Segmentation and Holocene Behavior of the Middle Strand of the North Anatolian Fault (NW Turkey)

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Key Points:

- Systematic measurements of horizontal cumulative offsets along the middle strand of the North Anatolian fault
- Statistical analysis of the dataset allows to identify the last large ruptures along the fault and the associated slip per-segment
- Comparison with independent constraints on past earthquakes leads to discuss past rupture scenarios

Abstract

The North Anatolian fault in the Marmara region is composed of three parallel strands all separated by ~50 km. The activity of the middle strand, which borders the southern edge of the Marmara Sea, is much debated because of its present-day very low seismicity. The weak seismic activity observed today along the middle strand contrasts with historical, archaeological and paleoseismological evidence, which suggest several destructive earthquakes have occurred during the last 2000 years. Our study aims to better constrain seismic hazard on the middle strand by exploring its Holocene paleoseismicity. For this, we mapped 148 km of the middle strand, using high-resolution satellite imagery. A series of landforms offset by the middle strand activity have been systematically measured to recover the past ruptures. Three Late Pleistocene-Holocene terraces have been dated with the terrestrial cosmogenic nuclide method, constraining a horizontal slip rate of ~4.3 mm/yr. The statistical analysis of the offsets evidences several major ruptures preserved in the landscape, with coseismic lateral displacements ranging between 3 and 6.5 m. This corresponds to Mw ~7.3 earthquakes able to propagate along several fault segments. As the approach used can only resolve large magnitude events, smaller events (e.g. Mw 6.8-7) likely occurred as well even if their geomorphological signature could not be detected. Historical seismicity and paleoseismology data suggest that the last large earthquakes along the MNAF happened in 1065 CE and between the 14th and 18th centuries CE. Since then, the MNAF may have accumulated enough stress to generate a destructive rupture.

1 Introduction

Seismic hazard in the highly inhabited areas of northwestern Turkey is mainly related to the activity of the North Anatolian fault (NAF), a 1000-km long, dextral strike-slip structure that accommodates the relative motion between the Eurasian and Anatolian blocks, with a total geodetic slip estimated around 3 cm/yr (Fig. 1; McClusky et al., 2000; Meade et al., 2002). During the 20th century, the NAF ruptured almost entirely during a westward sequence of major earthquakes from Erzincan, in 1939, to Düzce and Izmit, in 1999 (Ambraseys, 2001a; Hubert-Ferrari et al., 2000; Stein et al., 1997). A seismic gap remains in the Sea of Marmara, in front of Istanbul, where a major earthquake is expected to occur in the next decades (Parsons et al., 2000). In addition to the main northern strand of the NAF, one should also consider the seismic hazard due to the presence of two secondary strands known as the middle and southern strands (MNAF and SNAF, Fig. 1). The deformation rate on these strands is less constrained, although they could together accommodate as much as 25% of the total slip of the NAF (Armijo et al., 2002; Flerit et al., 2003), with estimated slip rates between 3 and 5 mm/yr on the MNAF (Ergintav et al., 2014; Gasperini et al., 2011; Özalp et al., 2013). While the SNAF experienced a Mw 7.2 earthquake in 1953 (Kürçer et al., 2008), no major earthquake ruptured the MNAF during the instrumental period, and the seismicity of the MNAF zone during the last eight decades does not include more than a couple of earthquakes larger than Mw 5. The microseismicity recently recorded has been mostly located west of Iznik Lake and around the Gulf of Gemlik, while the other segments in the east have been characterized by much fewer events and appear quiescent compared with the neighboring NAF strands (Baris et al., 2002; Gürbüz et al., 2000; Öztürk et al., 2009; Tsukuda et al., 1988). These observations explain that the middle strand has often been overlooked in the assessment of deformation of the Marmara region (Le Pichon et al., 2014). This current quiescence contrasts with a significant historical seismic activity documented by several chronicles mentioning the destruction of Iznik and other surrounding cities located close to the MNAF during large earthquakes occurring in the last 2000 years (Ambraseys, 2002, 2009; Ambraseys & Finkel, 1991; Ambraseys & Jackson, 1998; Guidoboni & Comastri, 2005; Fig.

2). This calls for a refinement of the paleoseismic activity of this fault zone.

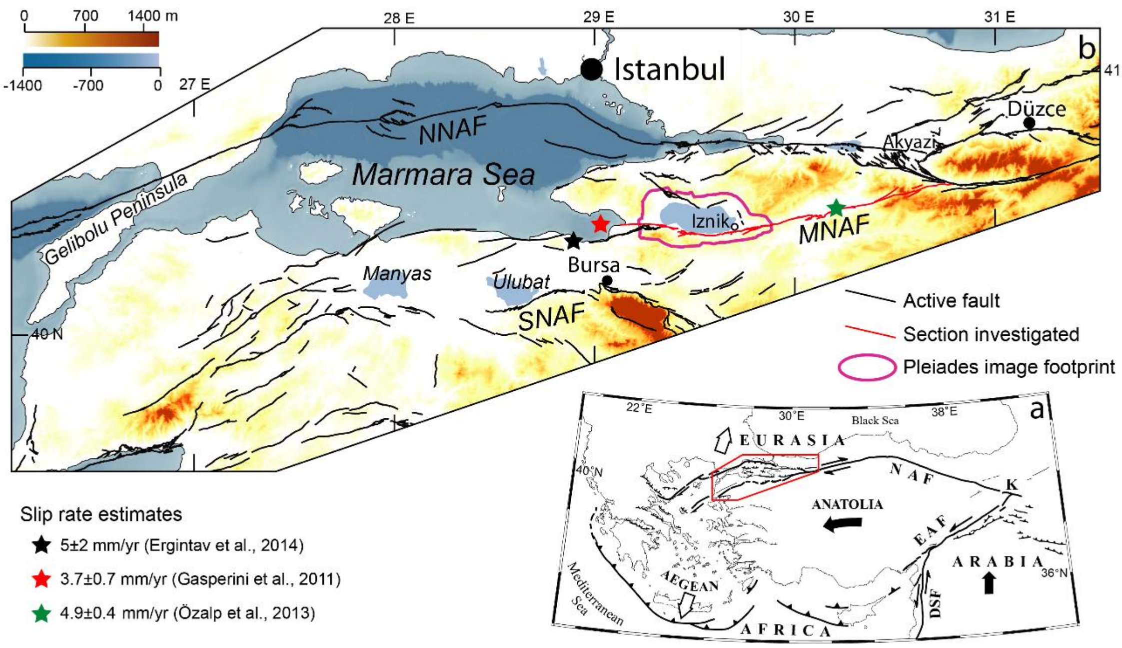


Figure 1. General tectonic context. (a) Schematic map of the main active fault zones of the Eastern Mediterranean (Armijo et al., 1999). NAF = North Anatolian fault, EAF = East Anatolian fault, DSF = Dead Sea fault. The red box surrounds the Marmara region. (b) Main active faults located within the Marmara region. The fault map was modified from Emre et al. (2011). NNAF, MNAF and SNAF refers to the northern, middle and southern strand of the NAF respectively. The bathymetry comes from the EMODnet Bathymetry Consortium (2018). The color stars locate fault sections where slip rates were estimated by geodesy or geomorphology studies (see Section 3 for details).

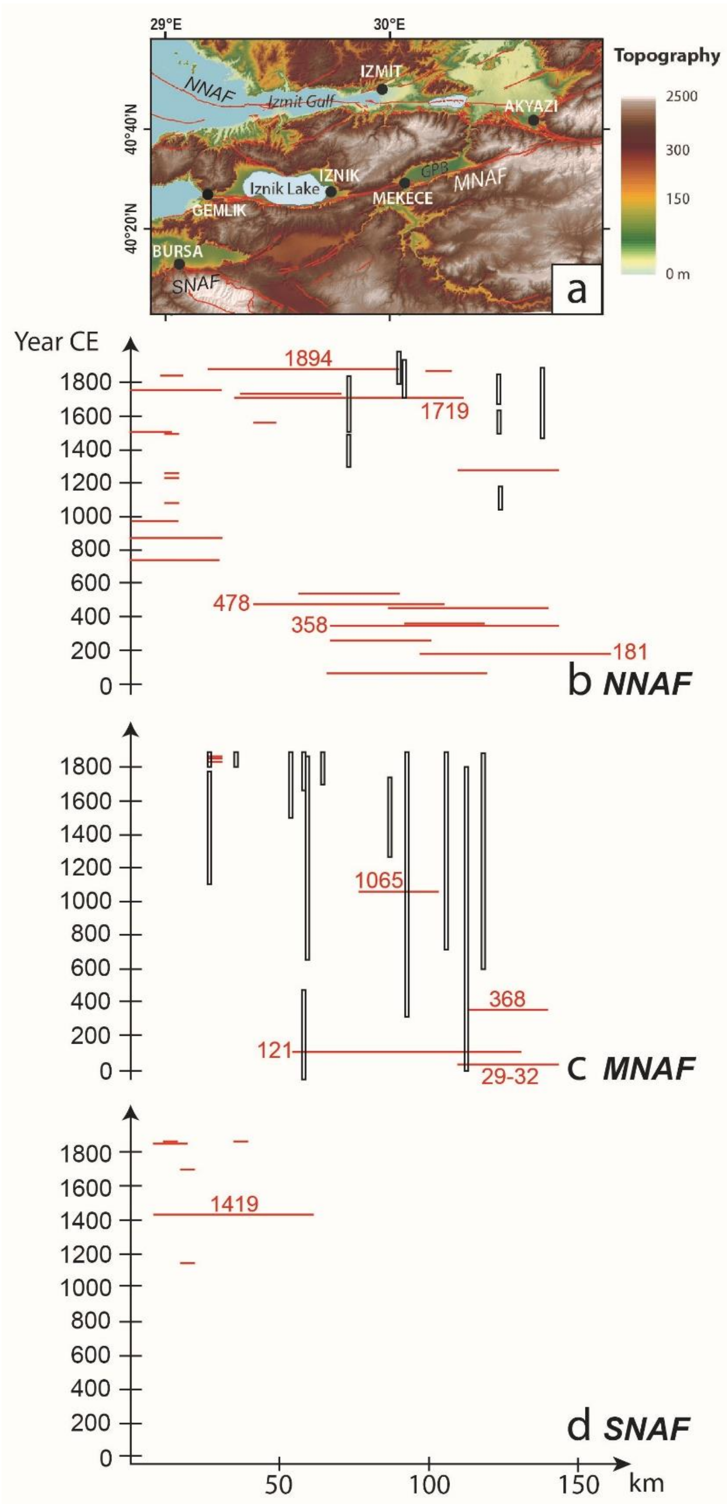


Figure 2. Historical seismicity of the eastern Marmara region before 1900 CE (Common Era). (a) Active faults and main geographic features of the Marmara region. GPB=Geyve-Pamukova Basin. (b, c, d) Historical earthquakes (horizontal red bars) and seismic events documented in palaeoseismological trenches (vertical boxes) along the three strands of the

NAF. The horizontal bars are positioned according to the epicentral areas interpreted from the sources. These epicentral areas are determined from the spatial distribution of the seismic intensities interpreted from historical descriptions, and their accuracy depends on the availability and quality of the written archives (Ambraseys et al., 2002). The length of each horizontal bar corresponds to the approximate rupture length of the earthquake. To estimate this length, we rely on the magnitude estimated by historical seismology studies (see Table S1 in Supporting Information), from which a surface rupture length was derived using the relationship of Wells and Coppersmith (1984). The length of the vertical boxes corresponds to the dating of the events within 2σ uncertainty (Civico et al., 2021; Dikbas et al., 2018; Dogan, 2010; Honkura & Isikara, 1991; Ikeda, Suzuki et al., 1991; Klinger et al., 2003; Özalp et al., 2013; Rockwell et al., 2009; see Table S2 in Supporting Information for detailed data).

In the last decades, the development of high-resolution satellite imagery has made it possible to measure the deformation and characterize in great detail the geomorphology of tectonically active regions on a large scale (Elliott et al., 2016; Fu et al., 2004; Klinger et al., 2011; Ren et al., 2018). These images enable us to accurately map active faults along several tens of kilometers, to describe their segmentation and therefore provide useful information on the possible extension of a given rupture (e.g. Ansberque et al., 2016; Choi et al., 2018; Klinger et al., 2005). Such data also make it possible to document the long-term, cumulative slip distribution along the fault through inventories of offset geomorphological markers. This approach has been successfully employed since the 1960s on various faults to extract coseismic slip values from cumulative offset measurements, and to discuss the impact of segmentation in modulating the cumulative along-strike displacement (Ansberque et al., 2016; Barka, 1996; Manighetti et al., 2015, 2020; McGill and Rubin, 1999; Sieh and Jahns, 1984; Zielke et al., 2015; Kurtz et al., 2018).

