidence ellipses shown with respect to the eastern part of Anatolia. Sites within the blue circle were used to define the reference frame (their names marked in Table S1 as R2). Abbreviations: NAT = North Aegean Trough, Pel = Peloponnese, DSF = Dead Sea fault, KTF = Kephalonia Transform fault, NAF = North Anatolian Fault, EAF = East Anatolian Fault, TG = Tuz Gölü fault.

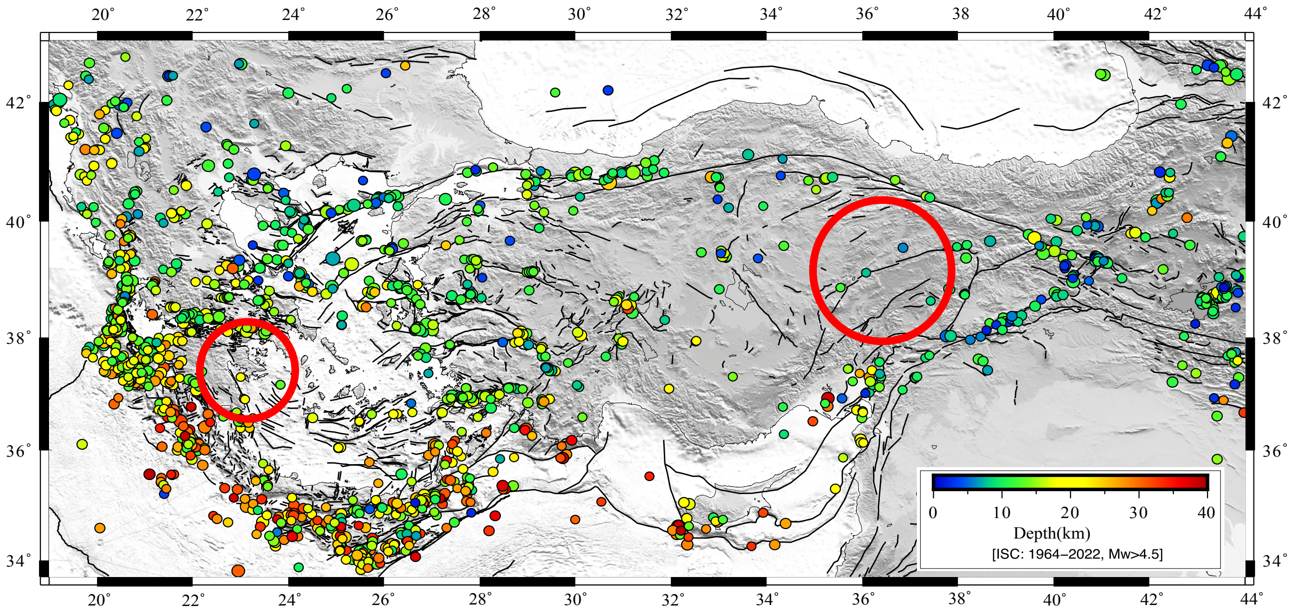

Figure 3. Shallow (depth < 40 km, Mw > 4.5) seismicity (from: Reviewed ISC Bulletin, 1964–2022) (Bondár and Storchak, 2011). Circles show areas used to define the reference frames in Figures 2 and 4. Thin black lines show active faults (Ganas et al., 2013; Emre et al., 2013). As expected, the activity coincides well with the fault zones.

To further quantify internal deformation within the Anatolia-Aegean region, we developed a simplified block model (McCaffrey, 2002), using the velocity field, with respect to E Anatolia (Figure 2) and major, seismically active faults (Figure 5; see Table S2 and Figure S1 for fault slip rates). Fault locking depths are constrained to 16 km, based on the depth of earthquakes along fault zones (Figure 3) (Wright et al., 2013). Many researchers

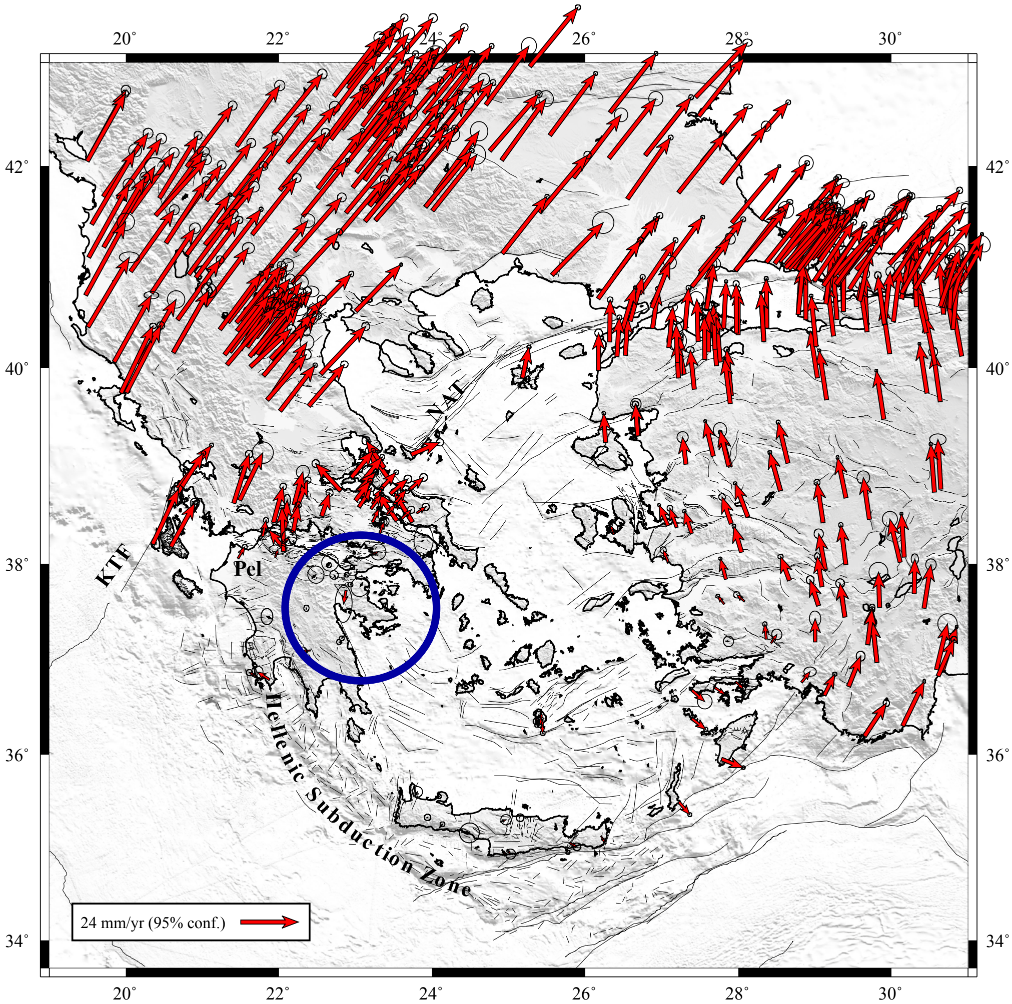

Figure 4. GNSS velocities and 95% confidence ellipses in and around the Aegean Sea region shown with respect to the southwestern Aegean (as Figure 2, see text for discussion). The blue circle shows the area of low seismicity identified in Figure 3 and the sites within were used to define the reference frame (their names marked in Table S2 as R3).

