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Deformation of continental blocks within convergent plates: Anatolia as a case study

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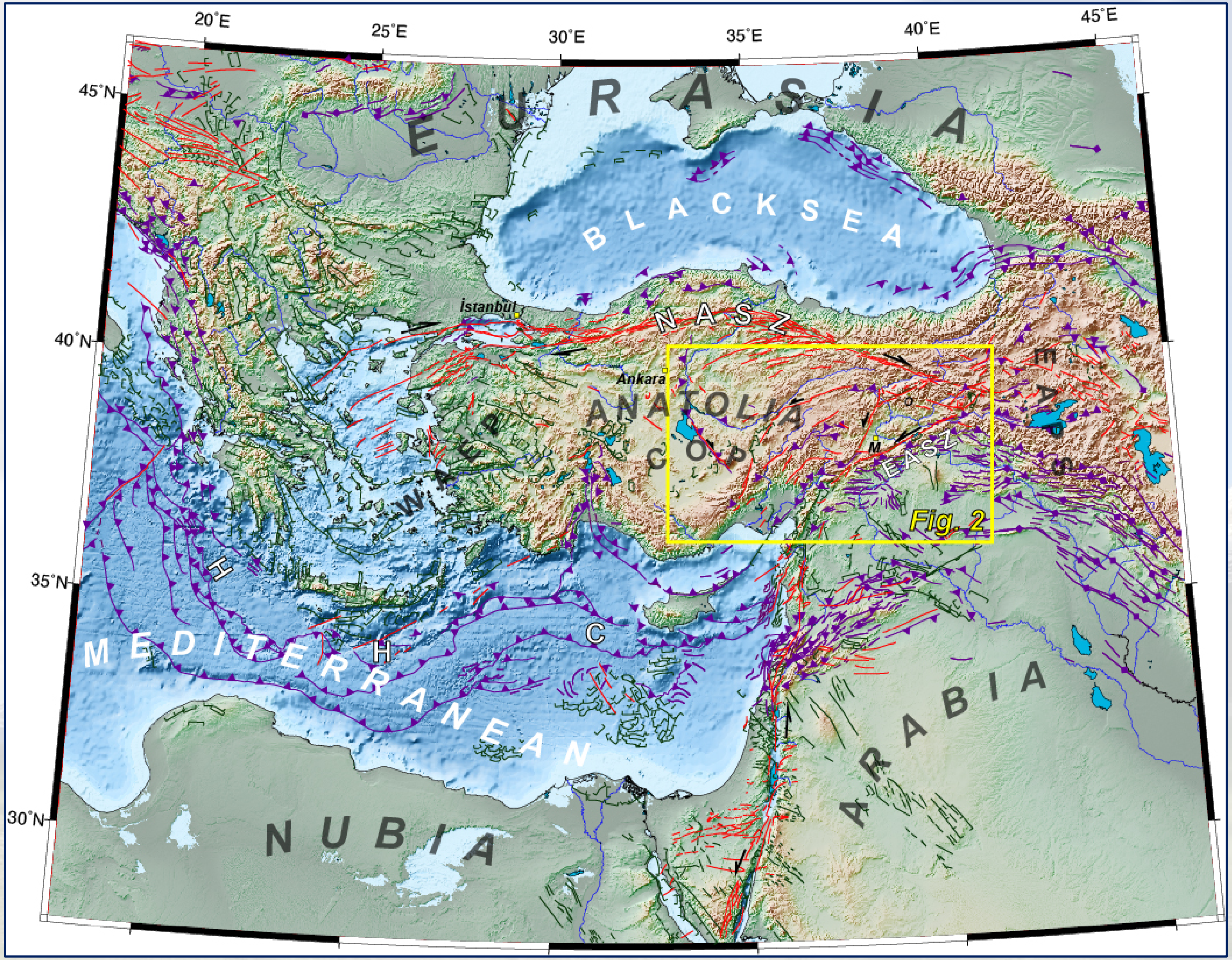
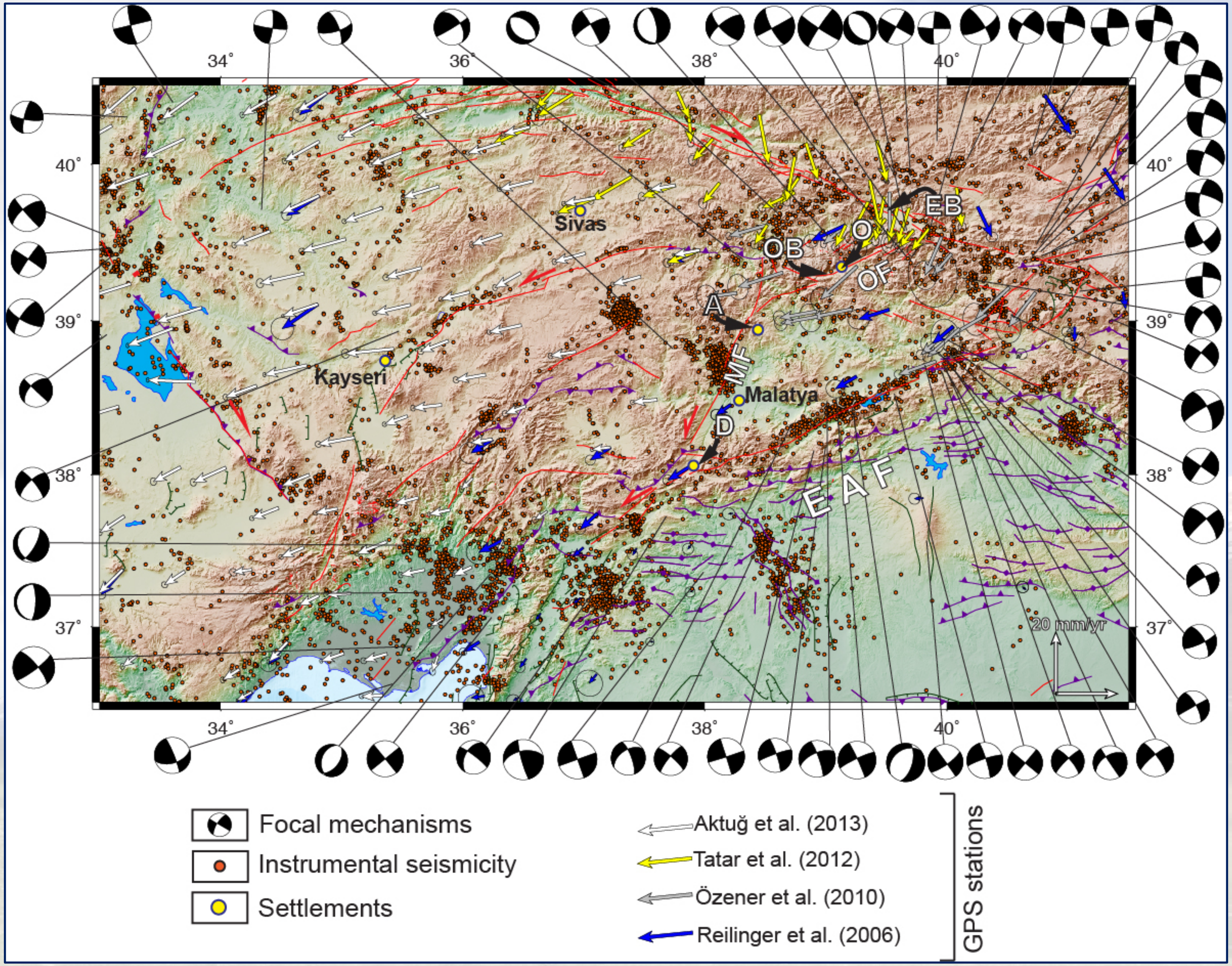


The active deformation of Anatolia and adjacent regions are mainly shaped by the interaction of three major plates; Nubia, Eurasia and Arabia. As result of the continuous convergence between these three plates, Anatolia 'extrudes' westward, mainly along its boundary structures; The *North (NASZ) and the East (EASZ) Anatolian shear zones*.