In this study, we use a set of high-resolution images and topography measurements obtained from Pleiades data to map the eastern part of the MNAF between Gemlik and Akyazi district (Fig. 2a), and to measure a series of lateral displacements recorded by geomorphological markers, mainly stream talwegs and risers. To gather additional age control on the observed cumulative deformation, we sample and date three levels of wave-cut terraces formed around Iznik Lake. This enables us to constrain a Holocene horizontal slip-rate for the central section of the MNAF. A statistical analysis of the offset measurements helps us to extract coseismic displacements for several of the largest past earthquakes and to discuss the slip distribution generated along the fault during these earthquakes. Comparison of these data with the historical seismicity record and previous paleoseismological data shows that this approach is not sensitive enough to detect the smaller events (Mw 6.8-7) that are also known to occur along the MNAF. We finally explore the implications of several plausible scenarios to help explain past slip history at the scale of the NAF system east of the Marmara Sea.

2 Geological context: the NAF in the Marmara region

The formation of the NAF initiated some 11-13 Ma ago within a wider pre-existing shear zone which progressively localized through time (Sengör et al., 2014). From the Messinian and during the Pliocene, the NAF has functioned as a narrow zone, cutting through and deforming several basins inherited from the previous tectonic stages (Barka, 1992; Yılmaz et al., 1995). While the deformation is localized in a narrow zone in the eastern and central part of the NAF, it is structured on a wider area west of Düzce with a distribution of the deformation across three main strands (Armijo et al., 1999; Fig. 1). The NAF strands show oblique kinematics, with local complex partitioning of the deformation between dextral strike-slip and extensional regimes (Koçyigit & Özacar, 2003). The northern strand (NNAF) continues along the strike of the main fault zone and crosses the northern part of the Marmara Sea from the Gulf of Izmit to Gelibolu Peninsula (Fig. 1). The middle strand (MNAF) branches off from the NNAF in Akyazi district, bounds to the south two successive basins known as the Geyve-Pamukova Basin and Iznik Lake, reaches the Marmara Sea through the Gulf of Gemlik and borders the southern shore of Marmara (Fig. 3a). The southern strand (SNAF) separates from the MNAF near Iznik and continues southwestwards to Ulubat and Manyas Lakes (Fig. 1b).

The MNAF has been traditionally divided into three major sections over a total length of 135 km (Fig. 3). (1) Between the Gulf of Gemlik and Iznik Lake, the fault shows a roughly E-W direction, until a 12 km long releasing bend around Sölöz delta, southwest of the Lake. (2) The fault follows the southern coast of Iznik Lake with an E-W orientation, and continues in the narrow valley of the Kirandere with a constant azimuth of ~80°. This section in the west of Iznik Lake is marked by greater structural complexity and distribution of the deformation across several overlapping faults. Öztürk et al. (2009) suggested the existence of a continuous strike-slip fault extending along the deepest area of Iznik Lake, while Gastineau et al. (2021) evidenced an active fault strand following the northeastern edge of the lake’s southern sub-basin (Fig. 3b). East of Iznik Lake, Sipahioglu and Matsuda (1986) reported the presence of two lineaments in this section: a geological boundary fault with no marker of Quaternary activation, and an active fault strand crosscutting and deforming recent alluvium. The eastern end of this section around the town of Mekece consists in a narrow, 1 km wide releasing step-over. (3) East of the step-over, the MNAF borders the south of the Geyve-Pamukova basin with a 70-80°N strike. The fault is associated to another fluvial system with the Sakarya River, collecting waters from the Anatolian plateau to the Black Sea. The river itself presents a large-scale right-lateral offset across the fault, estimated around 15-20 km (Koçyigit, 1988; Özalp et al., 2013). The eastern edge of the basin is marked by a short restraining bend, after which the fault continues with a similar strike in the mountainous area of Akyazi where it connects to the main NAF.

3 Previous slip-rates and paleoseismological studies on the MNAF

The most recent estimation of the long-term horizontal slip rate on the MNAF was obtained by Gasperini et al. (2011) who used the displaced edge of a 11,250 years old submerged delta in Gemlik Bay to derive a 3.7±0.7 mm/yr minimal rate (Fig. 1b). This rate is comparable with the rates of ~5±2 mm/yr derived from strain accumulation modeling of fault-perpendicular GPS measurement profiles (Ergintav et al., 2014; Straub et al., 1997). Another value of 4.9±0.4 mm/yr was derived from the 16±1 km long offset of the Sakarya river in the Pamukova plain since the Late Pliocene (Özalp et al., 2013). The vertical motion was documented by Ikeda et al. (1991) who estimated a 0.7-1.4 mm/yr minimal rate from tilted post-glacial beachridges located on the western shore of Iznik Lake.

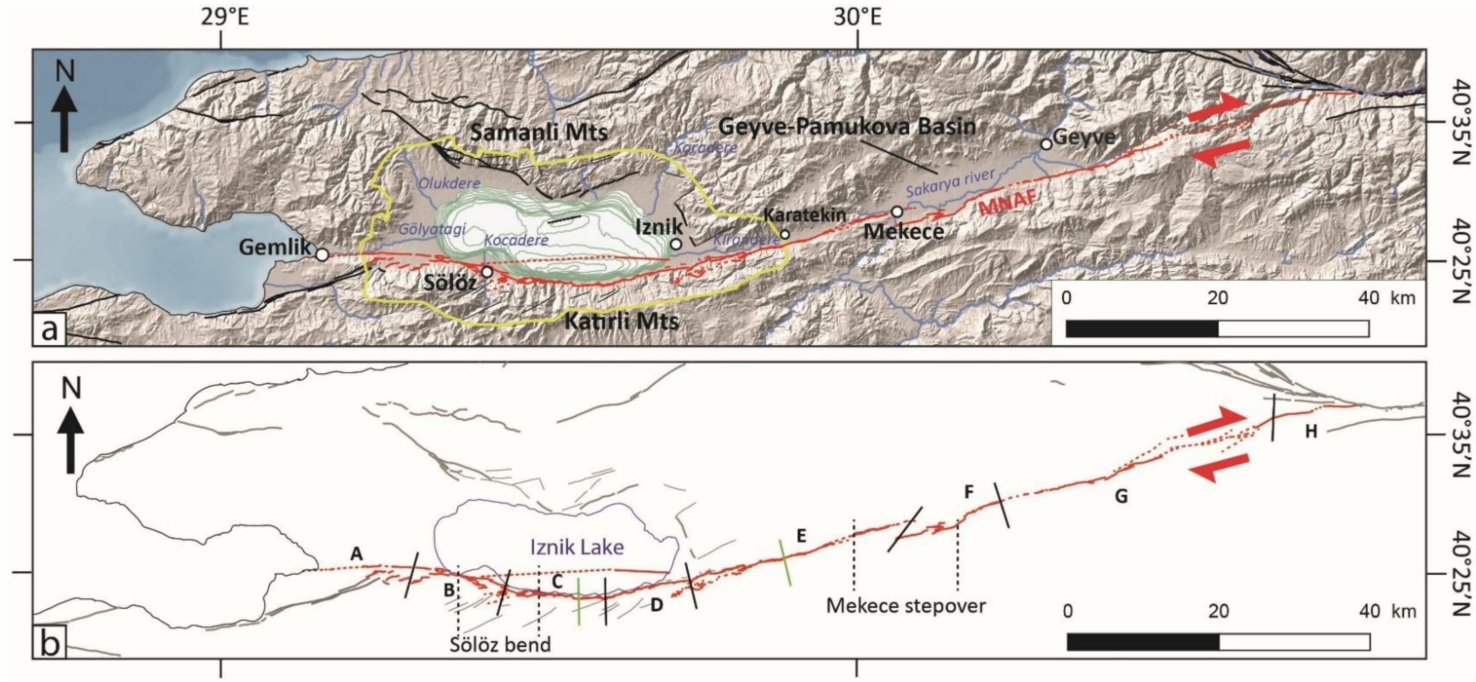


Figure 3. (a) General morphology of the eastern MNAF region. The footprint of the orthorectified Pleiades images (yellow) is superimposed on the Shuttle Radar Topography Mission (SRTM) model. The main rivers are drawn in blue. The MNAF is represented in red and the other active faults in black. Dotted lines indicate low confidence fault mapping (see section 4.2). The contours on the Iznik lake bottom are at a 5-meter interval (see Data Availability section). The fault traces within Iznik Lake are taken from Gastineau et al. (2021). (b) Segmentation of the main fault section analyzed in this study. Determined intersegments are located with black lines and alternative intersegments C/D et D/E with green lines (see section 4.3). Sölöz and Mekece step-overs' extent is shown with dashed lines.

A significant number of paleoseismological trenches have been dug along the MNAF (Akyuz & Zabci, 2012; Fraser et al., 2010) that led to the identification of several ruptures during the last 4000 years (Fig. 2c). Yoshioka and Kusçu (1994) studied a site near Geyve and identified a 3rd century BC rupture and a later undated one. In the same area, an unpublished trenching work by Akyüz et al. (2014) led to the identification of three presumed earthquakes. In the east of Iznik, the last rupture was dated between the 13-14th and 18th centuries CE (Honkura & Isikara, 1991; Ikeda, 1988). On the same segment, Barka (1993) opened nine trenches and found three ruptures since ~2000 BC, but none of them were dated precisely. In the eastern part of Iznik Lake, Gastineau et al. (2021) evidenced a historical event in sediment cores, that they correlated to the 1065 CE earthquake. South of the lake, Erginal et al. (2021) reported a 50 cm high coseismic scarplet in beachrock deposits that they attributed to an 8th century rupture. On the same segment, Civico et al. (2021) opened two trenches and evidenced one mid-19th century event, one penultimate event after the late 7th century and two older events before the mid-5th century CE. West of Iznik Lake, Ikeda et al. (1989) proposed a mid-19th century event from archaeological remains found in a natural fault exposure. In Gemlik, Özalp et al. (2013) found a similar age for the last event and dated the penultimate between the 12th and 18th centuries. So far, the largest trenching work has been conducted by Dogan (2010) who opened 11 trenches on various MNAF segments. In many cases, very few or no age data could be retrieved, which makes it difficult to discuss whether the identified ruptures are independent from each other. Thus, in terms of earthquake recurrence, the paleoseismological data along the MNAF remain largely inconclusive due to partial results or occasionally contradictory findings (Fig. 2c).

4 Fault geometry and segmentation analysis

4.1 Imagery datasets used

Four stereo-pairs of Pleiades images covering the area between the Gulf of Gemlik, Iznik Lake, and Karatekin (Fig. 3a) were processed to obtain a high-resolution DEM using the NASA Ames Stereo Pipeline (ASP) software (Broxton and Edwards, 2008; Moratto et al., 2010; Shean et al., 2016) without using ground control points (Fig. 4c,d). The original Pleiades images have a resolution of about 50 cm, while the derived DEM has a horizontal resolution of 2 m and an absolute vertical precision better than 10 m. The DEM was then used to orthorectify the original optical images with the same ASP software. For the area east of 29.88E, which was not covered by our Pleiades images, we relied on Google Earth images (Pleiades images from CNES/Airbus, and QuickBird and WorldView images from Maxar Technologies), the SRTM elevation model and the active fault map of Emre et al. (2011).

4.2 Fault mapping and along-strike geomorphology

The trace of the MNAF between Karsak pass and Akyazi was mapped using the satellite imagery described in the previous section and complementary observations gathered in the field (Fig. 2a, 4). In the area benefiting from Pleiades coverage, secondary faults north and east of Iznik Lake were also mapped (Fig. 3). To draw the fault trace, we especially relied on high confidence geomorphological features, such as series of horizontally offset gullies and ridges, shutter ridges, well-defined scarps and facets. Along some other sections, particularly those lacking multiple consistent offsets, the mapping relied on lower confidence features, including large scale lineaments and slope breaks (Fig. 4).