published different block models for the region (e.g., Reilinger et al., 2006; Aktuğ et al., 2009; Seyitoğlu et al., 2022), and others have investigated geodetic fault slip rates along the North and East Anatolian Faults directly from cross-fault observations (e.g., McClusky et al., 2000; Cavalié, and Jónsson, 2014; Ergintav et al., 2014; Vernant, 2015; and the references therein). Comparisons of geodetic fault slip rates are generally comparable to well-determined, longer-term geologic slip rate estimates (e.g., Hubert-Ferrari et al., 2002; Reilinger et al., 2006; Özbakır et al., 2017; Zabcı, 2019; Özbey 2022). Although we report model slip rates (Figure S1), the highly simplified block model is more appropriate to illustrate subtle variations within slowly deforming areas, providing upper bounds on the low internal deformation of large regions of the upper crust bordered by major fault zones.

Finally, to investigate possible links between processes in the upper mantle and the surface, we correlate the residuals of our highly simplified block model with tomographic images, including P wave velocity perturbations with respect to the AK135 velocity model (Kennett, 1995) at 100 km depth (Figure 6). The details of tomography are given in Karabulut et al. (2019a and 2019b).

4. Kinematics of the Anatolia-Aegean region

The velocity field shown in Figure 1 with respect to Eurasia (Table S1) better constrains well-known GNSS results for the active tectonics of the Anatolia-Aegean region referenced in the "Introduction", including (1) decoupling of Anatolia-Aegean from Eurasia along the NAF and its extension across the North Aegean Trough system and the

Table 2. Cartesian Euler Vectors and associated 1-sigma uncertainties (±) for the E Anatolia (EANATOLIA), West Aegean (WAEGEAN) reference frames, relative to ITRF2014. Abbreviations: Wx, Wy, Wz = Euler rotation rates around the X,Y,Z cartesian axes in degrees per million years (deg/Myr). RhoXY, RhoXZ, RhoYZ are the correlations between the X, Y, and Z rotation estimates.

Plate	ω_x (deg/Myr)	±	ω_y (deg/Myr)	±	ω_z (deg/Myr)	±	Covariance matrix		
							ρx	ρy	ρz
EANATOLIA	1.008722	0.075427	0.543127	0.057285	1.020384	0.076967	0.999	1.000	0.999
WAEGEAN	0.050898	0.101442	0.147426	0.044009	0.158303	0.083776	0.999	1.000	0.999

Corinth Gulf; (2) broad scale, counterclockwise rotation of Anatolia; (3) southwest motion of the Peloponnese and southern Aegean; and (4) rapid motion of the Hellenic trench over the subducting Nubian plate. Moreover, the new velocity field shows that the southward motion in northern Greece and the Balkans extends at least 300 km to the north of the Aegean Sea and involves clockwise rotation towards the western Hellenic trench.

Figure 2 shows the same velocity field with respect to E Anatolia, estimated by the methodology described in Section 3. This perspective illustrates well the internal deformation of Anatolia; in particular, right-lateral, elastic strain accumulation on the NAF, left-lateral motion across the EAF, and low internal deformation of Anatolia east of ~33°E, an area of over 126,000 km^2 with statistically significant velocities < 0.5 mm/year, indicating strain rates of < ~1.5 nanostrain/year. West of ~32°E, in SW Anatolia, velocities increase (due to the extension of Anatolia to the southwest) and rotate counterclockwise towards the Hellenic trench, inducing ~north-south extension across western Anatolia reaching ~20 mm/year (e.g., Aktuğ et al., 2009; Floyd et al., 2010). Additionally, new, subtle variations in the velocity field are apparent. For example, there is no resolvable convergence of Arabia with Anatolia across the EAF. Deformation is also transferred, at least in part, from the Dead Sea Fault Zone to the EAF in the northern part of Arabia and shows the spatial initiation stage of the diffuse tectonics in East Anatolia (Gomez et al., 2020). In the Marmara, there is no elastic strain accumulation resolvable around the southern branches of NAF and this part shows coherent internal deformation with the other parts of Anatolia at large scale. In the west, the Büyük Menderes graben system has a key role for the partitioning of north-south velocities.

To similarly illustrate deformation of the Aegean, we follow the same strategy used for E Anatolia to minimize velocities for defining a local reference frame (Table S1) using the same sites used by Floyd et al. (2022) located in the area of low shallow seismicity in the southwest Aegean (Figure 3); their names are marked in Table S1. This central Aegean reference frame (Figure 4) minimizes the large southwest motion of the southern Aegean and Peloponnese as a whole (~ 35 mm/year with respect to Eurasia, Figure 1), isolating the internal deformation of the Aegean. The small residual velocities throughout a broad area of the southern Aegean, northwest Crete, and the eastern Peloponnese (~50,000 km^2, Figure 4), and the close correlation between the region of low internal deformation (<1.5 mm/yr) and low levels of shallow seismicity (Figure 3), attest to the representative velocities of the sites used to define the local Aegean reference frame. This perspective illustrates well the concentration of deformation on the North Aegean Trough and Corinth Gulf (e.g., McClusky et al., 2000; Briole et al., 2000), low internal strain rates of the central and southern Aegean, and rapid trench-ward motion of the eastern side of the Hellenic subduction zone, and to a lesser extent the western side (western Peloponnese) (see Floyd et al., 2022, for a detailed description and interpretation).

5. Discussion

5.1. Kinematics

The velocity fields in Figures 1, 2, 4, and 5b provide an opportunity to investigate the contributions of distributed strain within crustal blocks, and deformation localized on block-bounding faults, to the overall deformation of the Anatolia-Aegean region. The continuously increasing GNSS velocities rotating toward the Hellenic subduction zone (Figure 1) have been interpreted to suggest that deformation is not confined to faults but can occur, at least in some areas, via aseismic, broadly distributed strain (e.g., Hatzfeld et al., 1997; Aktuğ et al., 2009; England et al., 2016; Barbot and Weiss, 2021). Figures 2 and 4 indicate broad areas of very low internal strain between the NAF and EAF in east Anatolia (E of 32°E), and within the Aegean Sea/Peloponnese, respectively. This low level of internal strain is remarkable given that E Anatolia is moving at ~20–25 mm/year and the Aegean at ~35 mm/year with respect to Eurasia, all occurring within the complex zone of the collision of Arabia and Nubia with Eurasia. As indicated by the simple block model in Figure 5, a broad region of western Turkey and the Aegean coast serves as an accommodation zone where deformation includes north-south extensional strain in southwestern-most