This complex setting also give rise to the formation of four major neotectonic provinces: (a) *The EAPS – East Anatolia Province of Shortening*, which is mainly characterized by N-S compression and related structures, (b) *The WAEP – West Anatolia Extensional Province* that defines a region under NNE-SSW extension, (c) *The COP – Central Anatolia 'ova' Province*, and (d) the *North Turkish Province* (Şengör et al. 1985)

Figure 1. The neotectonic structures of Anatolia and the surrounding region, which are still active or have been once active since the medial to late Miocene (modified from Şengör and Zabcı, 2019). Red lines are for strike-slip faults, whereas the green is for extensional (normal faults) and the purple is for compressional (thrusts and folds) structures. Key to lettering; H – Hellenic Subduction, C – Cyprus Subduction. The yellow rectangle marks the geographical extent of the next figure.



In this complex tectonic setting the deformation of Anatolia is mainly localized along its boundary structures (e.g. Reilinger et al., 2006). The internal structures within the COP are claimed to be the former eastern boundaries of Anatolia, which have a trend of eastward migration and to be abandoned (Chorowicz et al., 1999; Westaway and Arger, 2001).

However, recent microseismicity and GPS measurements in addition to many geological studies strongly shows that that there is a significant internal deformation within Anatolia, especially along NE-striking sinistral strike-slip shear zones.

This study is a simple attempt to understand the distribution and reason(s) of the internal deformation of Anatolia by using geological slip-rate and palaeoseismological studies.

Figure 2. The map showing the COP – Central Anatolian 'ova' Province. The arrows are for GPS measurements and red dots represent earthquakes (Kandilli Rasathanesi ve Deprem Araştırma Enstitüsü, 2020). Focal mechanisms are from CMT Harvard Database (Ekström et al., 2012). The basemap is the hill shade relief derived from SRTM 1-Arc second dataset (USGS). Key to Lettering; GPS – Global Positioning System, EAF – East Anatolian Fault, EB – Erzincan Basin, OB – Ovacık Basin, OF – Ovacık Fault, MO – Malatya Fault, O – Ovacık, A – Arapgir, D – Doğanşehir.

Paleoseismological and morphochronology-based slip rate studies in the COP

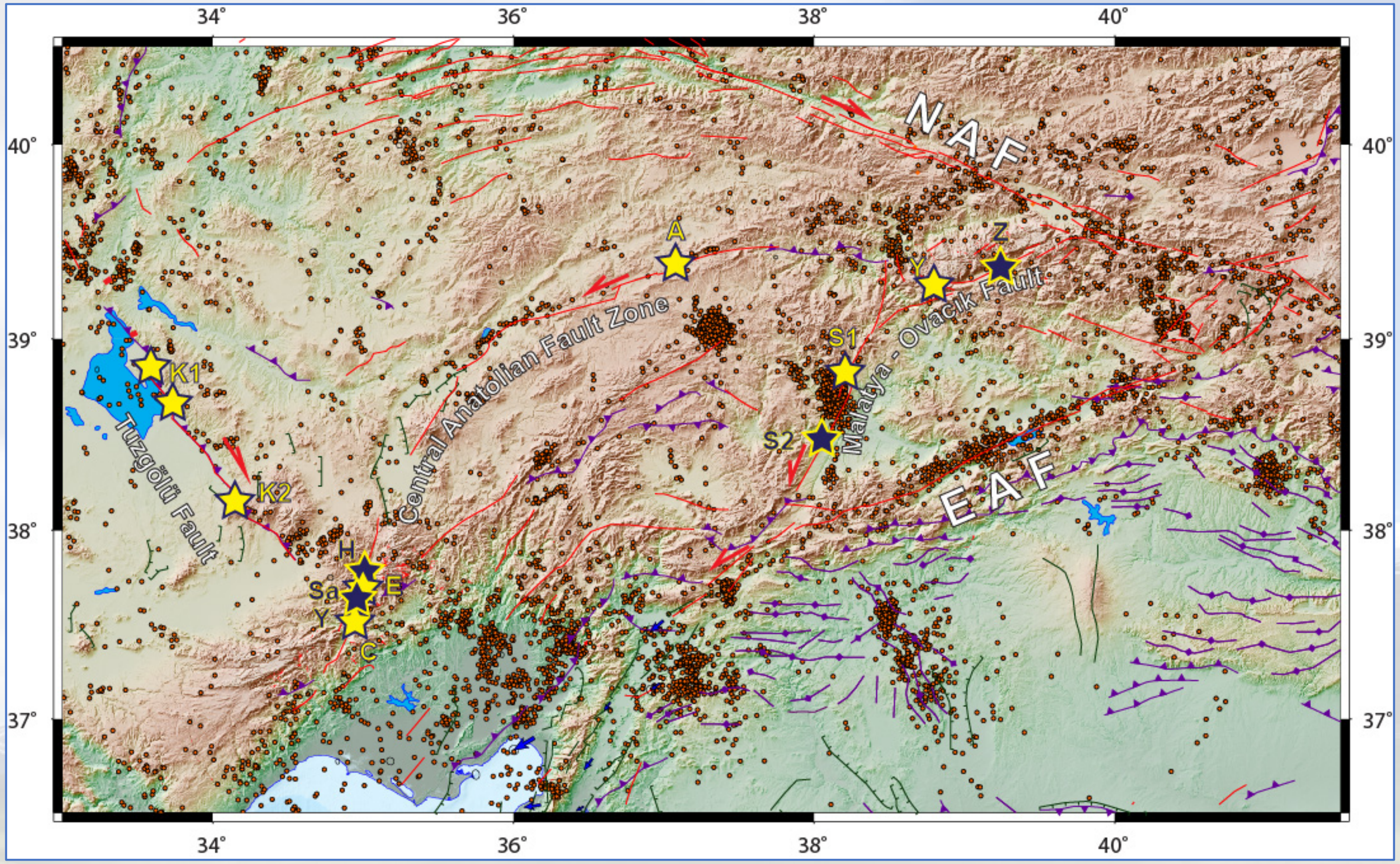


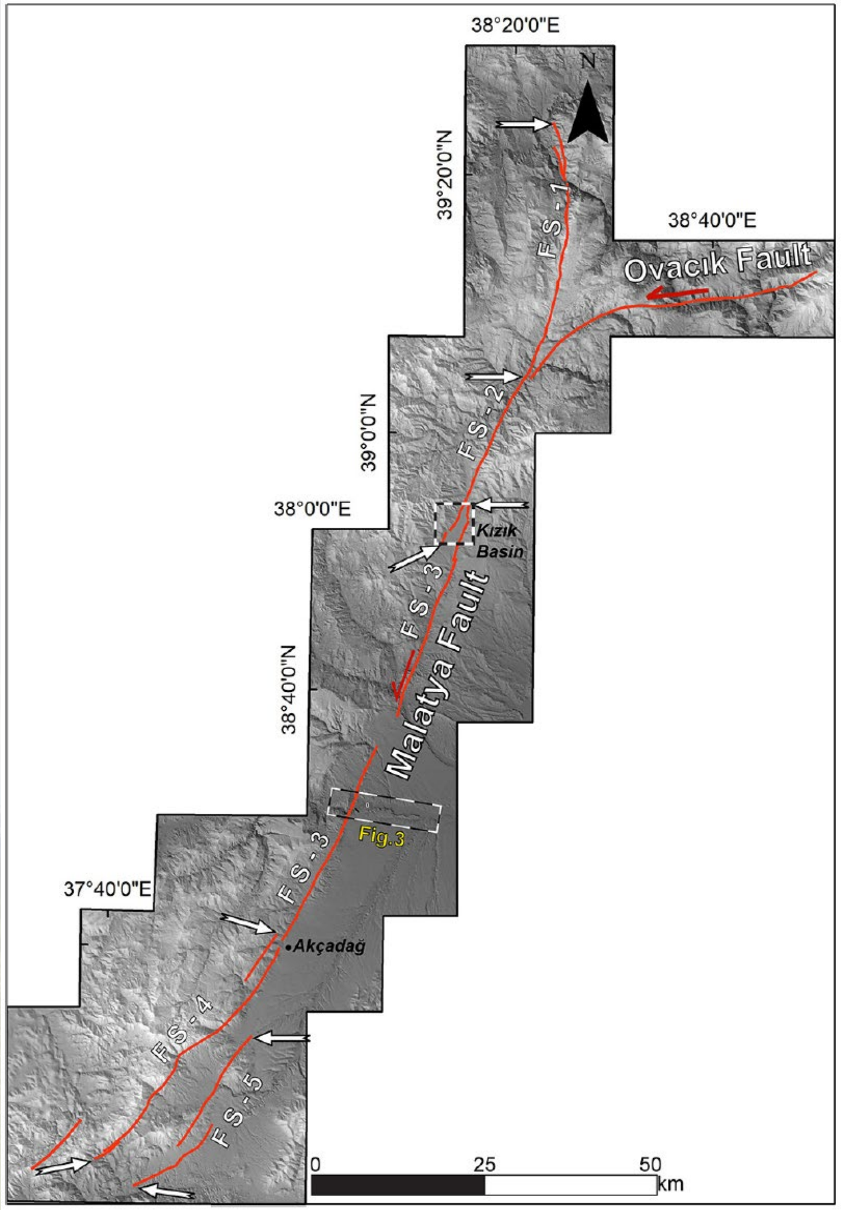
Figure 3. Geological slip rate and paleoseismological studies along the major faults of the COP. The dark blue stars (with yellow envelopes) show slip rate sites, whereas the yellow stars (with dark blue envelopes) are for the paleoseismological trench sites. Key to lettering (from west to east) – K1, Kürçer et al. 2011a; K2, Kürçer et al. 2011b; Y, Yıldırım et al. 2016; Sa, Sarıkaya et al., 2014; H – Higgins et al., 2015, C, Çetin , 2001; E – Şatır-Erdağ, 2007; A, Akyüz et al. 2012; S1, Sançar et al. 2019; S2, Sançar et al., 2020; Y – Yazıcı et al., submitted to J. of Seismology; Z – Zabcı et al., submitted to Tectonophysics).