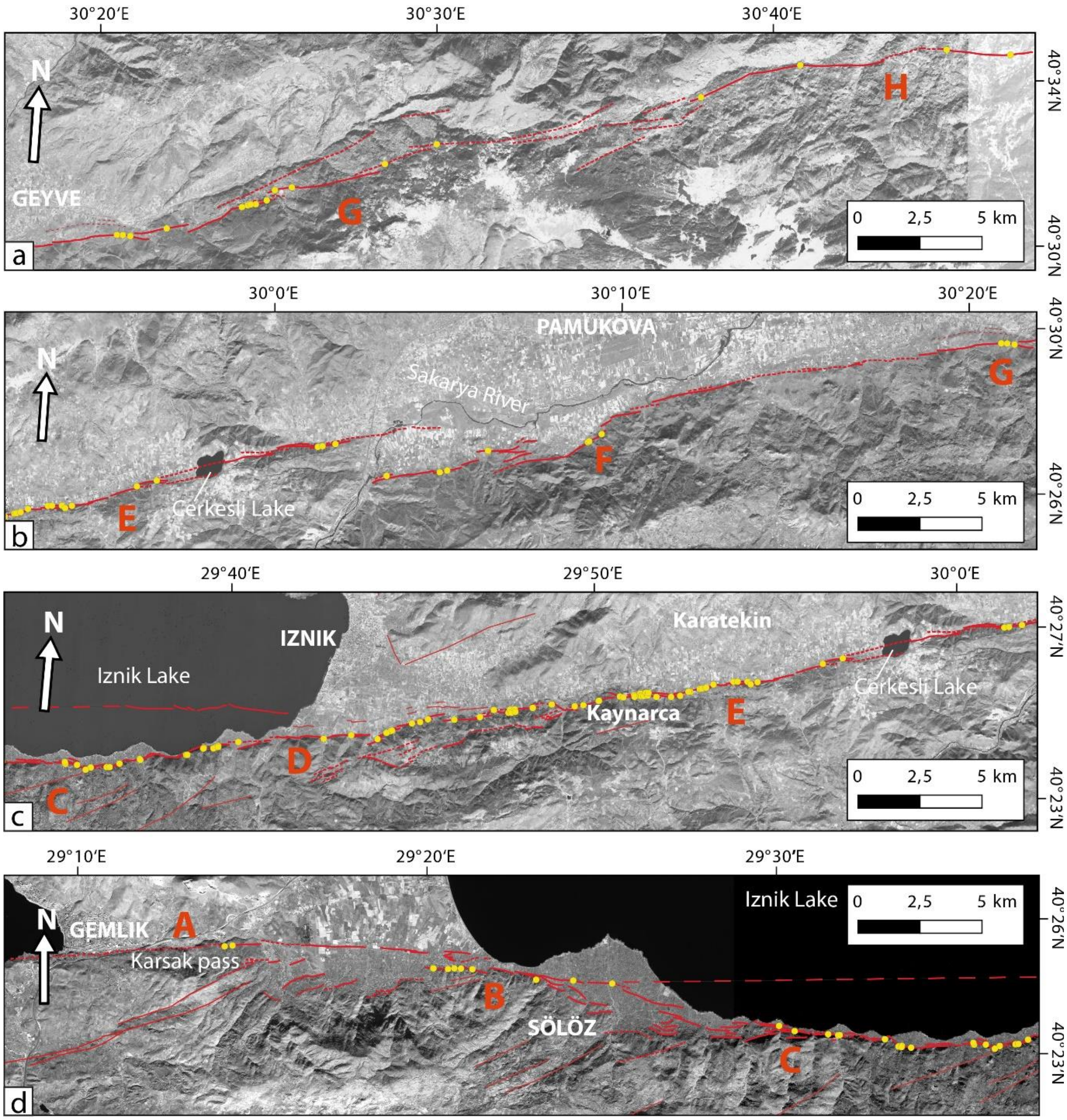


Figure 4. Surface trace of the eastern MNAF, superimposed on the Pleiades orthorectified images around Iznik Lake and Sentinel 2 images (Copernicus Sentinel Data [2018]) in other areas. Solid thick, dotted, and thin lines refer to high confidence, low confidence, and secondary fault mapping, respectively. The subaqueous fault trace is taken from Gastineau et al. (2021). The yellow dots locate the markers associated with the offsets measured. The areas (a to d) are presented from east to west. Our proposed segmentation (A to H) is also displayed.

Evidence for late Quaternary deformation can be observed in the landscape along the MNAF segments between the Gulf of Gemlik and Akyazi district (Fig. 2a, 3, 4). East of the Gulf of Gemlik, a small, E-W trending fault scarp borders the south of Gemlik alluvial plain and runs along the narrow Karsak pass (Fig. 4d). East of Karsak pass, several parallel faults stretch between the Eocene sedimentary rocks of the mountain range and the derived wide alluvial fan south of the Gölyatagi stream (Fig. 3a, 4d). Southwest of Iznik Lake, a set of overlapping and en echelon fault scarps are visible between the basement rocks and the Holocene alluvium of the large Sölöz delta, striking WNW-ESE. However, the horizontally offset markers are found along an E-W fault strand crossing the delta. This fault appears in the westward continuation of the fault scarp evidenced in the lake close to Iznik (Gastineau et al., 2021), and forms a releasing step-over with the fault section running south of the lake.

East of the delta, the fault shows again an E-W orientation with a succession of short, en echelon, recent scarps in the narrow coastal plain south of the lake (Fig. 4c, d). The association of several laterally offset gullies and vertical, south-facing scarplets (Fig. S1 and S2c) evidences the recent dextral motion across the fault with a normal component. A series of significant triangular facets have developed in the same section along the north-facing side of the Katirli range, which suggests long-term cumulative normal deformation in addition to the strike-slip tectonics. Southeast of the lake, the fault becomes more oblique to the main NAF direction, striking 80-85°N (Fig. 4c). East of Iznik Lake, the fault follows the southern edge of a 15 km long narrow, linear valley with a quasi-single, straight and more continuous trace (Fig. 4c). Between Iznik and Kaynarca, large-scale lineaments mark an oblique branch extending south of the main fault zone and striking N070. On the main fault line, markers of strike-slip deformation, such as shutter ridges, offset drainages and alluvial fan surfaces, are well developed (Fig. S2b). Occasionally, parallel or en echelon successive faults can be traced in the landscape. This is the case between Kaynarca and Karatekin where secondary branching can be traced through a series of fan surfaces showing several offsets (Fig. 4c). This geometrical complexity is associated with an orientation change to N080. Close to Mekece, a series of laterally displaced streams running along a north facing scarp show cumulative dextral offsets ranging between 10 m and 25 m.

Further east, the fault crosses the Sakarya river and forms a ~1 km wide releasing step-over (Fig. 4b). The eastern section of the stepover is composed of shorter, en echelon faults. The fault then follows the southern edge of the Geyve-Pamukova basin as a single, simple straight trace with a 70-80°N, but is associated with fewer markers of Holocene horizontal deformation. East of the Geyve plain, the fault runs in the middle of a mountainous area and the precise mapping of the junction with the main NAF strand is less certain (Fig. 4a).

4.3 Fault segmentation

To properly interpret the set of deformed markers observed along the fault, it is needed to first determine the fault segmentation. Such segmentation can also provide first-order constraints on the maximum length and magnitude of earthquake that can be expected. The kind of boundary between the successive segments (azimuth difference, width and length of the step-overs. . .) is also thought to control whether a given rupture is likely to propagate through several segments (Aki, 1984; Barka & Kadinsky-Cade, 1988; Wesnousky, 2006). We decomposed the eastern MNAF zone into several successive segments using the automatic procedure developed by Klinger (2010). The digitized MNAF trace was first simplified and resampled each 50 m. The numerical method models the fault as a continuous set of linear segments and seeks, for a given number of segments, the distributions of segment boundaries which best approximate the actual fault trace. We especially explored the solutions for the range between 8 and 19 segments which showed a good trade-off between data-model misfit and limited number of segments (Fig. S3). The locations of most frequently selected inter-segments for this range cluster on 12 points of the fault. Keeping the solutions that included the most visible geometrical discontinuities along strike (e.g. Sölöz and Mekece stepovers, kinks at 29°35’E and south of Iznik) led us to favor a decomposition of the MNAF into 8 segments (denoted A to H on Fig. 3b).

Overall, the boundaries most frequently selected correspond to the major strike change occurring south of Iznik Lake (C/D inter-segment, Fig. 3b) and the releasing bend at the eastern edge of the Geyve-Pamukova basin (G-H inter-segment). The significant discontinuities of Sölöz bend (B/C inter-segment) and Mekece stepover (E/F inter-segment) also correspond to recurrently selected boundaries. Some other chosen boundaries are less recurrent. The D/E inter-segment is associated with a minor variation in azimuth but also with a more visible change from multiple parallel branches to a single, simpler fault trace eastward. The F/G inter-segment also reflects a transition from small en echelon faults to a single linear fault line eastward.

5 Cumulative and coseismic offsets

5.1 Method of measurement and uncertainties

Major ground rupturing earthquakes generate meter-scale deformations that can be preserved in the morphology through several seismic cycles (e. g. Ansberque et al., 2016; Klinger et al., 2011; Kurtz et al., 2018). In the case of strike-slip ruptures, it is generally possible to measure in the days following the earthquake a series of laterally displaced markers such as roads, fences, walls, field or vegetation lines, terrace risers or gullies. Older morphological markers can also show larger, cumulative values of offset representing the summation of several coseismic displacements. If enough markers of various ages are preserved along the fault, the compilation of a large number of offset measurements is expected to give several clusters of values, corresponding to the cumulative displacement for various numbers of earthquakes (Beauprêtre et al., 2012, 2013). The offset measurements carried out after recent earthquakes have evidenced that the coseismic slip located on the fault often shows significant variations along-strike, as high as 30-40% around the mean displacement (Choi et al., 2018; Lin et al., 2020; Reitman et al., 2019; Rockwell et al., 2002; Zielke, 2018). Despite the erosive and sedimentary processes which tend to erase the smallest coseismic offsets, the measurement of cumulative offsets can also give access to this slip variability on longer time scales (Rizza et al., 2011).

	Total	Segment A	Segment B	Segment C	Segment D	Segment E	Segment F	Segment G	Segment H
Length (full mapping, km)	148	14.4	12.5	13.9	11.5	31.2	16.4	36.6	11.5
Length (confident mapping, km)	107	4.1	12.5	13.6	11.1	24.1	14.9	17.3	9.2
Number of measurements	114	2	10	14	15	50	7	12	4
Measured on Pleiades topography	45	1	6	8	8	22	0	0	0
% Pleiades topography	39	50	60	57	53	44	0	0	0
Measured on Pleiades image	32	1	4	6	7	14	0	0	0
% Pleiades image	28	50	40	43	47	28	0	0	0
Measured on Google Earth image	37	0	0	0	0	14	7	12	4
% Google Earth image	32	0	0	0	0	28	100	100	100
Mean quality /20	12	14	12	11.1	12.3	12.3	10.7	11.8	12.3
Density of data per km	0.77	0.14	0.80	1.01	1.30	1.60	0.43	0.33	0.35
Density of data (confident mapping)	1.07	0.49	0.80	1.03	1.35	2.07	0.47	0.69	0.43
Number of COPD peaks (2σ model)			5	7	11	8	4	6	
Number of COPD peaks (1σ model)			4	4	5	8	4	4	2

Table 1. Summary of the main characteristics of the fault mapping and offset measurements datasets used in this study.

Along a 148-km long portion of the eastern MNAF, we identified and systematically measured 114 offsets (Tables 1 and S3, see Data Availability section). 40% of the measurements were performed using Pleiades topographic data, while Pleiades ortho-rectified images and Google Earth images each represent 30% of the measurements. The displaced markers considered are river channels, gullies, terrace risers and more occasionally vegetation lines and ridges. We favored markers making a high angle with the fault in order to minimize the apparent offset linked to unaccounted-for vertical slip. For each marker, we define piercing lines, i.e. points that were aligned before the displacement, and that we project on the fault trace. The piercing points across the fault are then realigned by retro-deformation, which gives the offset value (Fig. 5). When one marker is displaced by several parallel fault strands, the offset value to be considered is the sum of the measurements on each fault line (Zielke et al., 2015). Five offsets were also measured in the field with tape (Fig. 6). One field measurement (marker 153) ranges significantly lower than the Pleiades measurement due to different reconstruction hypothesis. The other field measurements are in general in fair agreement with the values obtained from satellite imagery, though ~10% lower on average. The relative underestimation of field offset measurements compared to satellite imagery has been noticed in previous studies (see another example in Klinger et al., 2005) suggesting that the distributed deformation is better assessed in the latter case.