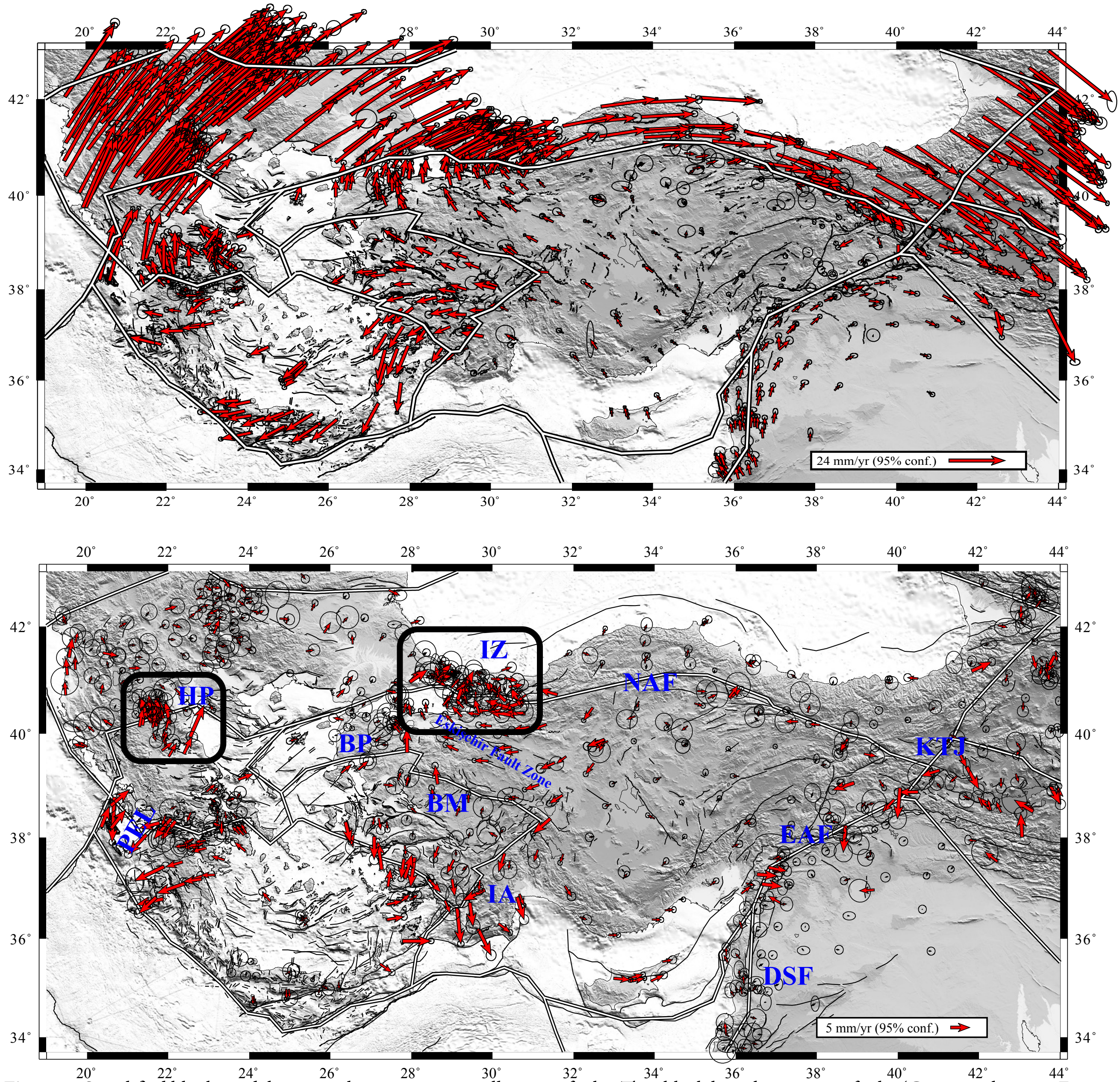

Figure 5. Simplified block model using only major, seismically active faults. Thin black line shows active faults (Ganas et al., 2013; Emre et al., 2013) and white lines indicate the border of the block model. (a) GNSS velocities plotted, with respect to E Anatolia reference frame for comparison to the model residuals. (b) GNSS residuals from the block model. Rectangles mark the GNSS sites affected by ongoing postseismic deformation of the Mw7.4/7.2, İzmit/Düzce earthquakes (IZ) (see Figure S2), and deformations of the very active zones around the Halkidiki Peninsula (HP). Abbreviations: BM = Büyük Menderes graben system, NAF = North Anatolian Fault, EAF = East Anatolian Fault, DSF = Dead Sea Fault, BP = Biga Peninsula, IA = Isparta Angle, KTJ = Karliova triple junction, PEL = Peloponnese.

Anatolia, and counterclockwise rotation of the Isparta Angle region that is superimposed on the broader rotation of Anatolia as a whole. The available geodetic observations are not sufficient to determine whether deformation in the accommodation zone is confined to faults or represents uniform aseismic strain, although the association with seismicity is apparent (Figure 3). We note that the larger trenchward motions in the Peloponnese, compared to those along the eastern Hellenic subduction zone are an artifact due to the greater number of well-determined GNSS velocities in the Peloponnese that bias the overall motion of the block towards the west.

As indicated in Figure 5, the main, well-known faults in our simplified block model account for the large majority of the observed deformation throughout the Anatolia-Aegean region, reducing the residual RMS of the velocities internal to Anatolia and the Aegean (Figures 2 and 4) by ~50%. It is notable that the large majority of strain accumulation across the NAF from the Karlıova triple junction to ~32°E (~700 km) can be accounted for with a single fault with uniform locking depth, and a single velocity for the Anatolian block (Vernant, 2015) (Figure S2). Together these observations attest well to the plate-like behavior of E Anatolia. However, further west where the Mw 7.6/7.4 İzmit/Düzce earthquakes occurred, and west of the main coseismic break in the Marmara region, the observed cross fault velocity profile requires a significantly shallower locking depth (<5 km; profile NAF10 on Figure S2). We interpret this as strain release that may be due to postseismic afterslip below the coseismic fault (Figures S2 and S3) (Ergintav et al., 2009; Çakır et al., 2012; Aslan et al., 2019; Özarpacı et al., 2021); possibly an indirect observation of a fault healing process. In the Sea of Marmara, the variations in fault coupling of fault segmentations occur as identified by Ergintav et al. (2014) (profile NAF10, 11 and 12 on Figure S2). Although the data are sparser, the same is roughly the case for the EAF (verified by InSAR by Cavalié and Jónsson 2014; Walters et al., 2014).

Residual velocities in western Anatolia are likely related to the Eskisehir fault zone (~3–4 mm/year) and Büyük Menderes (~5-6 mm/year) active graben system (Figure 5, e.g., Altunel and Barka, 1998; Bozkurt and Satır, 2000; Ocakoğlu, 2007), and those in southwestern Anatolia, east of the Hellenic subduction zone, to rotation of the Isparta Angle towards the Cyprus subduction zone (Tiryakioğlu et al., 2013). None of these well-known active faults were included in our simplified model. Scattered model residuals north and south of the western NAF are associated with deep, ongoing postseismic effects of the 1999 İzmit/Düzce earthquake sequence (Figure S3) as we discussed, above. Large residuals (>8 mm/year) in the Halkidiki (Thessaloniki) Peninsula, north of the Aegean Sea that show north-south extension is likely related to a system of seismically active, east-west-striking, normal faults traversing the peninsula (Martinod et al., 1997; Goldsworthy et al., 2002).