GPS-based geodetic studies suggest similar results for the slip-rate of major NE-striking sinistral faults (Malatya-Ovacık Fault - MOF and Central Anatolian Fault Zones - CAFZ), which are of about 1.5 mm/yr (average) and 1 mm/a, respectively (Aktuğ et al., 2013).

Geological rates agree with the geodetic ones for the CAFZ (Higgins et al., 2015). However, two distinct members of the MOF (Malatya and Ovacık faults) display different results when they are compared with the geodetic rates. The average horizontal slip rate of 1 mm/a for the last 1.4 Ma in the Tohma site (S2 on the map) is almost same with the geodetic rates (Sançar et al., 2020), whereas the Köseler Site suggest a much higher rate of about 2.5 mm/a that exceeds geodetic rated with factor of almost 2 (Zabcı, submitted to Tectonophysics).

Limited number of paleoseismological trenching suggest a similar recurrence (RI) of about 4000 years almost for the entire CAFZ (Akyüz et al. 2012; Şatır-Erdağ, 2007), whereas we observe another conflict for the MOF, when we compare the RI between trench results of the Malatya and Ovacık Faults (for details of these results, please see the following pages).

Slip rate sites along the MOF-I: Tohma Site (Sançar et al. 2020)



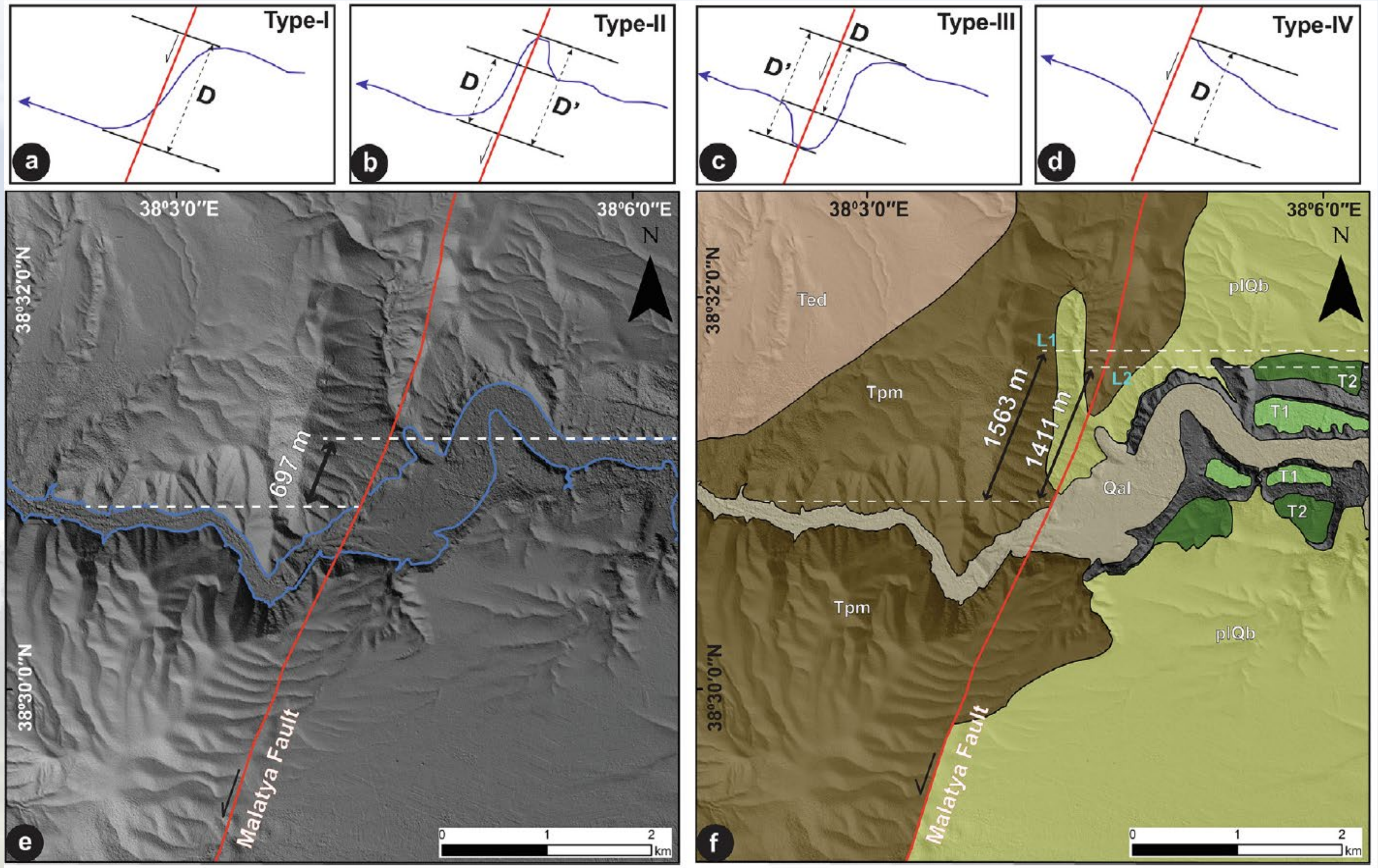


Figure 4. The offset scenario of Tohma River according to (e) modern channel boundaries on both sides of the fault and (f) between the northern modern channel margin at locations west of the fault and northern margin of the T2 terrace, which is considered to present the oldest channel at locations east of the fault.

The cosmogenic isochron burial and depth burial ages of remnant fluvial surfaces suggest min. 1.0 ± 0.01 and max. 1.12 ± 0.01 mm/a slip rates.