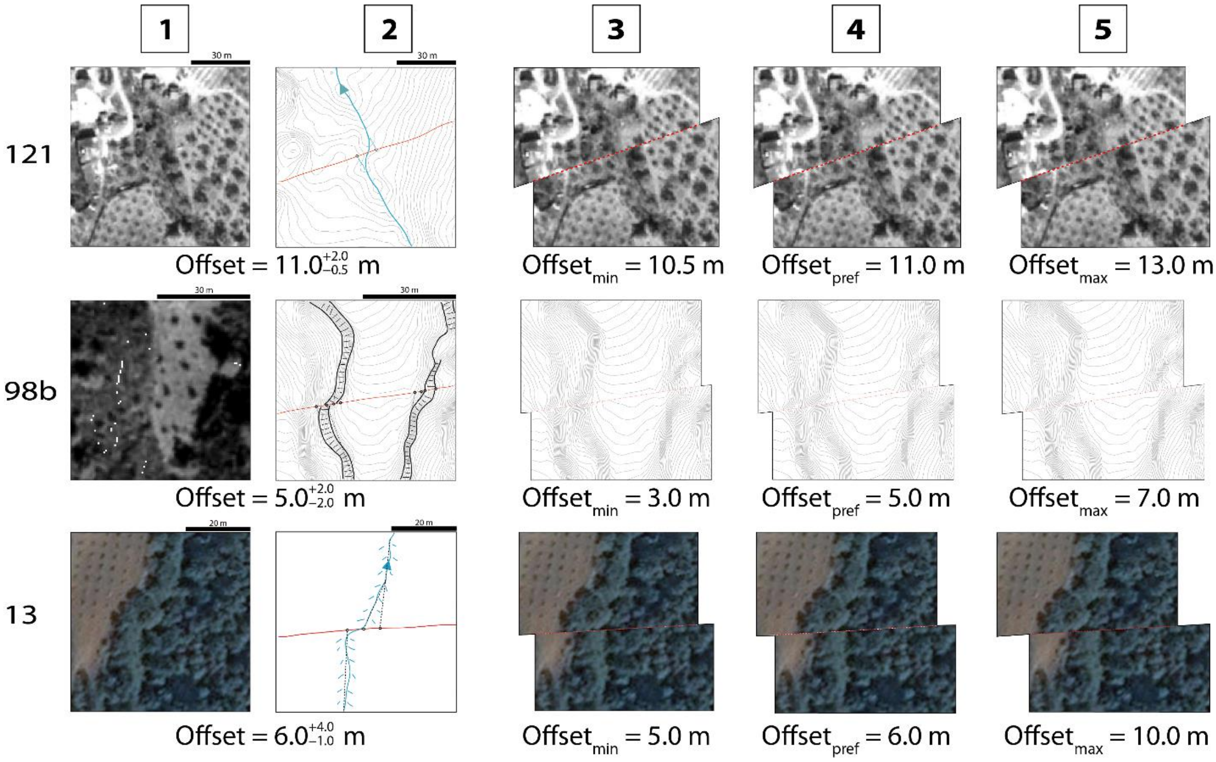


Figure 5. Examples of horizontal offset measurements. Marker ID code is indicated on the left. North direction is upward. From top to bottom, measurements were respectively done using the Pleiades image, topography, and the Google Earth image. Columns 1 and 2 show the original morphologies. The fault is drawn in red. Black lines and circles refer to the piercing lines and points. Columns 3, 4 and 5 show the retro-deformed morphologies giving the minimum, preferred and maximum offset values respectively. For the full dataset, see Data Availability section.

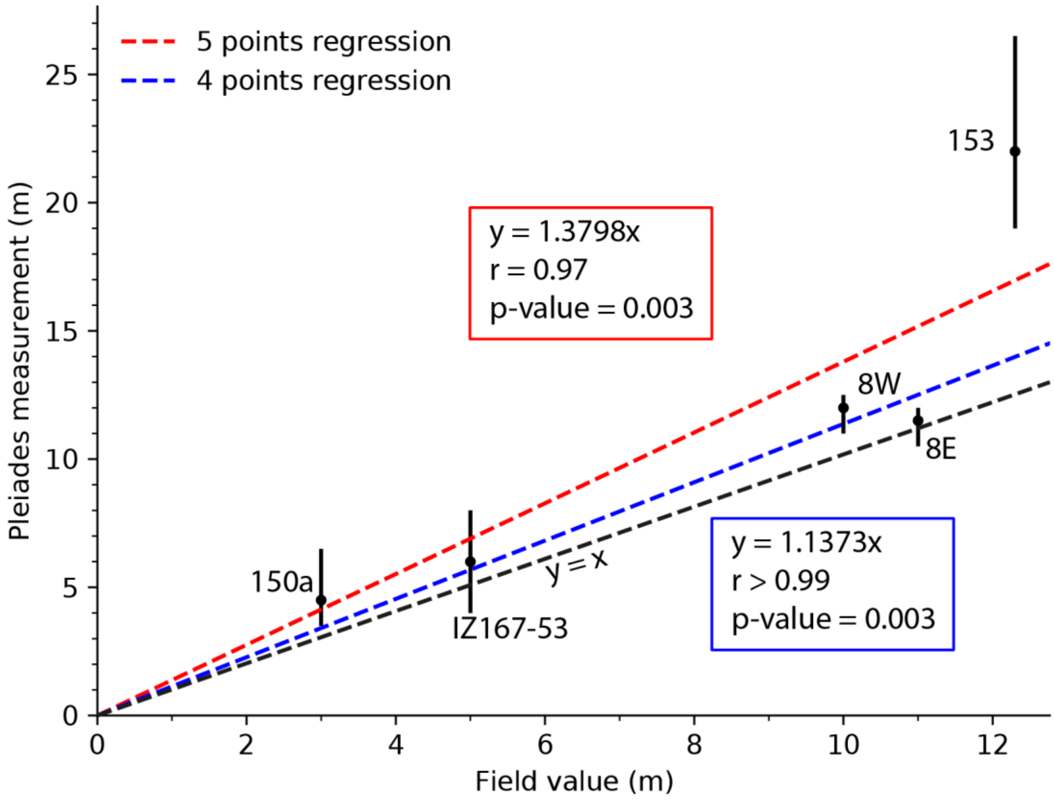


Figure 6. Comparison between field and Pleiades offset measurements. Two linear regressions are shown, including all data points (red) and excluding marker 153 (blue). For each regression we present the equation, Pearson's correlation coefficient *r* and the p-value.

The uncertainty of the offset measurement mainly originates from the various possibilities for interpreting and restoring the original, non-deformed geometry of the marker (Ansberque et al., 2016; Manighetti et al., 2015). Therefore, each measurement consists in our preferred value for the best reconstruction, and a minimum and a maximum value, each representing an extreme plausible reconstruction. We use conservative min/max reconstructions, larger than ±15% of the preferred value on average, so that there is only a small probability that the real offset falls out of this range (Gold et al., 2013). Each measurement is given a 20-points quality score, which reflects the intrinsic quality of each marker in providing a relevant measure (Beauprêtre et al., 2013; Choi et al., 2018; Kurtz et al., 2018; Zielke et al., 2012).

This score includes the following criteria: (a) confidence that the offset marker is of tectonic nature and weakly man-modified, (b) degree of preservation (marker visibility and sharpness), (c) marker shape (width and sinuosity), (d) fault zone complexity (plausible fault zone width and number of fault splays), (e) angle of marker with fault, (f) resolution of used dataset (a detailed explanation of how the quality score is determined can be found in Supporting Information).

5.2 Statistical analysis

The 114 offsets measured range between 2.5 and 64 m, with a majority of values smaller than 30 m (Fig. 7b, Table S3). In order to identify the most significant offset clusters along each fault segment, which could represent the cumulative signature of past ruptures, we represent the offset values as probability density functions (e.g. Beauprêtre et al., 2012; Kurtz et al., 2018; McGill and Sieh, 1991; Zielke et al., 2010). Each offset measurement is represented with an asymmetric Gaussian distribution, the preferred measured value being the peak of the Gaussian probability density function (PDF). Since the minimum and maximum offsets reflect geologically plausible bounds for the reconstruction values and do not directly correspond to real standard variations (Scharer et al., 2014), we compare two models where these maximum and minimum ranges are taken as $\pm 1\sigma$ and $\pm 2\sigma$ half-widths of the PDF (referred hereafter as “1σ model” and “2σ model”).

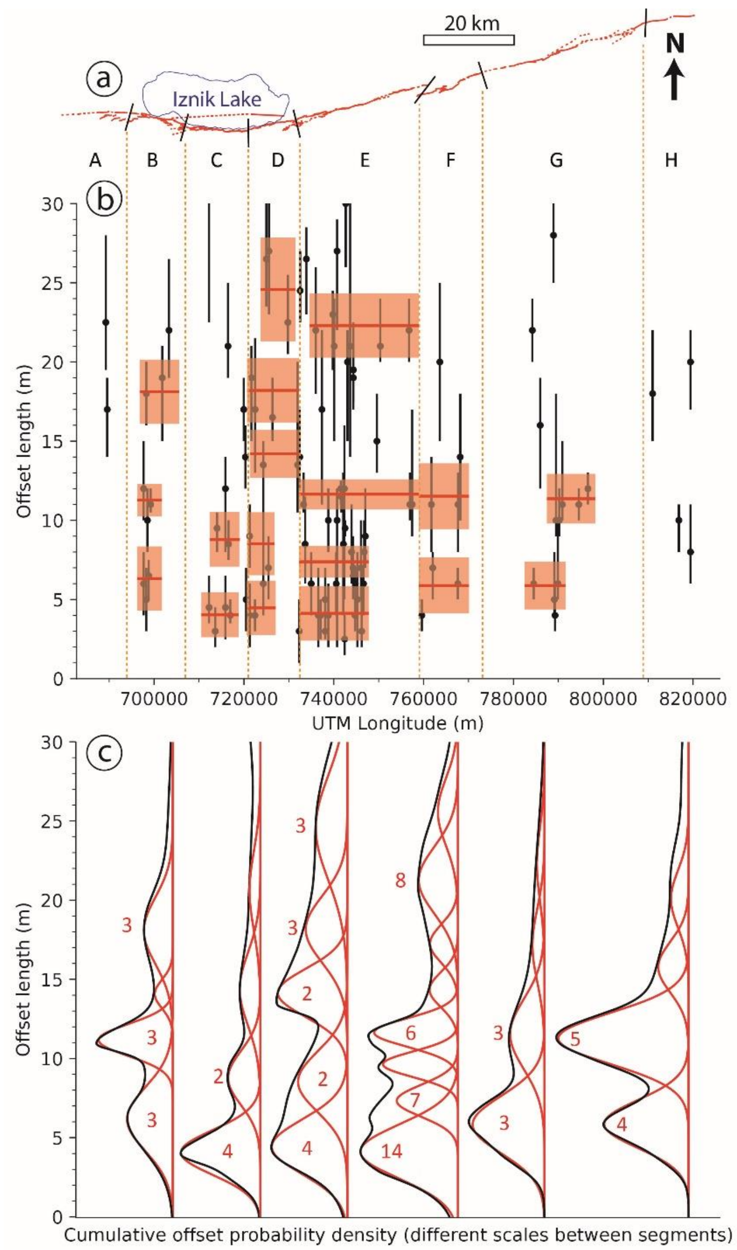


Figure 7. (a) Map of the fault section studied with our proposed segmentation. (b) Horizontal offsets measured along the fault in the range 0-30 m. The color boxes represent the best constrained peak values, within 1σ uncertainties, obtained on the cumulative offset probability distribution (COPD) curves for each segment. The segments are separated by the vertical orange broken lines. (c) COPD curves (black lines) and modeled average slips (red lines) for the 1σ model. The number of supporting individual measurements is indicated for the best constrained COPD peaks.

The individual PDFs for each segment are then summed into a cumulative offset probability distribution (COPD) curve, using the quality scores as weights for each individual offset measurement (Fig. 7c and 8a). The COPD generally presents local peak values, which indicate the most frequent offsets measured along the fault section considered. The contribution of each measurement in the shape of the COPD depends both on its uncertainty and on its quality score. A larger uncertainty corresponds to a wider and flatter individual PDF, which consequently contributes less to define a clear COPD peak. A lower quality score decreases the effect of the measurement in changing the shape of the COPD. For each COPD curve, it is assumed that the value associated to the first peak value corresponds to the offset related to the most recent large earthquake preserved along that specific segment. The average slip associated with this last rupture is empirically extracted from the COPD through several steps (Kurtz et al., 2018). (1) The rising part of the COPD curve is used to build a symmetric Gaussian function, which represents the modeled average slip associated to the most recent rupture along the segment considered. (2) This modeled function is subtracted from the COPD to derive a residual COPD (Fig. 8b). This residual curve is assumed to represent the cumulative tectonic deformation recorded in the landscape before the most recent earthquake occurred. (3) In general, the rising part of the COPD does not strictly follow a Gaussian function, which produces a residual negative artefact located ahead of the following peak values. This residual is discarded by resetting all negative values to zero before the next extraction. These steps are iterated (Fig. 8c) until the residual COPD curve becomes too flat to constrain another Gaussian fit. The minimum amplitude threshold for a peak to be extracted is fixed at 10% of the maximum amplitude of the original COPD.