Furthermore, the North and East Anatolian Faults, (fault parallel velocities are 18-20 mm/year and 8-10 mm/year, respectively) and the Dead Sea Fault (fault parallel velocity is around 5 mm/year within our study area) in this simplified model have slip rates (Figure S1) that generally agree within uncertainties with longer-term geologic estimates (see Vernant, (2015) and Zabcı, (2019) for the North Anatolian Fault, and Gomez et al., (2020) and Reilinger et al., (2006), for the Dead Sea and East Anatolian Faults, respectively). We take the large reduction in internal strains of the Anatolia-Aegean region, with a very simplified block model, and the fact that many mapped, seismically active faults were not included in the model (Figures 3, 5a, and 5b), as evidence that the seismogenic crust (above ~15 km) behaves elastically, even within this zone of complex, interacting geodynamic processes.

5.2. Contribution to long-debated geodynamic problems

The well-defined counterclockwise rotation and increase in rates of surface motion in western Anatolia and the Aegean toward the Hellenic Subduction Zone have been attributed to (1) extrusion of Anatolia caught between the Arabian indenter and Eurasia (e.g., Şengör and Yılmaz, 1981), a hypothesis similar to that proposed for the India-Eurasia collision (e.g., Tapponier and Molnar, 1977); (2) rollback of the subducting Nubian ocean lithosphere along the Hellenic subduction zone (e.g., Le Pichon and Angelier, 1979; Royden, 1993; Burchfiel et al., 2000; Allmendinger et al., 2007; Le Pichon and Kreemer, 2010; Royden and Faccenna, 2018); and (3) flow within the lithosphere due to gravitational potential energy (GPE) differences between the high eastern Turkey Plateau and the Aegean/Hellenic trench (e.g., England and McKenzie, 1982; Jackson and McKenzie, 1984; Houseman and Molnar, 1997; England et al., 2016).

As shown by our systemic approach to analyzing the updated GNSS observations, the notion that Anatolia is at present being squeezed out of the Arabia-Eurasia collision zone is difficult to reconcile with the absence of shortening (Figure 2) across the Arabia-Eurasia boundary (Bitlis-Zagros suture zone and East Anatolian Fault), the lack of thrust faulting, the dominance of strike-slip and extensional earthquake mechanisms throughout Anatolia (e.g., Jackson, 1994; Jackson and McKenzie, 1984), and the increase in GNSS velocities from eastern to western Turkey (Figure 2, Figure S1). However, it is clear from plate reconstructions and the geologic evolution of the collision zone that the initial collision at ~25–30 Myr involved major indentation of Arabia into Eurasia and associated deformation and uplift of the Turkish-Iranian plateau (e.g., Şengör et al., 2003; McQuarrie et al., 2003; McQuarrie and van Hinsbergen, 2013). The transition from compression and uplift to the present-day tectonics of eastern Anatolia that are dominated by westward motion and velocity gradient towards the Hellenic subduction zone apparently became dominant with the development of the North Anatolian fault at ~11 Myr (Şengör et al., 2004). This interpretation is supported by a recent analysis of the Tuz-Gölü fault zone in eastern centralAnatolia that reports a change from thrust faulting to strike slip faulting, albeit with a slow rate (<3 mm/year), shortly after the formation of the NAF (Özbey, 2022). The low level of possible slip on the fault is further illustrated by the small residual relative velocities in eastern central Anatolia (Figure 2).

There is no doubt that the sublithospheric mantle flows, as this is required by Plate Tectonics, and the ocean lithosphere penetrates into the mantle. The Nubia-Eurasia plate collision itself provides further evidence that sublithospheric processes associated with the subducting Nubian slab influence surface deformation. The GNSS velocities (Figure 2) show that counterclockwise rotation of the Antalya-Isparta Angle region, is superimposed on the broader counterclockwise rotation of southwestern Anatolia, possibly responding to the subducting Nubia slab beneath Cyprus (Güvercin et al., 2021) that may be retarding faster westward motion of Cyprus (Figure 5). The fragmented structure east of the Hellenic subduction zone(Spakman and Wortel, 2004; Biryol et al., 2011; Karabulut et al., 2019a) also contributes to this region being more responsive to slab geometry and dynamics (Sternai et al., 2014). Figure 6 shows a seismic tomographic image of the region at 100 km depth, below the overriding Anatolian-Aegean lithosphere (Karabulut et al., 2019a, 2019b). There is a correlation between the velocity variations at depth in the tomographic images and block model residuals at the surface (Figure 6). The GNSS residuals computed from the simplified block model show large residuals in the region between the Hellenic and Cyprus subduction zones (Figure 6). While the residuals are relatively small along the plate boundaries (NAF and EAF) indicating narrow zones of deformation, they are much larger and diffused over the regions of the observed slab segmentations.

Anomalous trenchward motions at both ends of the Hellenic subduction zone are associated with breaks and/or sharp warping of the subducting plate (Spakman and Wortel, 2004; Barka and Reilinger, 1997; Biryol et al., 2011; Pearce et al., 2012; Karabulut et al., 2019b; Floyd et al., 2022). We suggest that the eastern slab tear detaches the Hellenic slab from the more shallow-dipping Cyprus slab beneath the eastern side of the subduction zone and back arc, allowing the eastern side of Hellenic slab to founder and inducing southwest extension of the overriding plate. We further point out that the eastward extent of rapid Anatolian extension (~32°E, Figures 2 and 5) corresponds roughly to the western edge of the Cyprus slab at ~33°E (Figure 6; see also, Biryol et al., 2011, their figure 7 and Karabulut et al., 2019a), perhaps allowing mantle to flow around the subducting plate, thereby promoting western Anatolia motion towards the trench (Le Pichon and Kreemer, 2010). Indeed, we suggest here that many features of Anatolian deformation may result from or be modified by the dynamics of the subducted plate and associated mantle flow.