Slip rate sites along the MOF-II: Köseler Site (Zabcı et al. submitted)

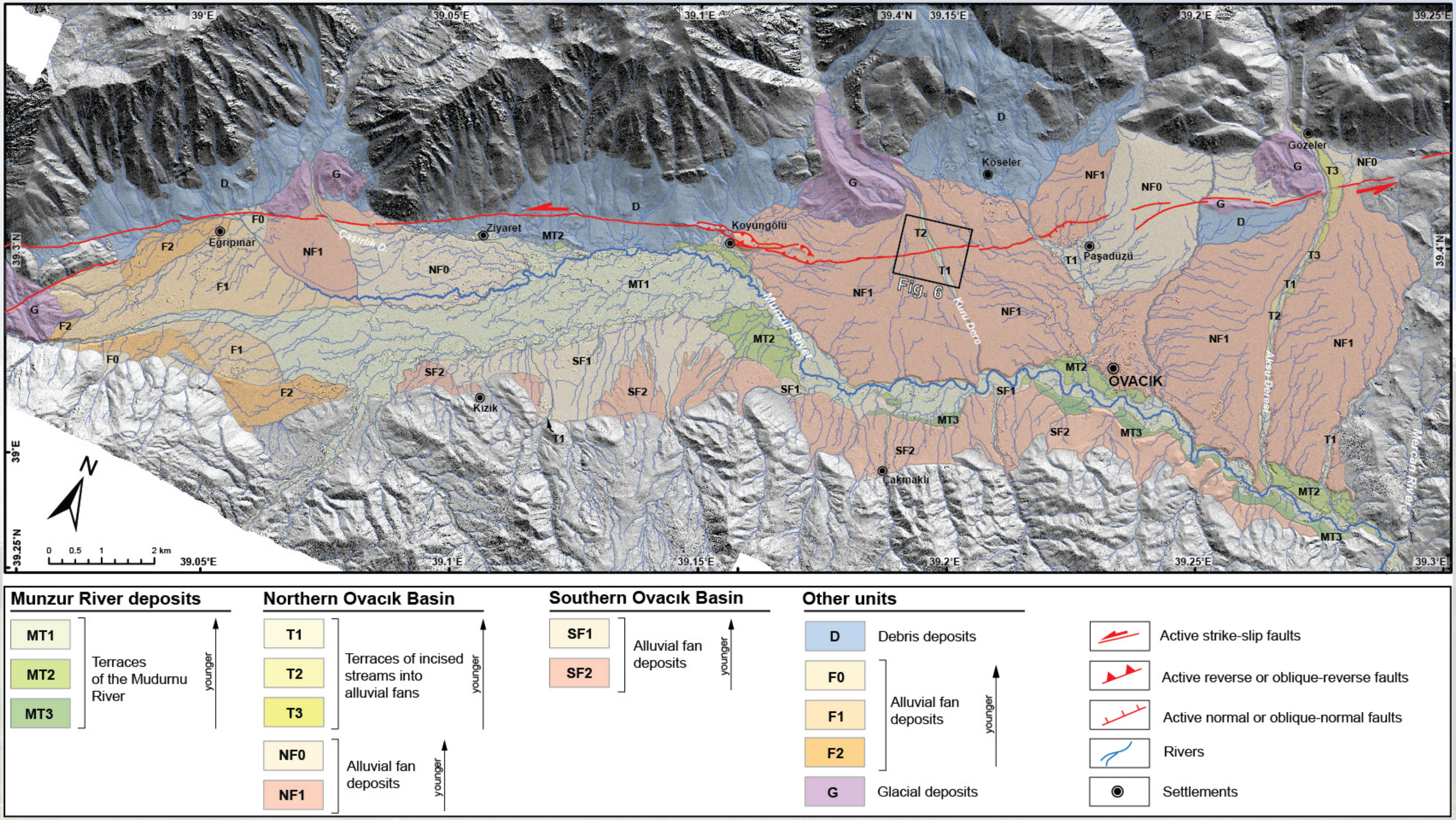


Figure 5. The geological map of the Quaternary formations of the Ovacık Basin along the Ovacık Fault. This section of the fault is represented by a single strand where the total strain is localized. The black rectangle marks the Köseler slip rate site (Zabcı et al., submitted to Tectonophysics).