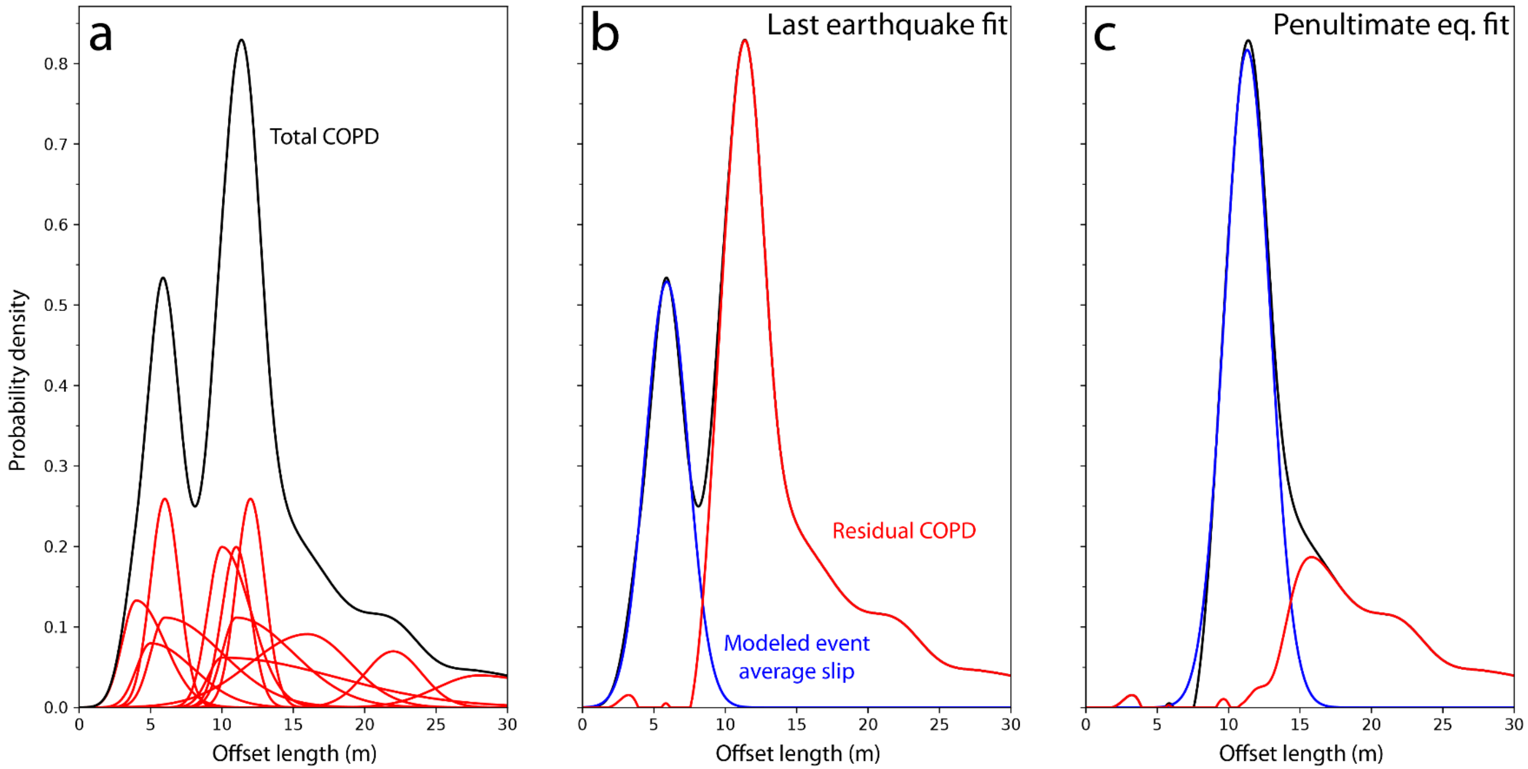


Figure 8. Illustration of the statistical analysis methodology used for the offset measurements of segment G. (a) Probability density functions of the individual measurements (in red) and corresponding Cumulative Offset Probability Density (COPD, in black). (b) Modeling of the last major surface rupture signal by fitting the increasing part of the COPD with a Gaussian curve (in blue). The red line is the residue of the COPD after subtracting this last rupture slip model. (c) Same process as (b) for the presumed penultimate event.

Interpreting COPD peaks as individual slip signals must be done with caution, especially when relative measurement uncertainties are high and when only few data points are available along a segment. Because of the natural variability in coseismic slip along strike, offset measurements from a single event can produce bimodal distributions (Lin et al., 2020; McGill & Rubin, 1999). Conversely, one large increment might hide two separate, smaller events, but undistinguished due to too few data and/or too large individual uncertainties (e. g. Liu-Zeng et al., 2006; Zielke et al., 2010). Once the COPD peaks are extracted for a given segment, we assess the statistical significance of each peak by looking at the following criteria (Tables 2 and 3): number of supporting individual measurements, spreading of the data supporting the first two peaks, degree of overlapping with preceding peak, sensitivity to alternative segmentation (for segments C, D, E).

5.3 Results

Tables 2 and 3 present the offset values extracted from the COPD peaks for each fault segment in the range 0-30 m. We extracted between 4 and 11 peaks per segment for the 2σ model and between 4 and 8 peaks for the 1σ model (Table 1). Smaller modeled uncertainties tend to increase the number of extracted peaks per segment. This effect is most significant for segment D where the number of peaks for the 2σ model is two times larger. However, most of the extracted peaks for the 2σ model show poor statistical robustness. Half of them are not supported by more than one individual measurement (Table 3). For some of them, the increment with the preceding peak is not significantly different from zero. Several of them do not pass the segmentation test. This likely results from a high degree of data scattering compared to uncertainties, especially for segments with small numbers of measurements. Segment E does not show this feature because of its high spatial density of measurements, which is more than twice as high as the average density of the other segments (Table 1).

To check for potential biases resulting from this higher density of measurements, we performed a supplementary test on segment E. We produced and analyzed five random subsets of 18 measurements obtained on segment E, so that the measurement density of the subsets equals the average density of the other segments, i.e. 0.75 measurement per km. We then identified which extracted peaks remained consistent between all subsets. The sensitivity tests for that segment suggest that only the first two peaks are statistically robust. These peaks still present a high degree of overlapping.

Most peaks obtained with the 1σ model are statistically stronger than those obtained with the 2σ model (Table 2). When only the more robust peaks are considered, both models show similar results (Table 4, Fig. 7b). Segments A and H did not provide statistically significant peaks due to the very small number of measurements.

We identified two to five statistically robust cumulative slip increments for segments B to G, ranging between 4 and 25 m. Offset values show consistency between all segments for the first two extracted peaks at ~5 and ~10 m. However, the central segments C, D and E show lower mean values of increments, from 3.2 m to 4.7 m, while they range between 5 and 6.2 m on segments B, F and G. On segment E, despite the higher density of measurements, the events are harder to separate and their respective displacement is less constrained due to the larger scattering of data points. Peak values differ more for higher peaks (Table 4).

Segment	Mean value	(±1σ)	Increment with preceding peak	(±1σ)	Number of supporting measurements	Mean quality	Spreading with previous peak	Overlapping coefficient with previous peak	Sensitivity to segmentation	Sensitivity to downsampling
B	6.2	2			3	12.7				
B	11.2	1	5	3	3	12	<30%	0.09		
B	14.1	0.9	2.9	1.9	0			0.13		
B	18.1	2.1	4	3	3	12		0.16		
C	4.1	1.4			4	14.3				
C	8.8	1.7	4.7	3.1	2	11	<30%	0.13		
C	14.4	2.3	5.6	4	3	9		0.16	x	
C	20.6	2.5	6.2	4.8	1	11		0.2		
D	4.5	1.7			4	12.3				
D	8.6	1.9	4.1	3.6	2	10	<30%	0.25		
D	14.2	1.5	5.6	3.4	2	14.5		0.1		
D	18.2	2.1	4	3.6	3	14		0.26		
D	24.6	3.3	6.4	5.4	3	11.3		0.23		
E	4.2	1.7			14	12.8				
E	7.4	1	3.2	2.7	7	12.1	<30%	0.23		
E	9.7	0.8	2.3	1.8	4	10.8		0.2		x
E	11.7	0.9	2	1.7	6	13.3		0.24		
E	14.4	1.1	2.7	2	2	11		0.18		x
E	17.3	1.2	2.9	2.3	2	13		0.21	x	x
E	21.3	2.1	4	3.3	8	11.6		0.21		
E	25.6	2.1	4.3	4.2	3	13.7		0.31	x	x
F	5.9	1.8			3	10.7				
F	11.6	2.2	5.7	4	3	10	<30%	0.15		
F	17.2	2.3	5.6	4.5	0			0.21		
F	22.3	2.3	5.1	4.6	1	13		0.27		
G	5.9	1.5			4	11.3				

G	11.3	1.6	5.4	3.1	5	13.2	<30%	0.08
G	15.8	1.6	4.5	3.2	1	16		0.16
G	20.1	1.8	4.3	3.4	1	7		0.21
H	9.4	2			2	13		
H	18.7	2.7	9.3	4.7	2	11.5	30-40%	0.05

Table 2. COPD peaks extracted for the 1σ model. Mean quality is computed on the set of individual measurements supporting each peak. Spreading value is expressed in % of the mean of measurements supporting the first two peaks per segment. The overlapping coefficient is computed using normalized distributions.

Segment	Mean value	(±1σ)	Increment with preceding peak	(±1σ)	Number of supporting measurements	Mean quality	Spreading with previous peak	Overlapping coefficient with previous peak	Sensitivity to segmentation	Sensitivity to downsampling
B	6.1	1.3			3	12.7				
B	9.9	0.6	3.8	1.9	1	13	<30%	0.04		
B	11.1	0.4	1.2	1	1	15		0.22		
B	12.3	0.9	1.2	1.3	1	8		0.32		
B	18.2	1.4	5.9	2.3	2	13.5		0.01		
C	3	0.5			1	17				
C	4.2	0.5	1.2	1	3	13.3	>40%	0.23		
C	5.4	0.5	1.2	1	0			0.23		
C	9	0.8	3.6	1.3	3	10	<30%	0.05		
C	13.9	1.6	4.9	2.4	1	11		0.04	x	
C	17.2	0.7	3.3	2.3	1	8		0.14	x	
C	21.2	1.6	4	2.3	1	11		0.07		
D	4.2	0.8			3	14				
D	6.8	1	2.6	1.8	2	6.5	30-40%	0.15		

D	9	1	2.2	2	1	14	<30%	0.27		
D	13.2	1.9	4.2	2.9	0			0.14	x	
D	13.7	0.5	0.5	2.4	2	14.5		0.42		
D	14.9	0.5	1.2	1	0			0.23		
D	16.6	0.7	1.7	1.2	2	15		0.15		
D	18.2	0.9	1.6	1.6	1	12		0.31	x	
D	19.8	0.6	1.6	1.5	1	12		0.26		
D	22.5	1.2	2.7	1.8	1	14		0.16	x	
D	26.5	1.7	4	2.9	2	10		0.16		
E	3.8	1			10	13				
E	6.4	0.9	2.6	1.9	7	11.3	<30%	0.17		
E	8.3	0.6	1.9	1.5	4	13.8		0.2		x
E	9.6	0.5	1.3	1.1	4	10.8		0.24		x
E	11.4	0.7	1.8	1.2	6	13.3		0.13	x	x
E	14.4	1.5	3	2.2	3	11.7		0.16	x	x
E	19.7	1.7	5.3	3.2	6	12.8		0.1		x
E	24	2.6	4.3	4.3	5	11.4		0.31	x	
F	4	0.5			1	9				
F	6.2	0.8	2.2	1.3	2	11.5	>40%	0.09		
F	11.1	1.5	4.9	2.3	3	10	<30%	0.03		
F	19.6	3	8.5	4.5	1	13		0.06		
G	4.1	0.6			2	9				
G	6	0.7	1.9	1.3	2	13.5	>40%	0.14		
G	8	0.5	2	1.2	0			0.09		
G	11.3	1.2	3.3	1.7	5	13.2	<30%	0.05		
G	15.2	1.2	3.9	2.4	1	16		0.1		
G	22	1.1	6.8	2.3	1	7		0.003		

Table 3. COPD peaks extracted for the 2σ model. Mean quality is computed on the set of individual measurements supporting each peak. Spreading value is expressed in % of the mean of measurements supporting the first two peaks per segment. The overlapping coefficient is computed using normalized distributions.