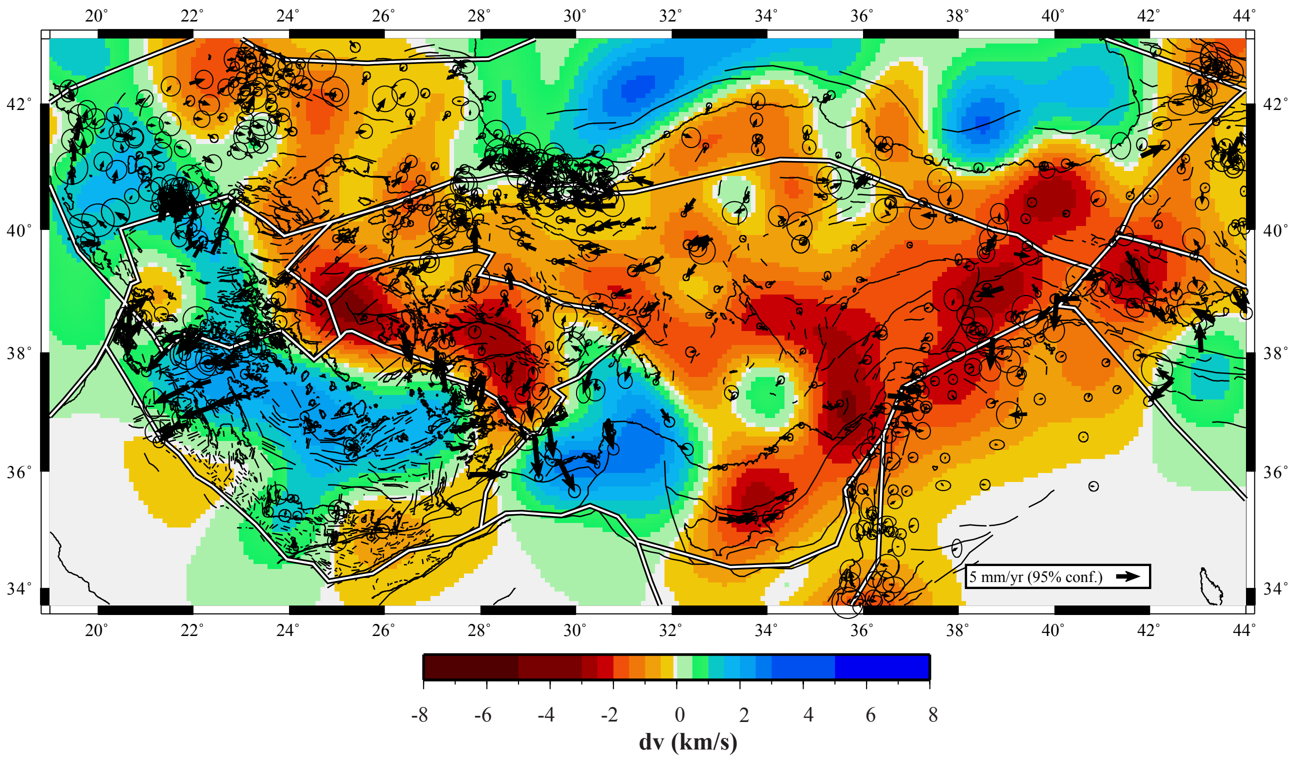

Figure 6. P wave velocity perturbations with respect to the AK135 model at 100 km depth (reference velocity is 8.1 km/s) showing the break in the subducting Nubia slab near the junction of the Hellenic and Cyprus subduction zones, the warp (or break) in the slab beneath the western side of the Hellenic subduction zone, and the eastern edge of the subducted slab beneath central Anatolia (Karabulut et al., 2018, 2019a) that corresponds to the location where Anatolia begins to extend and rotate towards the Hellenic subduction zone. Black arrows show the residual GNSS velocities of the simplified block model. Other map features are as described for Figures 1, 2, and 5

The absence of earthquakes below the upper crust (~15 km in western Anatolia and ~20 km in eastern Anatolia (Figure 3) and low GNSS residuals from our simplified block model (Figure 5b) are consistent with models where the lower crust is weaker than the upper crust, possibly as a result of thin lithospheric mantle beneath the Aegean-Anatolian region (e.g., Houseman and Molnar, 1997; Mutlu and Karabulut, 2011; Karabulut et al., 2018; Karabulut et al., 2019a). While the weaker lower crust is expected to deform in response to geodynamic processes, the contribution of GPE to tectonic interactions associated with the late stages of Nubia-Eurasia plate convergence is still debatable. We also note that the Arabian plate has penetrated at least 400 km into Eurasia's southern boundary since ~25 Myr with minimum slowing of Arabia (e.g., McQuarrie et al., 2003; Hatzfeld and Molnar, 2009), consistent with weak continental lithosphere, possibly weakened by a few 100 Myr of Tethys northward subduction (e.g., Şengör and Yılmaz, 1981; Barazangi et al., 2006).

The coincidental timing of the opening of the Mediterranean basins with the slowing of the rate of Nubia-Eurasia convergence in the early Miocene (McQuarrie et al., 2003), including the Alboran basin (Cloetingh et al., 1992), the Tyrannian basin (Dewey et al., 1989; Krijgsman and Garces, 2004), and the Aegean basin (Le Pichon and Angelier, 1979; Jackson, 1994; Jolivet and Faccenna, 2000), suggests that processes directly related to the slowing of Nubia, rather than those associated with the Arabia collision in E Anatolia, or processes internal to the Anatolia-Aegean lithosphere, are responsible for the initiation of basin extension. Turcotte and Shubert (2002, pg. 242-244) derive a simple analytical expression relating the dip angle of the subducting slab to the convergence rate. The model implies that, all else being equal, slab dip increases as the convergence rate decreases, supporting the hypothesis that slowing of Nubia-Eurasia plate convergence causes sinking of the subducting slab that, in turn, causes the plate interface to migrate out over the slab, inducing rapid extension in the overriding plate (e.g., Le Pichon X and Kreemer C, 2010; Reilinger and McClusky, 2011; Royden and Faccenna, 2018).

6. Conclusions

The principal results of our analysis of the most recent GNSS velocity field in and around the Anatolian-Aegean region are (1) the upper, seismogenic crust of this complexly deforming region, which involves continental collision and ocean subduction, behaves elasticallyand, to the best of our ability to measure crustal strain, deformation of the surface is controlled mostly by faulting; (2) there is no resolvable convergence of Arabia with Anatolia across the East Anatolian Fault that is the principal active boundary between these plates; (3) extensional strain rate and rotation of GNSS velocities in Anatolia and the Aegean region towards the Hellenic subduction zone, and the coincidence in the timing of extension of the major Mediterranean basins with slowing of Nubia-Eurasia convergence, support the hypothesis that the subducting slab is a dominant process responsible for motion and internal deformation of the Anatolia-Aegean region; and (4) comparison of surface deformation with a subsurface seismic tomographic image indicates that segmentation of the Hellenic and Cyprus slabs has a first-order influence on the active tectonics of the overriding Aegean-Anatolian domain.

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We have used GNSS data that are in the public domain (UNAVCO, IGS, EUREF) and in the supplementary materials of the previously published studies and open data repositories. We also provide the calculated velocity fields, with respect to selected velocity reference frames in the Auxiliary Section of this manuscript.

Supplementary Data

Supplementary data can be accessed at the following link: https://aperta.ulakbim.gov.tr/record/252404#.ZFziZS9Bxqs

References

Agard P, Omrani J, Jolivet L, Whitechurch H, Vrielynck B et al. (2011). Zagros orogeny: a subduction-dominated process. Geological magazine 148: 692-725. https://doi.org/10.1017/S001675681100046X

Argus DF, Gordon RG (1996). Tests of the rigid-plate hypothesis and bounds on intraplate deformation using geodetic data from very long baseline interferometry. Journal of Geophysical Research 101 (B6): 13555–13572. https://doi.org/10.1029/95jb03775

Aktuğ B, Nocquet JM, Cingöz A, Parsons B, Erkan Y et al. (2009). Deformation in western Turkey from a combination of permanent and campaign GPS data: Limits to block behavior. Journal of Geophysical Research 114: B10404. https://doi.org/10.1029/2008JB006000

Allmendinger RW, Reilinger R, Loveless J (2007). Strain and rotation rate from GPS in Tibet, Anatolia, and the Altiplano. Tectonics 26: TC3013. https://doi.org/10.1029/2006TC002030

Altamimi Z, Rebischung P, Métivier L, Collilieux X (2016). ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. Journal of Geophysical Research Solid Earth 121: 6109-6131. https://doi.org/10.1002/2016JB013098

Altamimi Z, Métivier L, Rebischung P, Rouby H, Collilieux X (2017). ITRF2014 plate motion model. Geophysical Journal International 209: 1906-1912. https://doi.org/10.1093/gji/ggx136

Altunel E, Barka A (1998). Eskişehir Fay Zonu'nun İnönü-Sultandere arasındaki neotektonik aktivitesi. Türkiye Jeoloji Bülteni 2: 41-52 (in Turkish with English abstract).