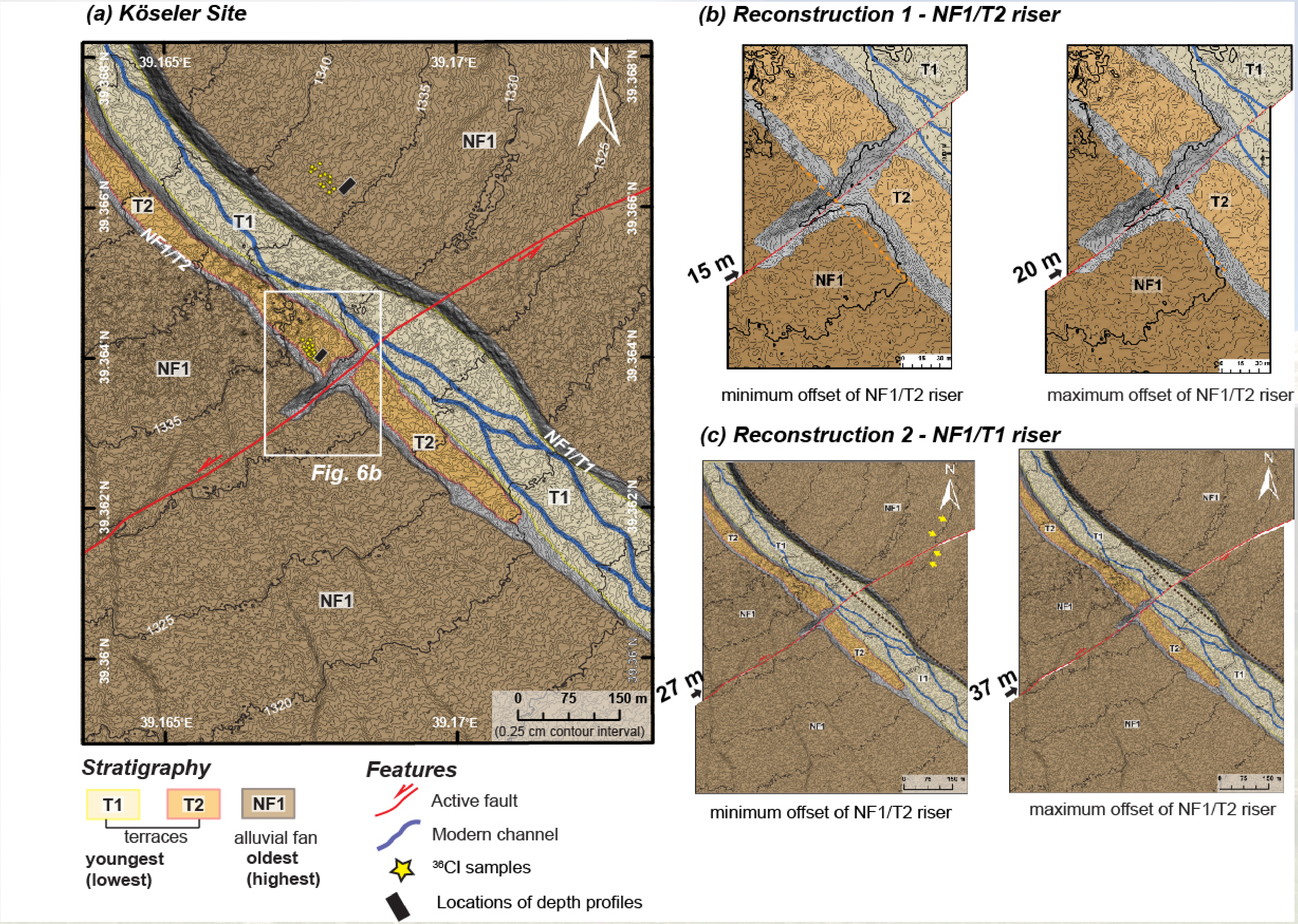
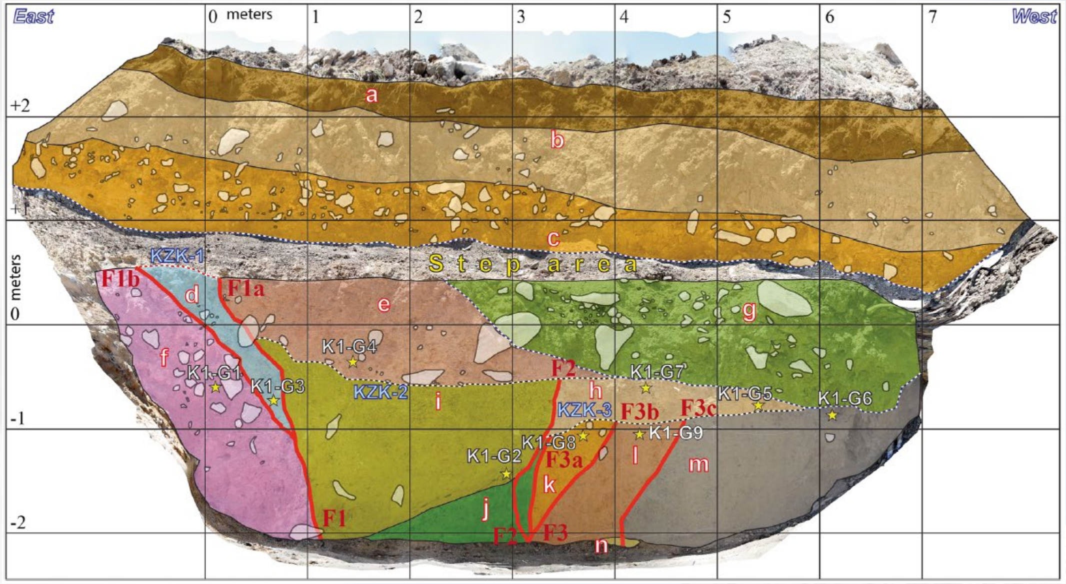
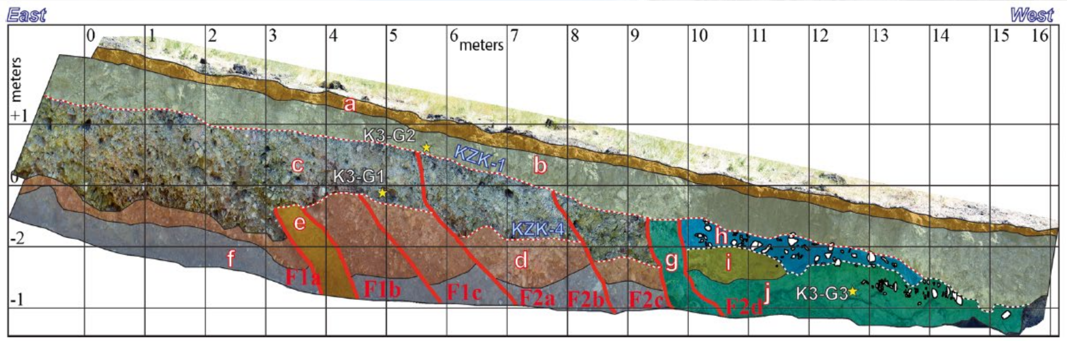
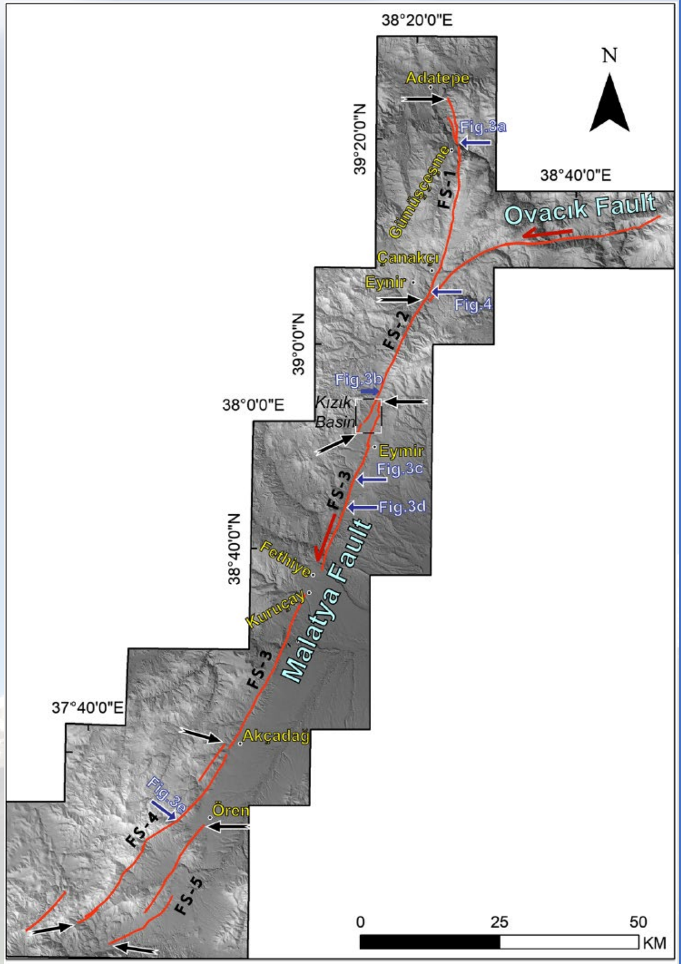


Figure 6. (a) Topographic and surface geological map of the Köseler Site. The modern south flowing stream channel is incised into a broad alluvial fan (NF1) and forms a single-paired strath terrace (T2) at its western flank. The modern fluvial deposits are symbolized by T1. Two offsets are measured at preserved or partly preserved risers, NF1/T2 and NF1/T1, respectively. Small figures show two different offset models, reconstructed by using the displacement of (b) NF1/T2 and (c) NF1/T1, which are marked with dashed lines at each scenario. Moreover, the ~27 m of slip along the 1325 m elevation contour is shown with arrows. The spatial coverage of first reconstruction is indicated with white rectangle on the main figure.
In case of reliability, the NF1/T2 riser together with depth-profile burial cosmogenic ages are used, which yield a slip rate estimate of 2.5 +0.7/-0.6 mm/a for the Ovacık Fault at the Köseler Site (Zabcı et al., submitted to Tectonophysics).

Palaeoseismological trenching on the MOF-I (Sançar et al. 2019)