	COPD peak values (m)					Increments between peaks (m)				
	Peak 1	**Peak 2**	**Peak 3**	**Peak 4**	**Peak 5**	**Peak 1**	**Peak 2**	**Peak 3**	**Peak 4**	**Peak 5**
B	**6.2±2** (6.1±1.3)	**11.2±1.0**	**18.1±2.1** (18.2±1.4)			**6.2±2** (6.1±1.3)	**5±3.0**	**6.9±3.1** (12.1±2.6)		
C	**4.1±1.4** (4.2±0.5)	**8.8±1.7** (9.0±0.8)				**4.1±1.4** (4.2±0.5)	**4.7±3.1** (4.8±1.3)			
D	**4.5±1.7** (5.5±1.8)	**8.6±1.9**	**14.2±1.5** (13.7±0.5)	**18.2±2.1** (16.6±0.7)	**24.6±3.3** (26.5±1.7)	**4.5±1.7** (5.5±1.8)	**4.1±3.6**	**5.6±3.4** (8.2±2.3)	**4.0±3.6** (2.9±1.2)	**6.4±5.4** (9.9±2.4)
E	**4.2±1.7** (3.8±1.0)	**7.4±1.0** (6.4±0.9)	**11.7±0.9**	**22.3±2.1**		**4.2±1.7** (3.8±1.0)	**3.2±2.7** (2.6±1.9)	**4.3±1.9**	**10.6±3.0**	
F	**5.9±1.8** (5.1±1.3)	**11.6±2.2** (11.1±1.5)				**5.9±1.8** (5.1±1.3)	**5.7±4.0** (6.0±2.8)			
G	**5.9±1.5** (5.1±1.3)	**11.3±1.6** (11.3±1.2)				**5.9±1.5** (5.1±1.3)	**5.4±3.1** (6.2±2.5)			

Table 4. Best constrained cumulative offsets and slip increments computed for each fault segment in the offset range 0-30 m. The retained peaks respect the following conditions: significant increment with preceding peak, more than one supporting individual measurement, less than 30% of spreading with previous peak, consistency through varying segmentation and downsampling. Uncertainties are 1σ. Bold values are from the 1σ model. Values in brackets are those deduced from the 2σ model. We underline values showing consistency between the two models.

Terrace	Sample code	Depth (cm)	Dissolved quartz mass (g)	^{9}Be carrier solution (g)	^{10}Be/^{9}Be ratio ± 1σ AMS uncertainty (10^{-15} blank corrected)	^{10}Be (10^{4} at/g)	^{10}Be concentration uncertainty (%)	Sampling site location
Tl3	15TUR5-0a	0	17.179	0.2988	9.913 ± 1.208	1.1499	23.05	40.397°N - 29.697°E
Tl3	15TUR5-0b	0	18.480	0.2990	23.17± 6.328	2.5003	34.99	94±4 m asl
Tl3	15TUR5-20	20-35	2.864	0.3010	3.428 ± 0.744	2.4060	69.82	TS = 0.997
Tl3	15TUR5-60	60-70	10.739	0.2995	8.012 ± 0.956	1.4902	25.69	
Tl3	15TUR5-80	80-90	16.347	0.2980	12.25 ± 1.234	1.4896	17.91	
Tl3	15TUR5-130	130-140	6.789	0.2976	3.808 ± 0.556	1.1132	49.12	
Tl2	15TUR3-0a	0	20.549	0.3043	178.5 ± 6.176	17.6296	3.65	40.496°N - 29.681°E
Tl2	15TUR3-0b	0	18.510	0.3078	89.09 ± 5.310	9.8809	6.52	127±3 m asl
Tl2	15TUR3-60	60-85	20.824	0.2989	53.09 ± 4.953	5.0837	10.65	TS ~ 1
Tl2	15TUR3-110	110-130	19.941	0.2905	245.1 ± 8.848	23.8183	3.75	
Tl2	15TUR3-150	150-175	17.038	0.2993	200.4 ± 32.61	23.4781	16.79	
Tl1	15TUR4-0a	0	20.838	0.2979	226.9 ± 75.69	21.6293	34.27	40.503°N - 29.686°E
Tl1	15TUR4-0b	0	20.514	0.2973	313.7 ± 11.86	30.3225	3.89	164±3 m asl
Tl1	15TUR4-30	30-40	20.550	0.2958	255.4 ± 7.943	24.5165	3.24	TS ~ 1
Tl1	15TUR4-80	80-90	23.547	0.2981	292.6 ± 11.47	24.7008	4.03	
Tl1	15TUR4-130	130-140	20.510	0.2984	326.3 ± 10.80	31.6621	3.41	
Tl1	15TUR4-260	260-270	22.204	0.2966	184.8 ± 9.776	16.4640	5.52	
Tl1	15TUR4-370	370-380	20.771	0.2980	243.5 ± 12.71	23.2995	5.38	

Table 5. Characteristics of the terrace samples and results of the nuclide measurements. The ^{10}Be/^{9}Be ratio of the blank is 6.200.10^{-15} with an analytical uncertainty of 19%. TS is topographic shielding value. The total measurement error includes the uncertainties associated with the AMS measurement, the blank value, the dissolved quartz mass and the spike mass weighing and concentration.

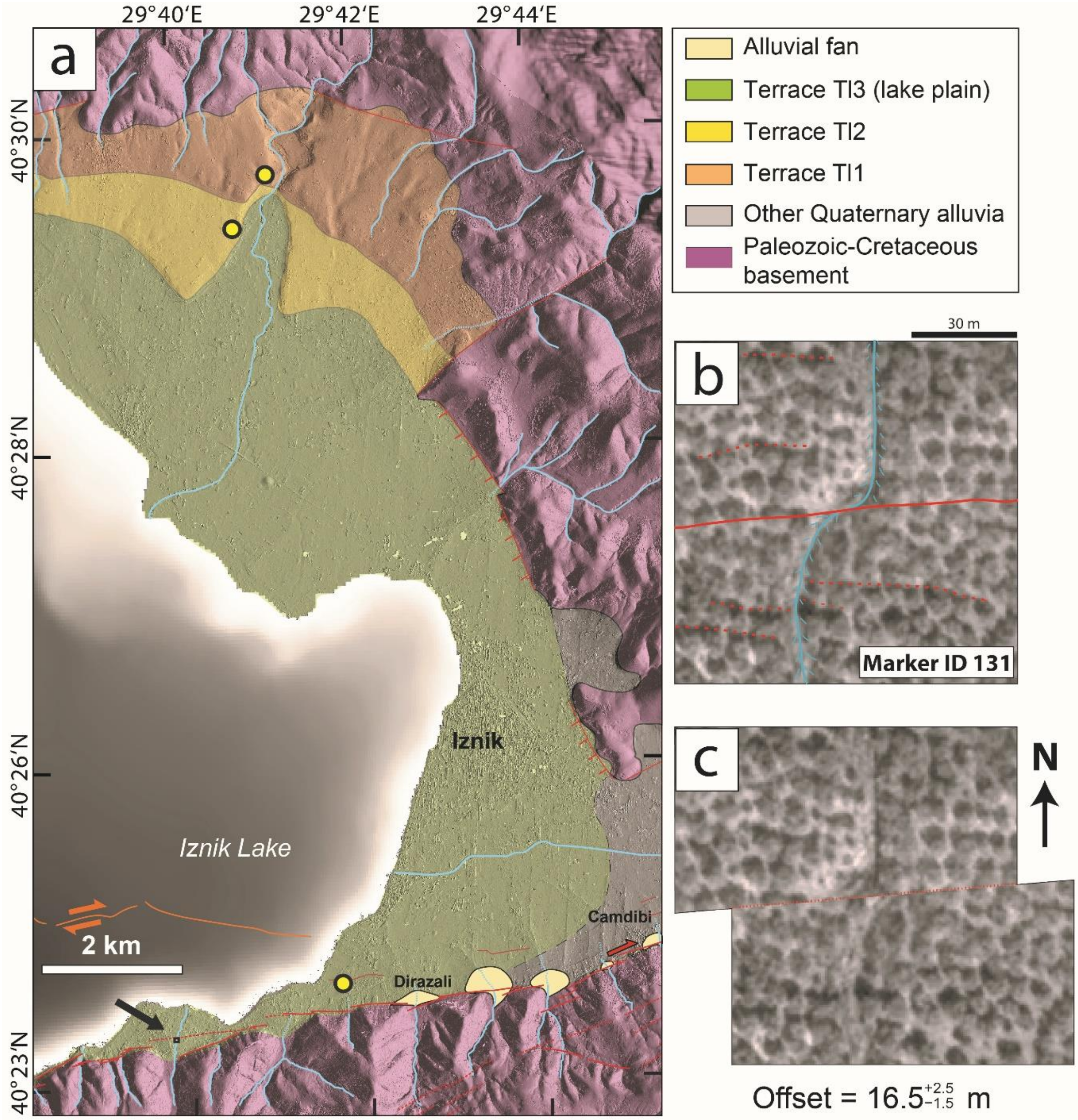


Figure 9. (a) General location of the terrace sampled for cosmogenic dating (yellow dots). Active faults are mapped in red-orange and main streams are drawn in blue. The subaqueous fault trace is taken from Gastineau et al. (2021). The eastern limit of terrace Tl3 is not well defined in the geomorphology and was drawn assuming a constant elevation. The marker used to derive a minimum horizontal slip rate is indicated with a black arrow. (b) Interpreted Pleiades image of the present-day marker morphology. (c) Preferred retro-deformed morphology.

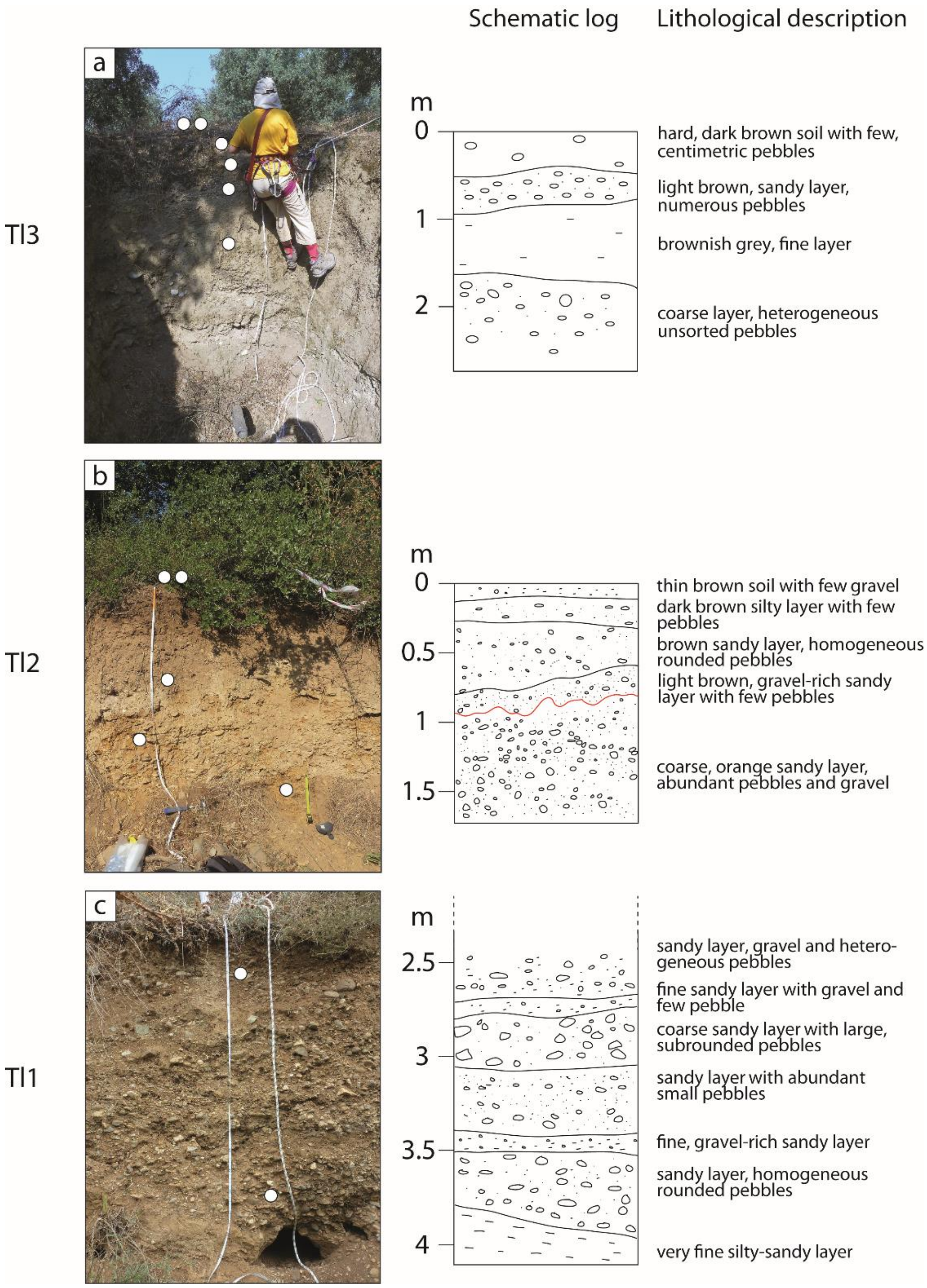


Figure 10. Field photographs (left) and interpreted stratigraphy (right) of the terrace profiles sampled for dating, Tl3 (a), Tl2 (b), and Tl1 (c). The samples are represented with white circles. The first meters of Tl1 profile were covered with bushes, and consisted of a homogeneous brown, silty-sandy unit with a few centimetric pebbles.