Armijo R, Meyer B, King G, Rigo A, Papanastassiou D (1996). Quaternary evolution of the Gulf of Corinth rift and its implications for the Late Cenozoic evolution of the Aegean. Geophysical Journal of the Royal Astronomical Society 126: 11-53. https://doi.org/10.1111/j.1365-246X.1996.tb05264.x

Aslan G, Lasserre C, Çakır Z, Ergintav S, Özarpaci S et al. (2019). Shallow creep along the 1999 Izmit earthquake rupture (Turkey) from GPS and high temporal resolution interferometric synthetic aperture radar data (2011–2017). Journal of Geophysical Research: Solid Earth 124: 2218– 2236. https://doi.org/10.1029/2018JB017022

Barazangi M, Sandvol E, Doğan D (2006). Structure and tectonic evolution of the Anatolian plateau in eastern Turkey. In: Dilek Y, and Pavlides S, (editors). Post-collisional tectonics and magmatism in the Mediterranean region and Asia, Geological Society of America, Special Paper 409: 463-474. https://doi.org/10.1130/2006.2409(22)

Barbot S, Weiss JR (2021). Connecting subduction, extension and shear localization across the Aegean Sea and Anatolia, Geophysical Journal International 226 (1): 422–445. https://doi.org/10.1093/gji/ggab078

Barka A, Reilinger R (1997). Active tectonics of the eastern Mediterranean region: Deduced from GPS, neotectonic, and seismicity data. Annali Geofisica 40: 587-610. https://doi.org/10.4401/ag-3892

Blewitt G, Lavallée D (2002). Effect of annual signals on geodetic velocity. Journal of Geophysical Research 107 (B7): 2145. https://doi.org/10.1029/2001JB000570

Blewitt G, Lavallée D (2003). Correction to "Effect of annual signals on geodetic velocity". Journal of Geophysical Research 108 (B1): 2010. https://doi.org/10.1029/2002JB002297

Biryol CB, Beck SL, Zandt G, Özacar AA (2011). Segmented African lithosphere beneath the Anatolian region inferred from teleseismic P-wave tomography. Geophysical Journal International 184: 1037-1057. https://doi.org/10.1111/j.1365-246X2010.04910.x

Bondár I, Storchak DA (2011). Improved location procedures at the International Seismological Centre. Geophysical Journal of International 186: 1220-1244. https://doi.org/ 10.1111/j.1365-246X.2011.05107.x

Bozkurt E, Satir M (2000). The southern Menderes Massif (western Turkey); geochronology and exhumation history. Geological Journal 35: 285–296. https://doi.org/10.1002/gj.849

Briole P, Rigo A, Lyon-Caen H, Ruegg JC, Papazissi K et al. (2000). Active deformation of the Corinth rift, Greece: Results from repeated Global Positioning System surveys between 1990 and 1995. Journal of Geophysical Research 105: 25605-25625. https://10.1029/2000JB900148

Burchfiel BC, Tzankov T, Nakov R, Royden LH (2000). Northern part of the Aegean extensional regime. Geological Society, London, Special Publications 173(1): 325-352. https://doi.org/10.1144/GSL.sp.2000.173.01.16

Cavalié O, Jónsson S (2014). Block-like plate movements in eastern Anatolia observed by InSAR. Geophysical Research Letters 41: 1-6. https://doi.org/ 10.1002/2013GL058170

Çakır Z, Ergintav S, Özener H, Doğan U, Akoğlu A et al. (2012). Onset of aseismic creep on major strike-slip faults. Geology 40 (12): 1115– 1118. https://10.1130/G33522.1

Cloetingh S, van der Beek A, van Rees D, Roep TB, Biermann C et al. (1992). Flexural interaction and the dynamics of Neogene extensional basin formation in the Alboran-Betic region. Geo Marine Letters 12: 66-75. https://doi.org/10.1007/BF02084914

Dewey JF, Helman ML, Turko E, Hutton DH, Knott SD (1989). Kinematics of the western Mediterranean. Geological Society London Special Publications 45: 265-283. https://doi.org/10.1144/GSL.SP.1989.045.01.15

Dixon JE, Robertson AHF (1984). The Geological Evolution of the Eastern Mediterranean. Geological Society, London, Special Publications, 17. https://doi.org/10.1144/GSL.SP.1984.017.01.02

Emre O, Duman TY, Özalp S, Olgun S, Şaroğlu F (2013). Active Fault Map of Turkey with an Explanatory Text, General Directorate of Mineral Research and Exploration, Special Publication Series 30, Ankara, Turkey.

England P, McKenzie D (1982). A thin viscous sheet model for continental deformation. Geophysical Journal International 70 (2): 295-321. https://doi.org/10.1111/j.1365-246X.1982.tb04969.x

England P, Howell A, Jackson, Synolakis C (2015). Paleotsunamis and tsunami hazards in the Eastern Mediterranean. Philosophical Transactions of the Royal Society A 373: 20140374-20140374. http://doi.org/10.1098/rsta.2014.0374

England P, Houseman G, Nocquet JM (2016). Constraints from GPS measurements on the dynamics of deformation in Anatolia and the Aegean. Journal of Geophysical Research 121: 8888–8916. https://doi.org/10.1002/2016JB013382

Ergintav S, McClusky S, Hearn E, Reilinger RE, Çakmak R et al. (2009). Seven years of postseismic deformation following the 1999, M = 7.4 and M = 7.2, Izmit-Düzce, Turkey earthquake sequence. Journal of Geophysical Research 114: B07403. https://doi.org/10.1029/2008JB006021

Ergintav S, Reilinger RE, Çakmak R, Floyd M, Çakır Z et al. (2014). Istanbul's earthquake hot spots: Geodetic constraints on strain accumulation along faults in the Marmara seismic gap. Geophysical Research Letters 41: 5783-5788. https://doi.org/10.1002/2014GL060985

Floyd MA, Billiris H, Paradissis D, Veis G, Avallone A et al. (2010). A new velocity field for Greece: Implications for the kinematics and dynamics of the Aegean. Journal of Geophysical Research 115: B10403. https://doi.org/10.1029/2009JB007040

Floyd MA, King R, Paradisis D, Karabulut S, Ergintav S et al. (2022). Variations in Coupling and Deformation Along the Hellenic Subduction Zone. Turkish Journal of Earth Sciences.