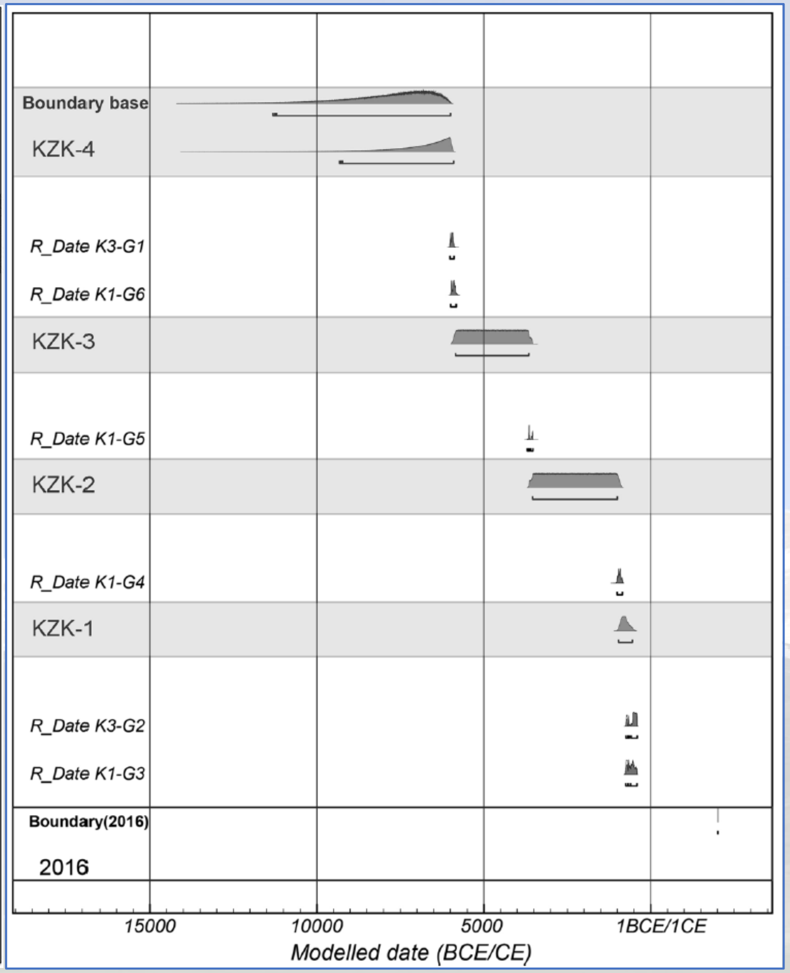
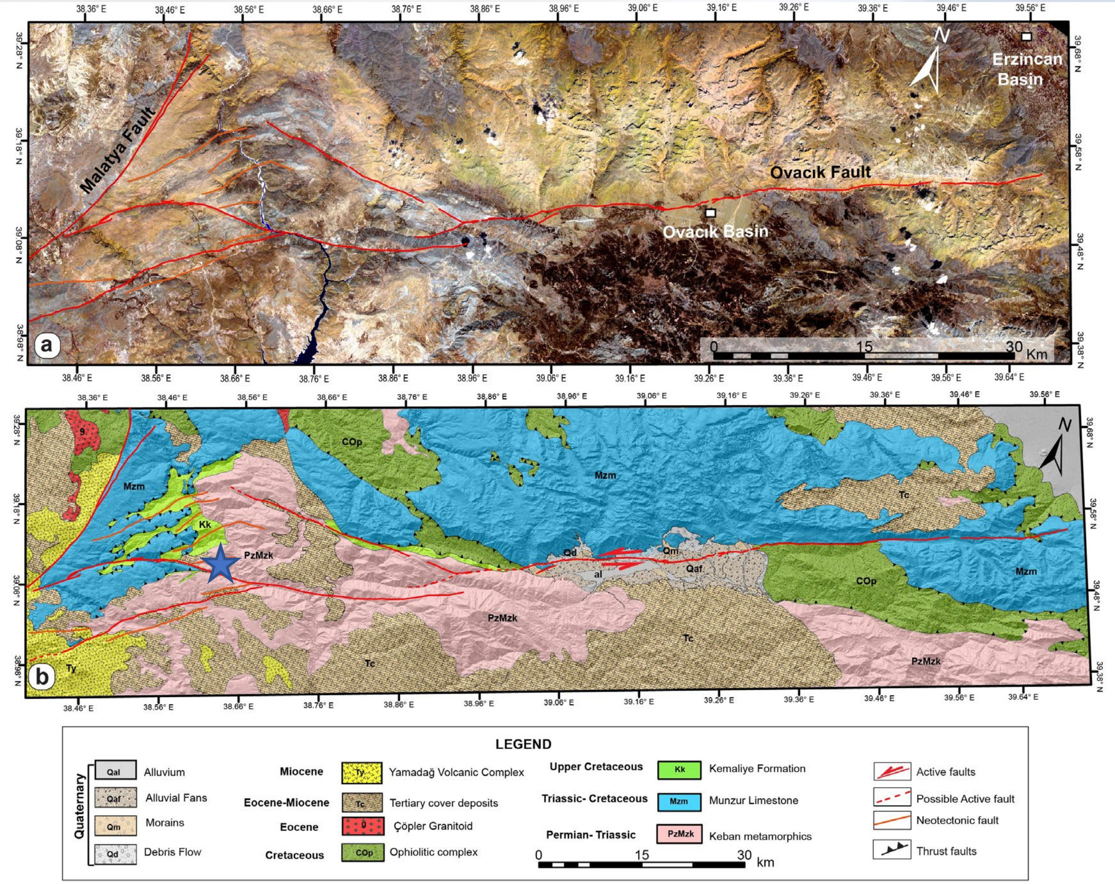


Figure 7. The first palaeoseismological study on the Malatya Fault, made of three trenches in two different sites, reveal evidence for four events for the same geometric segment of the fault. The radiocarbon dates from above and below the event horizons suggest that the last event should have happened between 965 and 549 BCE.
Recurrence interval (RI) was calculated **2275 ± 605** years.

Palaeoseismological trenching on the MOF-II (Yazıcı et al., submitted to the J. of Seismology)



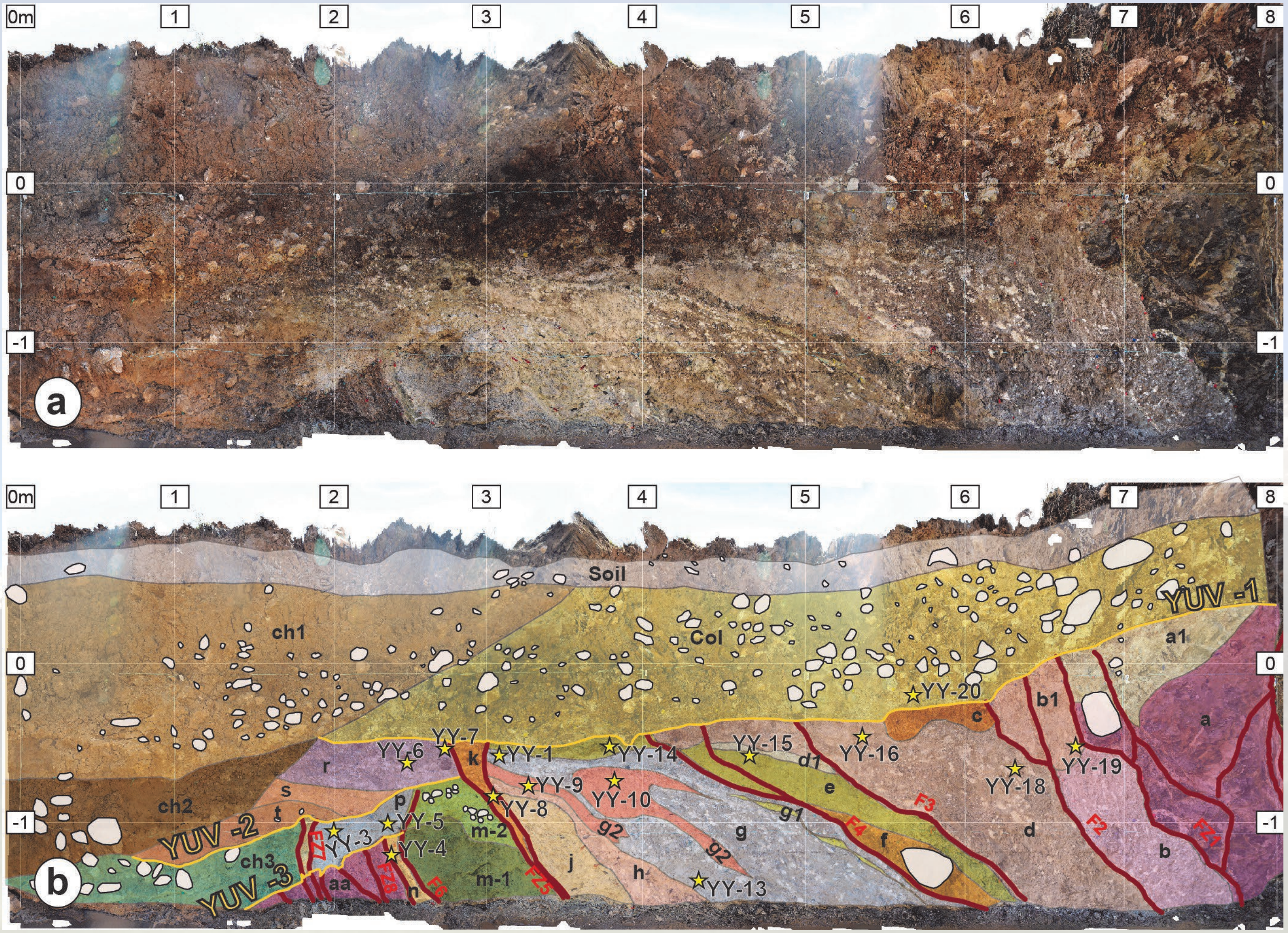
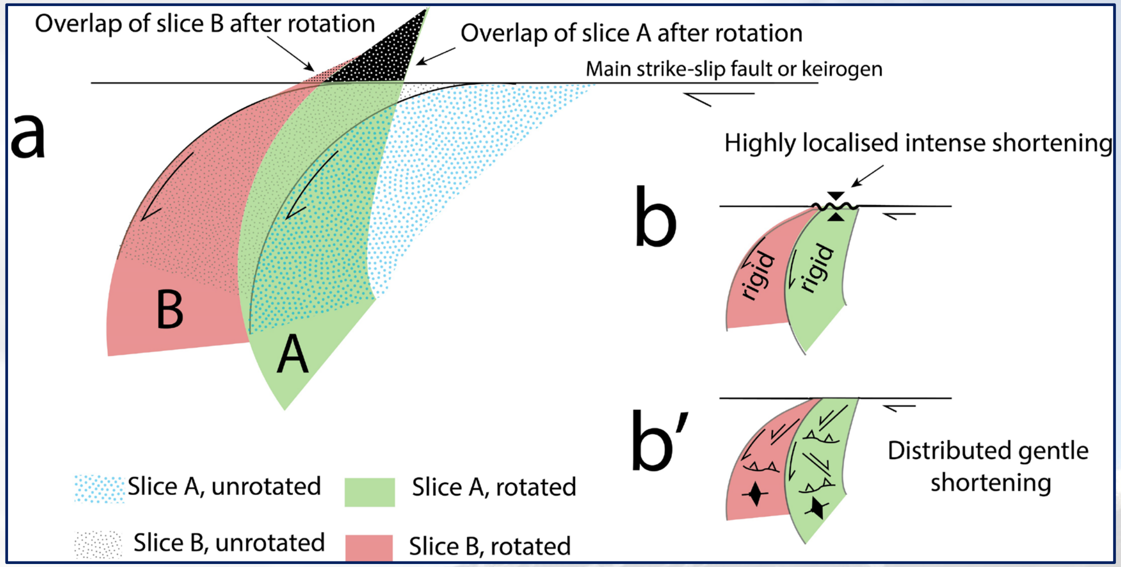