6 Terrace dating

Actually, the statistical analysis of cumulative offsets evidences the occurrence of past ruptures along the MNAF and documents the associated slip-per-event, but does not inform the age of these events. To narrow down the age range for the identified events and estimate the late Quaternary slip rate of the MNAF, we need constraints on the age of the terranes that were offset by the fault. For this, we targeted three levels of terraces, which appear particularly well-developed north and east of Iznik Lake (Ikeda et al., 1991; Fig. 9a).

6.1 Sampling and analytical method

To date the terraces, we used the *in-situ* produced terrestrial cosmogenic nuclide (TCN) method. The terraces were sampled along vertical profiles (Fig. 10, Table 5). For terraces Tl1 and Tl2, samples were taken on pre-existing scarps, and for terrace Tl3, which represents the younger, abandoned lake plain, we benefited from a pit dug in the plain for hydrological maintenance. The outcrops displayed alternations of fine sand and coarser gravel-rich conglomerate with graded bedding, with no evidence of buried paleosoils. Tl1 and Tl3 mainly showed alluvial facies, the former displaying evidence of paleochannels and cross-stratification. Tl2 showed lateral facies variations, with finer, lacustrine deposits on the north-central shore of the lake, and coarser fluvial deposits in the east at the sampling site. While Tl1 and Tl3 profiles can be assumed to represent a continuous sedimentation sequence, Tl2 profile displays an irregular interface at 1 m depth that suggests an interruption in the sedimentation process potentially associated with emersion and erosion (Fig. 10b). For each profile, we collected two samples on the surface of the terrace, and when possible, three to four samples in the first 1.5 m below the surface, and one to two deeper samples at the bottom of the profile to constrain the potential inherited nuclide content. We sampled pebbles made of silicate material in order to have ~100 g of quartz per sample.

The beryllium was extracted at the Geo-thermo-chronology platform (ISTerre, University Grenoble Alpes, France). Quartz was obtained from the 250-500 µm fraction after isolation of the non-magnetic grains by repeated leaching in a H_2SiF_6-HCl mixture. The samples were then processed following the chemical procedure of Brown et al. (1991) and Merchel and Herpers (1999). The beryllium was finally measured as a $^{10}Be/^{9}Be$ ratio at the ASTER Accelerator Mass Spectrometer in Aix-en-Provence, France (Arnold et al., 2010).

6.2 Age determination

The obtained concentration-depth-profiles (Table 5 and Fig. 11, 12, 13) were modelled with a Monte Carlo approach using the code ^{10}Be profile simulator version 1.2 developed by Hidy et al. (2010). This approach enables to find the combination of parameters that best fits the measured profile, including the exposure age, the erosion rate and the inherited TCN concentration. The halflife of ^{10}Be (1.387±0.012 Ma) was taken from Chmeleff et al. (2010). We used a reference production rate of 4.06±0.23 atoms.$g^{-1}.a^{-1}$ for the neutron induced spallogenic production at sea level and high latitude using the CREp program (Martin et al., 2017), with the Lifton-Sato-Dunai scaling scheme (Lifton et al., 2014), the ERA40 atmosphere model (Uppala et al., 2005), and the Lifton VDM 2016 geomagnetic correction (Lifton, 2016). The muonic production was calculated using the theoretical equations of Heisinger et al. (2002a,b) and determined at the sampling site's elevation and for a given depth following the approach of Balco et al. (2008). The cumulative bulk density of the material above each sample was assumed constant over depth, with an average value of 2.2 g/cm^3, previously measured in similar gravel-based terraces (Hidy et al., 2010). For the first iterations, the initial parameters for age, inheritance and erosion rate were allowed to vary largely.

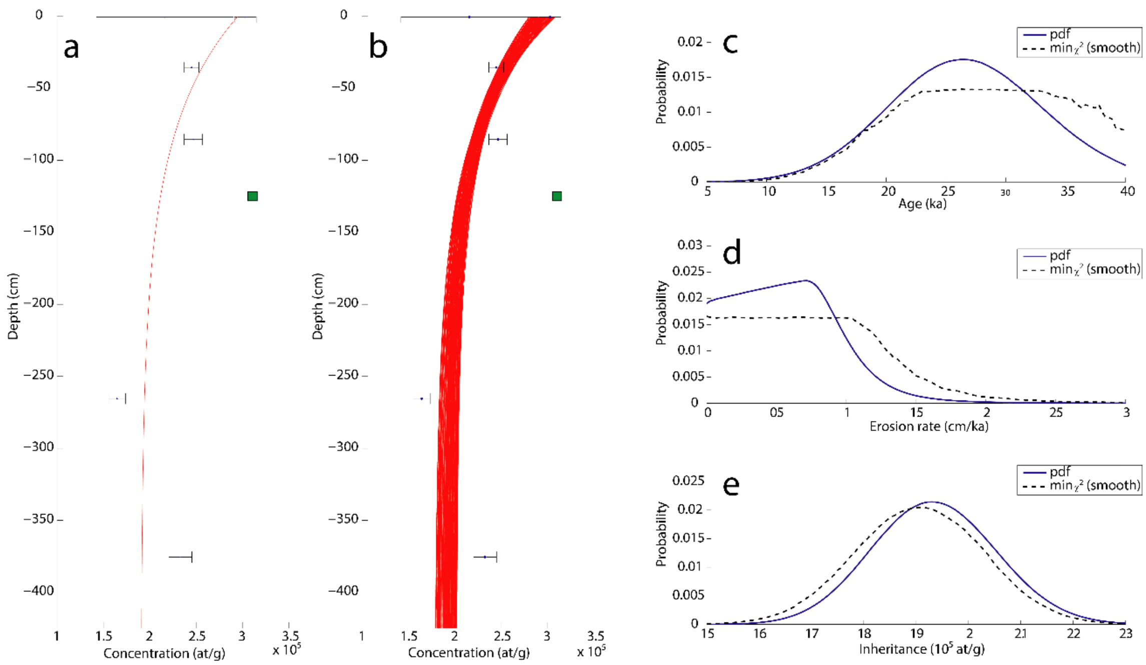


Figure 11. Result of the Monte Carlo simulations for terrace Tl1. (a) ^{10}Be concentrations measured along depth and best fit obtained. (b) All the solutions found in the parameter solution space defined as inputs. The sample excluded from the inversion is shown as a green box. (c, d, e) Probability density functions (solid lines) and minimum χ^2 distributions (dashed line) for the exposure age, erosion rate and inheritance concentration respectively.

Terrace Tl1 profile presents one point (15TUR4-130) with a high concentration, larger than the surface samples, which is incompatible with the theoretical depth profile. The deepest sample also shows (15TUR4-370) a high concentration, intermediate between 15TUR4-260 and the shallower samples. We ran the simulation only excluding sample 15TUR4-130. The algorithm was not able to find solutions in the 2σ confidence windows, and we had to increase the χ^2 cut-off value to 11. The 250,000 solutions obtained provided a most probable, modal age of 27.0 ^{10}Be ka (Fig. 11), a low erosion rate ranging below 1 cm/ka, and a much higher inheritance around ~190,000 at/g.

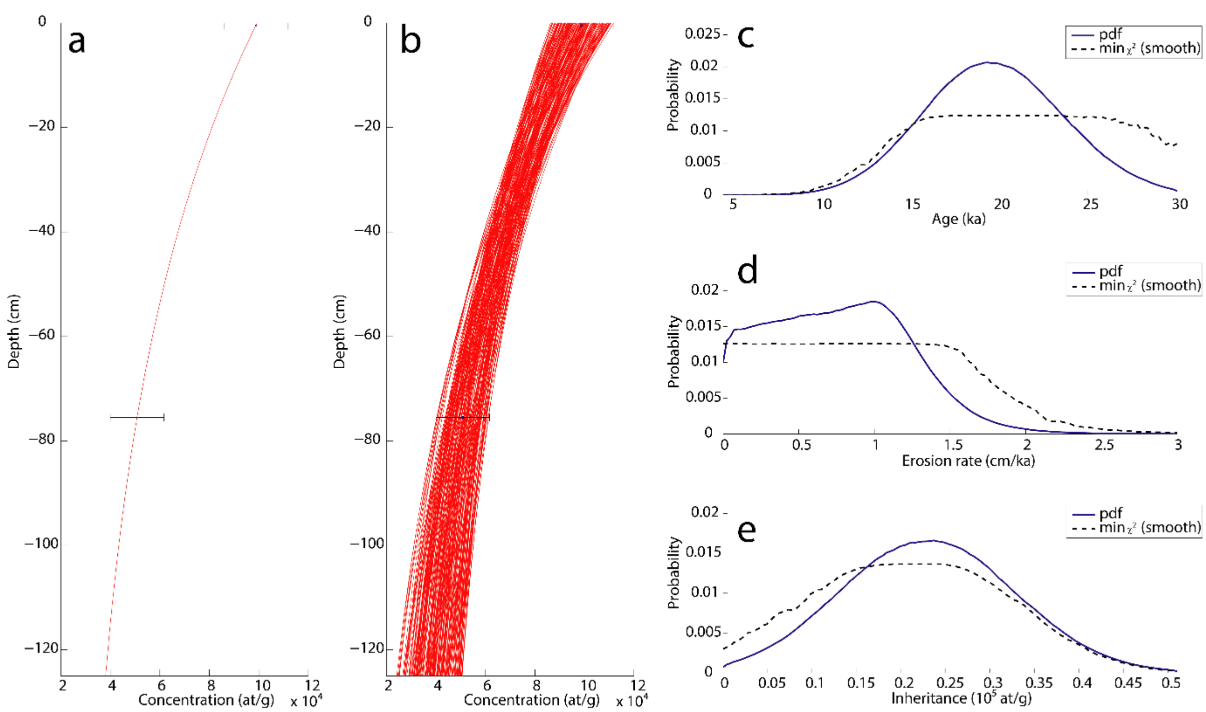


Figure 12. Result of the Monte Carlo simulations for terrace Tl2. (a) ^{10}Be concentrations measured along depth and best fit obtained. (b) All the solutions found in the parameter solution space defined as inputs. The three samples excluded from the inversion show concentrations above 120,000 at/g. (c, d, e) Probability density functions (solid lines) and minimum χ^2 distributions (dashed line) for the exposure age, erosion rate and inheritance concentration respectively.

Terrace Tl2 profile presents more complexity, especially because the two deepest samples (15TUR3-110 and 15TUR3-150) have the highest nuclide concentrations of all the dataset. As the outcrop stratigraphy suggests, they are likely to belong to a previous deposition sequence which was eroded before the onset of a new sedimentation sequence over it. Therefore, we excluded the two deep samples for the simulation. The algorithm could not converge towards a solution for the three remaining points, even when we allowed worse models to be accepted by increasing the χ^2 parameter. We then redid the test excluding sample 15TUR3-0a or 15TUR3-0b, which allowed the algorithm to converge. When keeping the sample 15TUR3-0a, the obtained age was similar to the age found on Tl1. The other surface sample 15TUR3-0b seems more reliable as it shows a nuclide concentration intermediate between the surface samples of the other terraces. With only two samples, it is impossible to determine statistically robust solutions for the age, erosion rate and inheritance at the same time. To narrow down the solution space, we constrained the initial inheritance using the concentration of sample 15TUR3-60 as upper bound, and the initial age below the age obtained for Tl1. We finally obtained 250,000 solutions within the 2σ confidence window, giving a most probable age of $\mathbf{19.6^{+7.7}_{-7.2}}$ ^{10}Be ka (Fig. 12).