Ganas A, Oikonomou I, Tsimi C (2013). NOA faults: a digital database for active faults in Greece. Bulletin of the Geological Society of Greece 47 (2): 518-530. https://doi.org/10.12681/bgsg.11079

Goldsworthy M, Jackson J, Haines J (2002). The continuity of active fault systems in Greece. Geophysical Journal International 148: 596-618. https://doi.org/10.1046/j.1365-246X.2002.01609.x

Gomez FW, Cochran R, Yassminh R, Jaafar R, Reilinger R et al. (2020). Fragmentation of the Sinai Plate indicated by spatial variation in present-day slip rate along the Dead Sea Fault system. Geophysical Journal International 221 (3): 1913-1940. https://doi.org/10.1093/gji/ggaa095

Gordon RG (1998). The plate tectonic approximation: Plate nonrigidity, diffuse plate boundaries, and global plate reconstructions. Annual Review of Earth and Planetary Sciences 26 (1): 615–642. https://doi.org/10.1146/annurev.earth.26.1.615

Güvercin SE, Konca AÖ, Özbakır AD, Ergintav S, Karabulut H (2021). New focal mechanisms reveal fragmentation and active subduction of the Antalya slab in the Eastern Mediterranean. Tectonophysics 805: 228792. https://doi.org/10.1016/j.tecto.2021.228792

Hatzfeld D, Martinod J, Bastet G, Gautier P (1997). An analog experiment for the Aegean to describe the contribution of gravitational potential energy. Journal of Geophysical Research 102 (B1): 649– 659, https://doi.org/10.1029/96JB02594

Hatzfeld D, Molnar P (2010). Comparisons of the kinematics and deep structures of Zagros and Himalaya and of the Iranian and Tibetan plateaus and geodynamic implications. Reviews Geophysics 48: RG2005. https://doi.org/10.1029/2009RG000304

Herring TA, King RW, Floyd MA, McClusky SC (2018). Introduction to GAMIT/GLOBK. In release 10.7, pp. 54, Massachusetts Institute of Technology.

Houseman GA, Molnar P (1997). Gravitational (Rayleigh-Taylor) instability of a layer with non-linear viscosity and convective thinning of continental lithosphere. Geophysical Journal International 128(1): 125–150. https://doi.org/10.1111/j.1365-246X.1997.tb04075.x

Hubert-Ferrari A, Armijo R, King G, Meyer B, and Barka A (2002). Morphology, displacement, and slip rates along the North Anatolian Fault, Turkey. Journal of Geophysical Research: Solid Earth 107: 2235. https://doi.org/10.1029/2001JB000393

Jolivet L, Faccenna C (2000). Mediterranean extension and the Africa-Eurasia Collision. Tectonics 19: 1095-1106. https://doi.org/10.1029/2000TC900018

Jackson J, McKenzie DP (1988). The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East. Geophysical Journal International 93: 45-73. https://doi.org/10.1111/j.1365-246X.1988.tb01387.x

Jackson J (1994). Active tectonics of the Aegean region. Annual Review of Earth and Planetary Sciences 22: 239-271. https://doi.org/10.1146/annurev.ea.22.050194.001323

Karabulut H, Özbakır AD (2018). Pn tomography of the Eastern Mediterranean Region. In: EGU General Assembly Conference Abstracts; Vienna. Vol. 20, p. 8663.

Karabulut H, Aksarı D, Değer Özbakır AD, Paul A (2019a). A new P-wave tomographic model of the Aegean-Anatolia Domain and its implications for small scale dynamics. In: EGU General Assembly Conference Abstracts; Vienna. Vol. 21, p. 10365.

Karabulut H, Paul A, Özbakır AD, Ergün T, Şentürk S (2019b). A new crustal model of the Anatolia–Aegean domain: evidence for the dominant role of isostasy in the support of the Anatolian plateau. Geophysical Journal International 218 (1): 57–73. https://doi.org/10.1093/gji/ggz147

Kennett BLN, Engdahl ER and Buland R (1995). Constraints on seismic velocities in the Earth from traveltimes. Geophysical Journal International 122 (1): 108-124. https://doi.org/10.1111/j.1365-246X.1995.tb03540.x

Kreemer C, Blewitt G, Klein EC (2014). A geodetic plate motion and Global Strain Rate Model. Geochemistry, Geophysics, Geosystems 15(10): 3849-3889. https://doi.org/10.1002/2014GC005407.

Krijgsman, W, Garces M (2004). Paleomagnetic constraints on the geodynamic evolution of the Gibraltar arc.Terra Nova 16 (5): 281-287. https://doi.org/10.1111/j.1365-3121.2004.00564.x

Le Pichon X, Angelier J (1979). The Hellenic arc and trench system: A key to the evolution of the Eastern Mediterranean area. Tectonophysics 60: 1-42.

Le Pichon X, Chamot-Rooke N, Lallemant S, Noomen R, Veis G (1995). Geodetic determination of the kinematics of central Greece with respect to Europe: Implications for eastern Mediterranean tectonics. Journal of Geophysical Research 100 (B7): 12: 675-690. https://doi.org/10.1029/95JB00317

Le Pichon X, Kreemer C (2010). The Miocene to present kinematic evolution of the Eastern Mediterranean and Middle East and its Implications for dynamics. Annual Reviews Earth Planetary Sciences 38: 323-351. https://doi.org/10.1146/annurev-earth-040809-152419

Martinod J, Hatzfeld D, Savvaidis P, Kasambalos K (1997). Rapid N-S extension in the Mygdonian graben (northern Greece) deduced from repeated geodetic surveys. Geophysical Research Letters 24: 3293-3296. https://doi.org/10.1029/97GL03186

McCaffrey R (2002). Crustal block rotations and plate coupling. Plate Bounday Zones. In: Stein S, Freymueller J (editors). Geodynamic Series 30: 101-122, AGU, Washington, DC. https://doi.org/10.1029/GD030p0101

McClusky S, Balassanian S, Barka A, Demir C, Ergintav S et al. (2000). Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. Journal of Geophysical Research 105 (B3): 5695– 5719. https://doi.org/10.1029/1999JB900351

McKenzie DP (1972). Active tectonics of the Mediterranean region. Geophysical Journal of the Royal Astronomical Society 30: 109-185. https://doi.org/10.1111/j.1365-246X.1972.tb02351.x

McQuarrie N, Stock JM, Verdel C, Wernicke BP (2003). Cenozoic evolution of the Neotethys and implications for the causes of plate motions. Geophysical Research Letters 30: 2036. https://doi.org/10.1029/2003GL017992

McQuarrie N, van Hinsbergen DJJ (2013). Retrodeforming the Arabia-Eurasia collision zone: Age of collision versus magnitude of continental subduction. Geology 41: 315-318. https://doi.org/10.1130/G33591.1

Mutlu AK, Karabulut H (2011). Anisotropic Pn tomography of Turkey and adjacent regions. Geophysical Journal International 187 (3): 1743-1758. https://doi.org/10.1111/j.1365-246X.2011.05235.x

Nocquet JM (2012). Present-day kinematics of the Mediterranean: A comprehensive review of GPS results. Tectonophysics 579: 220-242. https://doi.org/10.1016/j.tecto.2012.03.037

Ocakoğlu F (2007). A re-evaluation of the Eskisehir fault zone as a recent extensional structure in NW Turkey. Journal of Asian Earth Sciences 31: 91-103. https://doi.org/10.1016/j.jseaes.2007.05.002

Oral MB, Reilinger RE, Toksöz MN, Barka A, Kınık I (1993). Preliminary Results of 1988 and 1990 GPS Measurements in Western Turkey and their Tectonic Implications. In: Smith DE, Turcotte DL (editors), Contributions of Space Geodesy to Geodynamics: Crustal Dynamics, Crustal Dynamics Series 23, American Geophysical Union, Washington.