Figure 8. Palaeoseismic trenching at a single site (blue star on the geological map) reveals evidence for three palaeoevents for a single geometric segment of the Ovacık Fault. This palaeoseismic history is only for one structural element of a wider shear zone where the total strain is distributed between three segments of the OF in its western parts (Yazıcı et al., submitted to the Journal of Seismology). Thus, the apparent similarity of the calculated Recurrence Interval of 2400 ± 765 years with the RI of the MF trenches show that the Ovacık Fault must have a higher deformation rate as it is calculated for the Köseler Site.

A mechanism to explain the internal structures of Anatolia: Fish-bone structures (Şengör et al. 2019)



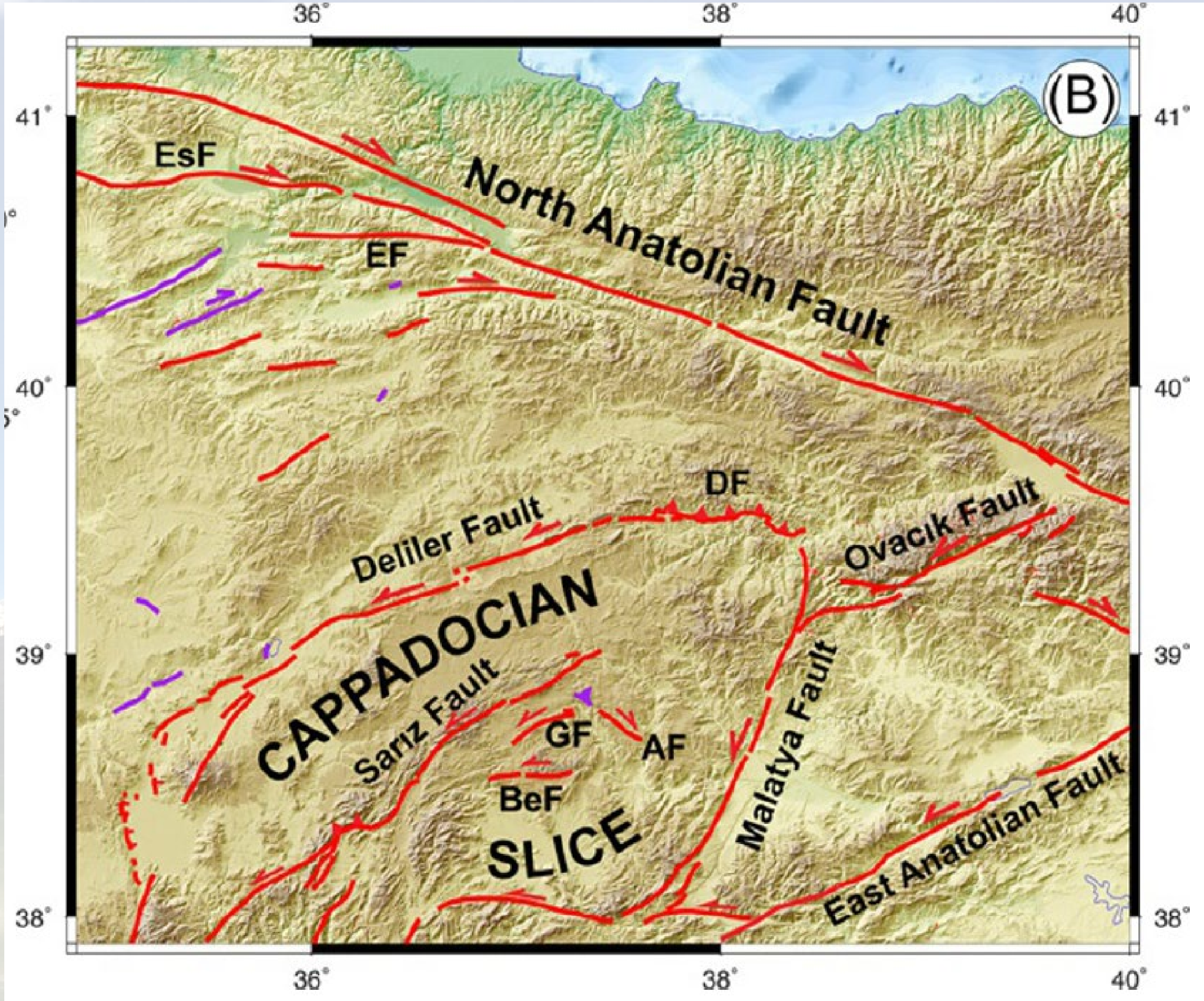
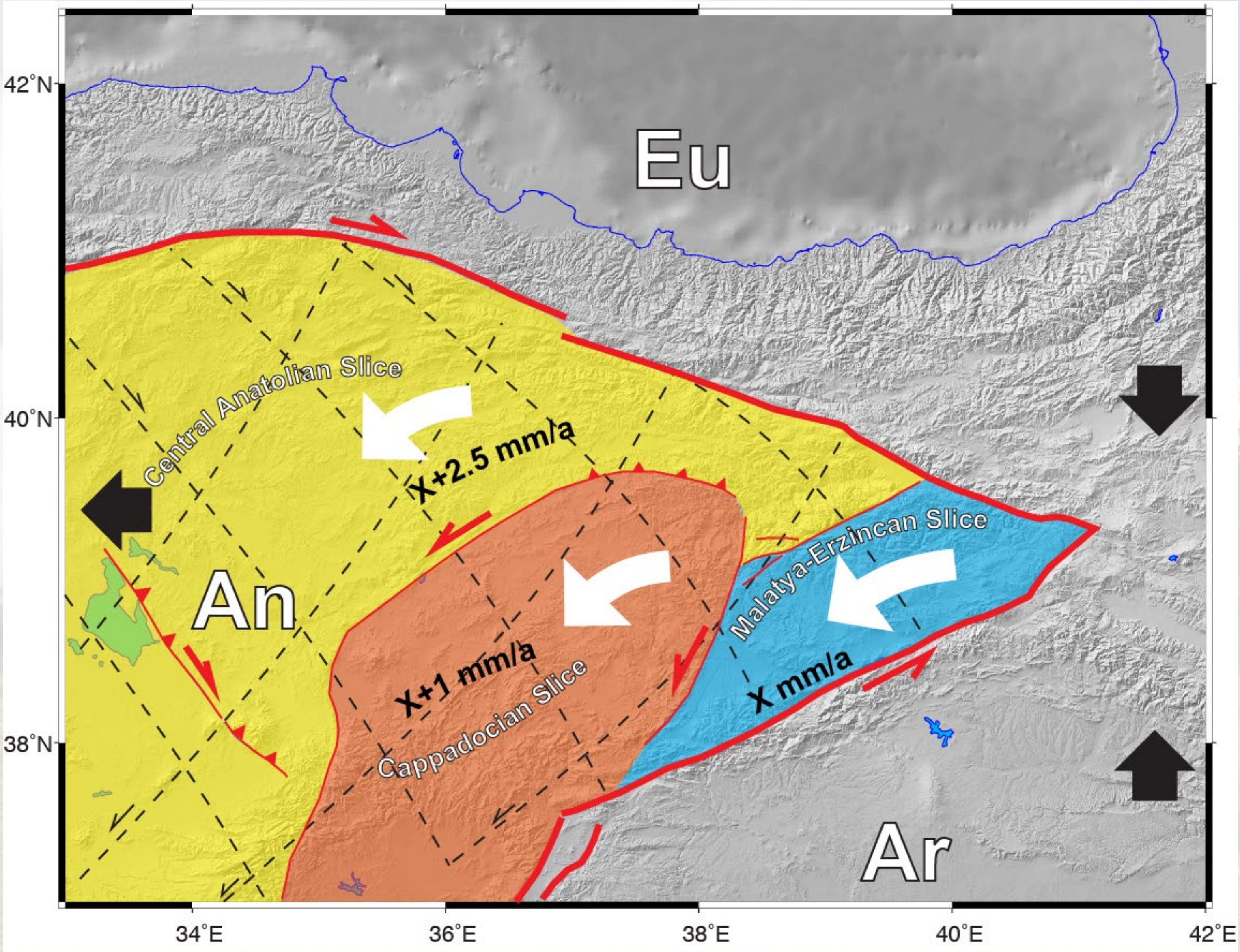