Özbey V, Şengör AMC, Özeren M (2022). Tectonics in a very slowly deforming region in an orogenic belt. Tectonophysics 827: 229272. https://doi.org/10.1016/j.tecto.2022.229272

Özeren M, Holt W (2010). The dynamics of the eastern Mediterranean and eastern Turkey. Geophysical Journal International 183 (3): 1165–1184. https://doi.org/10.1111/j.1365-246X.2010.04819.x

Özarpacı S, Doğan U, Ergintav S, Çakır Z, Özdemir A et al. (2021) Present GPS velocity field along 1999 Izmit rupture zone: evidence for continuing afterslip 20 yr after the earthquake, Geophysical Journal International 224 (3): 2016–2027. https://doi.org/10.1093/gji/ggaa560

Özbakır AD, Govers R, Wortel R (2017). Active faults in the Anatolian-Aegean plate boundary region with Nubia. Turkish Journal of Earth Sciences 16: 30-56. https://doi.org/10.3906/yer-1603-4

Pearce F, Rondenay D, Sachpazi S, Charalampakis M, Royden LH (2012). Seismic investigation of the transition from continental to oceanic subduction along the western Hellenic Subduction Zone. Journal of Geophysical Research 117: B07306. https://doi:10.1029/2011JB009023

Reilinger R, McClusky S (2011). Nubia-Arabia-Eurasia plate motions and the dynamics of Mediterranean and Middle East tectonics. Geophysical Journal International 186: 971-979. https://doi.org//j.1365-246X.2011.05133.x

Reilinger R, McClusky S, Vernant P, Lawrence S, Ergintav S et al. (2006). GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions. Journal of Geophysical Research 111: B05411. https://doi.org/10.1029/2005JB004051

Royden L (1993). The tectonic expression of slab pull at continental convergent boundaries. Tectonics 12: 303-325. https://doi.org/10.1029/92TC02248

Royden L, Faccenna C (2018). Subduction orogeny and the late Cenozoic evolution of the Mediterranean arcs. Annual Review of Earth and Planetary. Sciences 46: 261-89. https://doi.org/10.1146/annurev-earth-060115-012419

Seyitoğlu G, Aktuğ B, Esat K, Kaypak B (2022). Neotectonics of Turkey (Türkiye) and surrounding regions: a new perspective with block modelling. Geologica Acta, 20 (4): 1-21. https://doi.org/10.1344/GeologicaActa2022.20.4

Şengör AMC, Tüysüz O, İmren C, Sakinc M, Eyidogan H (2004). The North Anatolian fault: A new look. Annual Reviews of Earth and Planetary Sciences 33: 1-75. https://doi.org/10.1146/annurev.earth.32.101802.120415

Şengör AMC, Özeren S, Genç T, Zor E (2003). East Anatolian high plateau as a mantle-supported, north-south shortened domal structure. Geophysical Research Letters 30: 8045. https://doi.org/10.1029/2003GL017858

Şengör AMC, Görür N, Şaroğlu F (1985). Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study, in Strike--slip Faulting and Basin Formation. IN: Biddle KT, Christie-Blick N (editors). Society of Economic Paleontologists and Mineralogists 37: 227-264. https://doi.org/10.2110/pec.85.37.0227

Şengör AMC, Satır M, Akkök R (1964). Timing of tectonic events Menderes Massif, western Turkey: Implications for tectonic evolution and evidence for Pan-African basement in Turkey. Tectonics 3: 693-707. https://doi.org/10.1029/TC003i007p00693

Şengör AMC, Yazıcı M (2020). The aetiology of the neotectonic evolution of Turkey. Mediterranean Geoscience Reviews 2: 327–339. https://doi.org/10.1007/s42990-020-00039-0

Şengör AMC, Yılmaz Y (1981). Tethyan evolution of Turkey: A plate tectonic approach. Tectonophysics 75: 181-241. https://doi.org/10.1016/0040-1951(81)90275-4

Smith DE, Kolenkiewicz R, Robbins JW, Dunn PJ, Torrence MH (1994). Horizontal crustal motion in the central and eastern Mediterranean inferred from Satellite Laser Ranging measurements. Geophysical Research Letters 21: 1979-1982. https://doi.org/10.1029/94GL01612

Spakman W, Wortel R (2004). A Tomographic View on Western Mediterranean Geodynamics. In: Cavazza, W., Roure, F., Spakman, W., Stampfli, G.M., Ziegler, P.A. (editors) The TRANSMED Atlas. The Mediterranean Region from Crust to Mantle. Springer, Berlin, Heidelberg.

Sternai P, Jolivet L, Menant A, Gerya T (2014). Driving the upper plate surface deformation by slab rollback and mantle flow. Earth and Planetary Science Letters 405: 110-118. https://doi.org/10.1016/j.epsl.2014.08.023

Tiryakioğlu İ, Floyd M, Erdoğan S, Gülal E, Ergintav S et al. (2013). GPS constraints on active deformation in the Isparta Angle region of SW Turkey. Geophysical Journal International 195 (3): 1455–1463. https://doi.org/10.1093/gji/ggt323

Turcotte DL, Shubert G (2002). Geodynamics, 2nd edition, Cambridge Univ. Press, Cambridge, UK.

Vernant P (2015). What can we learn from 20 years of interseismic GPS measurements across strike-slip faults? Tectonophysics 644-645: 22-39. https://doi.org/10.1016/j.tecto.2015.01.013-0040-1951

Walters RJ, Parsons B, Wright TJ (2014). Constraining crustal velocity fields with InSAR for Eastern Turkey: Limits to the block-like behavior of Eastern Anatolia. Journal of Geophysical Research Solid Earth 119: 5215– 5234. https://doi.org/10.1002/2013JB010909

Wright TJ, Elliott JR, Wang H, Ryder I (2013). Earthquake cycle deformation and the Moho: Implications for the rheology of continental lithosphere. Tectonophysics 609: 504-523. https://doi.org/ 10.1016/j.tecto.2013.07.029

Yılmaz H, Över S, Özden S (2006). Kinematics of the East Anatolian fault between Türkoğlu (Kahramanmaraş) and Çelikhan (Adıyaman), Earth, Planets, and Space 58 (11): 1463-1473. https://doi.org/10.1186/BF03352645

Zabcı C (2019). Spatio-temporal behaviour of continental transform faults: implications from the late Quaternary slip history of the North Anatolian Fault, Turkey. Canadian Journal of Earth Sciences 56 (11): 1218-1238. https://doi.org/10.1139/cjes-2018-0308