Figure 9. Şengör et al. (2019) suggest that synthetic splays form the main strike-slip cause rotating slices (a), which may cause two possible cases: (b) highly localized intense shortening along the overlapping part of the main trunk or (b') distributed gentle shortening within these slices.
Authors define Cappadocian Slice and interpret its inner structures as result of being members of rotating slices manner (B – Active faults are simplified from Emre et al. 2013).

An alternative (and detailed slice geometry) for Anatolia (Zabcı et al., submitted to Tectonophysics)



Zabci et al. claim that Anatolia, especially its central and eastern parts, is not a perfect rigid body, but it is sliced by secondary strike-slip faults to several pieces such as the Malatya-Erzincan, Cappadocian and Central Anatolian slices. This is similar to the model of Higgins et al. (2015), but with a major change in boundary geometries and relative velocities of slices. The OF makes the direct boundary between the Central Anatolian and Malatya-Erzincan slices, whereas the MF and the CAFZ are the eastern and western boundaries of the Capaddocian Slice with the Malatya-Erzincan and Central Anatolian slices, respectively.

This configuration also well explains the velocity difference between slip rate of the OF and the very long-term slip rate of the MF, which drives the slices relatively faster from east to west (i.e. x mm/a for the Malatya-Erzincan Slice, x + 1 mm/a for the Cappadocian Slice, and x + 2.5 mm/a for the Central Anatolian Slice). The locations of these secondary strike-slip faults are strongly controlled by the distribution of Tethyan sutures (Şengör et al. 2019b and next figure).

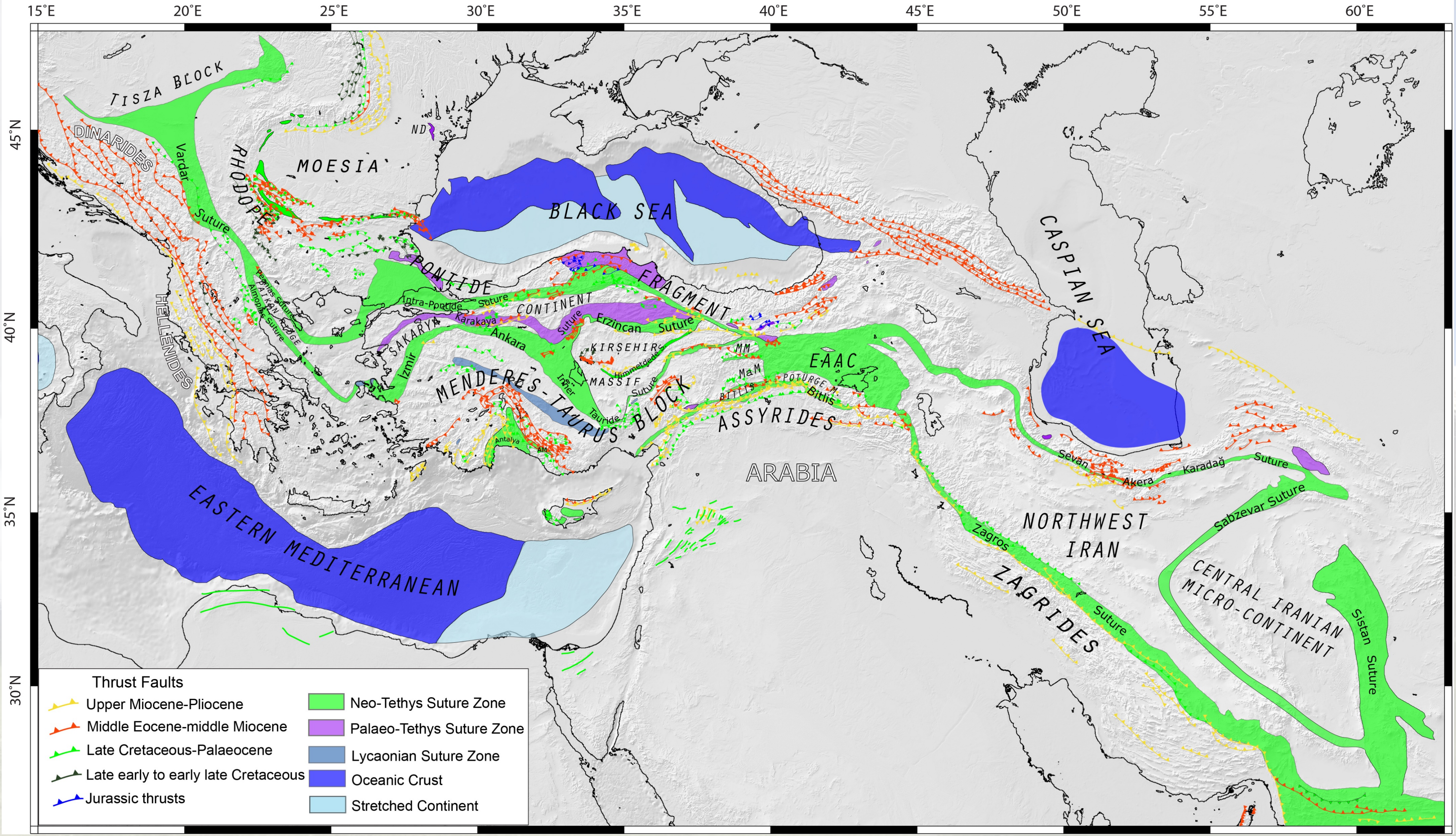


Figure 10. Distribution of Tethyan sutures within and around Anatolia (Şengör et al., 2019b). Please note that, many strike-slip faults of the COP correspond to these suture zones.

Conclusion

- Internal strike-slip faults of Anatolia are still active and they participate to the total deformation of this continental piece.
- The NE-striking sinistral and NW-striking dextral strike-slip faults correspond the slip lines of a passive Prandtl Cell Model of Varnes (1962), where the boundary faults move toward each other and the material between the plates moves away from the apex of the wedge.
- These secondary faults slice Anatolia into several pieces giving formation of the Malatya-Erzincan, Cappadocian and Central Anatolian slices, where the geometry is strongly controlled by the distribution of weak zones, the Tethyan Suture Zones.
- This configuration and relative motion of these slices also well explains the velocity difference between horizontal slip rates of the Malatya Fault, Ovacık Fault and the Central Anatolian Fault Zone.

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