For terrace Tl3, the simulator was not able to produce solutions when all the data of the profile were included, especially because one surface sample (15TUR5-0a) showed a very low concentration comparable to the deepest sample (15TUR5-130). We assumed this sample to be an outlier, likely to originate from recent excavation and deposition during agricultural work. We observed that the profile data did not permit to constrain the erosion rate. We tested initial maximum erosion rates of 1, 2 and 3 cm/kyr and obtained similar results between the three simulations. Using a moderate erosion rate of 1 cm/kyr as initial upper bound, the 250,000 solutions found within the 2σ confidence window gave a most probable age of $\mathbf{3.8^{+6.3}_{-2.7}}$ ^{10}Be ka.

This involves an inheritance of ~8000 at/g (i.e. 30% of the surface sample) (Fig. 13e).

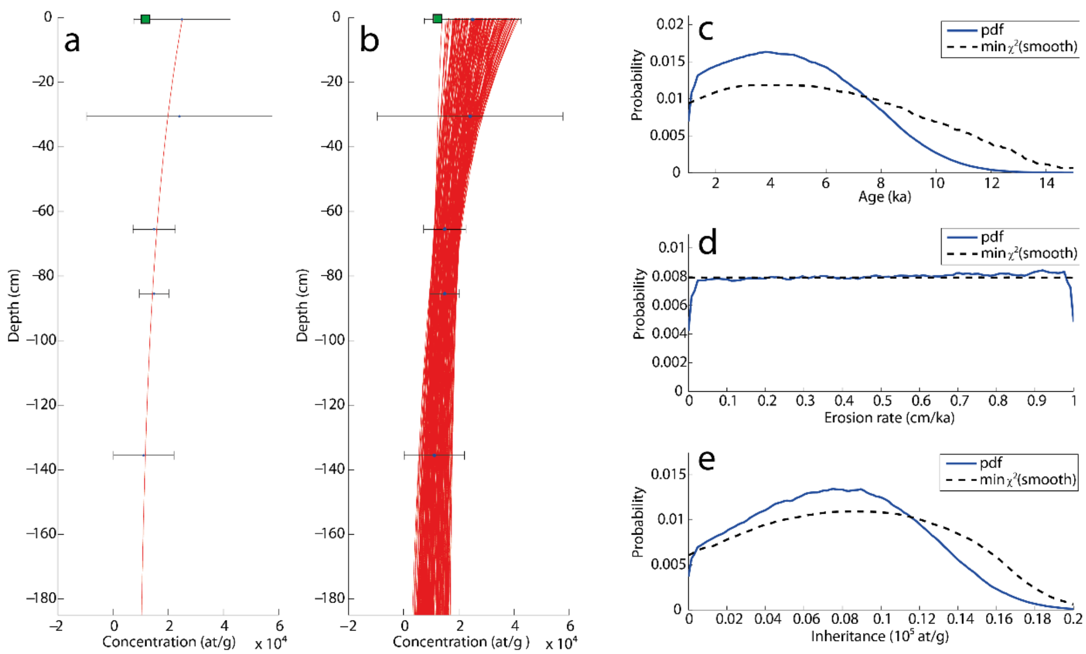


Figure 13. Result of the Monte Carlo simulations for terrace Tl3. (a) ^{10}Be concentrations measured along depth and best fit obtained. (b) All the solutions found in the parameter solution space defined as inputs. The sample excluded from the inversion is shown as a green box. (c, d, e) Probability density functions (solid lines) and minimum χ^2 distributions (dashed line) for the exposure age, erosion rate and inheritance concentration respectively.

7 Discussion

7.1 Horizontal slip rate estimate

Horizontal slip rates are usually constrained by dating sedimentary units laterally displaced by the faults (Le Béon et al., 2010; Rizza et al., 2011; van der Woerd et al., 2006). This kind of estimation is preferentially done with cumulative offsets of several hundreds of meters in order to average out the variability of individual coseismic displacements (see e.g. Wechsler et al., 2018). This type of measurement will yield a minimum slip rate as the offset is considered to be as old as the emplacement of the sediments, although it could also be much younger without a way for us to know about it.

Southeast of the lake, the MNAF segments have displaced Holocene streams incising in terrace Tl3, that we have dated at $\mathbf{3.8^{+6.3}_{-2.7}}$ ^{10}Be ka. Among the markers identified, the largest quality 1 offset measured was $\mathbf{16.5^{+2.5}_{-1.5}}$ m on a river located ~3.5 km west of Dirazali village (Fig. 9). The COPD results suggest that this corresponds to the cumulative slip of the last 3-4 large earthquakes. The ratio between the mean offset and the age of Tl3 provides a minimum horizontal slip rate of 4.3 mm/yr. This value is in the same range as the rate of 3.7±0.7 mm/yr estimated by Gasperini et al. (2011) on Gemlik segment. Due to the large 2σ upper range for the age of Tl3, the obtained minimum rate comes with a high level of uncertainty. Dividing the minimum offset by the 2σ upper age gives a lower bound rate of 1.4 mm/yr.

7.2 Past seismic events evidenced along-strike

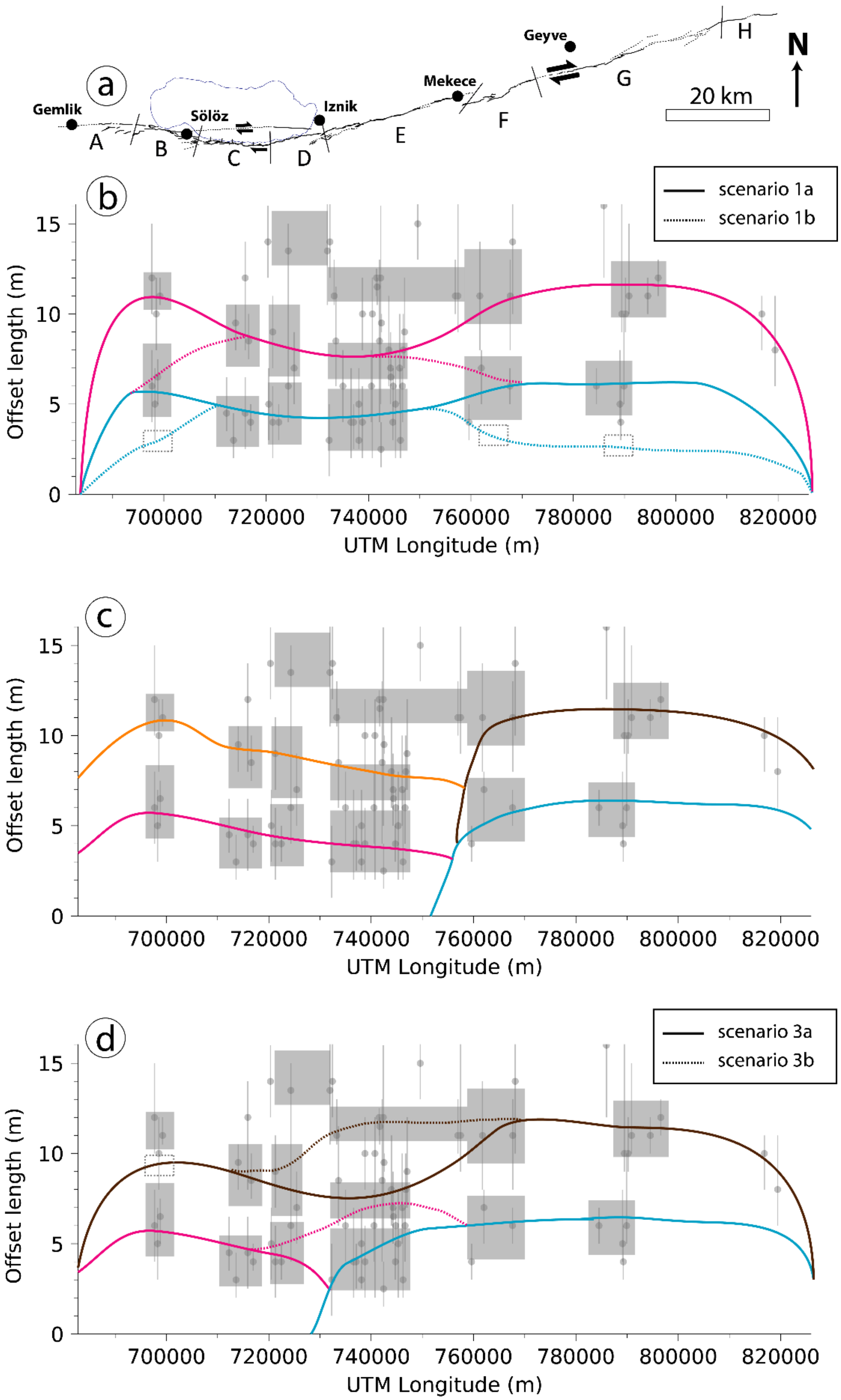
Our study of cumulative offsets along the MNAF provides valuable information on earthquake propagation along this fault, in terms of rupture extent, slip amount and distribution. It also allows us to discuss the behavior of the MNAF segments during the last major earthquakes.

If we assume the first two peaks to be the signature of the last two large earthquakes, with respective maximum coseismic slips of 6.2±2 m and 5.7±4 m, empirical scaling laws suggest that they correspond to events of moment magnitude of 7.2±0.2 to 7.4±0.2, with rupture lengths of 73±28 to 97±42 km (Wells & Coppersmith, 1994; using all-slip-type and strike-slip regressions respectively). Conversely, a rupture extending along the entirety of the 148 km long studies section would correspond to an earthquake of moment magnitude 7.6±0.3 and maximum coseismic displacements of 6.7-6.8 m, using the same scaling relationships. Our results are therefore compatible with large earthquakes able to rupture large parts of the eastern MNAF. Wesnousky (2006) has shown that there exists a maximal step-over size (3-4 km fault-perpendicular) which tends to stop rupture propagation. In our case, Sölöz bend and Mekece, which are the largest identified step-overs of the eastern MNAF, have widths of 2.5 and 1.5 km respectively, and it can thus be assumed that past large ruptures may have propagated through them.

Our results show significant along-strike variability of the total number of recorded slip events and the associated slip values. Mean slip values tend to be lower for segments C, D and E. We also note that segments D and E document more individual slip events than the other segments. It has been observed that the COPD curve shows an exponential decay in the peaks' amplitude with increasing cumulative slip (Klinger et al., 2011), as older markers tend to be less preserved in the landscape. We find this kind of pattern for some segments (e.g. segment C), but for segments B and G we observe that peak 1 is smaller than peak 2. The central segments are characterized by higher slopes. This implies more dynamic hydrologic conditions and geomorphic marker formation, and thus a higher capacity to preserve the traces of successive earthquakes (Zielke et al., 2015). By contrast, the lower slopes of the other segments may have favored more intensive agricultural activities, thus partly erasing traces of past ruptures.

Therefore, a first possibility to explain the along-strike slip-per-event variability is to assume that COPD peak 1 on segments B, F and G is cumulative, and that the last event was not preserved enough on segments B, F and G to produce a strong COPD peak (Fig. 14b).

Alternatively, the slip decrease observed in the central segments may be related to their higher geometrical complexity (fault bends and obliquity, overlapping segments and branching, see sections 2 and 4.2). Distribution of the deformation across several structures implies that only part of the slip can be measured on the investigated MNAF strand, leading to apparent local slip decrease. A more oblique slip vector with a larger, unaccounted for vertical component, especially along segments C and D, may have a similar effect. Lower horizontal coseismic slip values along these segments may also suggest partial partitioning, with the subaqueous Iznik fault accommodating a part of the horizontal displacement (see e.g. de Michele et al., 2010; King et al., 2005 for recent examples of this). Finally, structural complexities may act as a barrier for the propagation of ruptures, leading to smaller offsets through slip tapering (Ward, 1997; Zielke et al., 2015).


a
Gemlik
Sölöz
Iznik
Mekece
Geyve
A
B
C
D
E
F
G
H
N
20 km
b
scenario 1a
scenario 1b
Offset length (m)
UTM Longitude (m)
0
5
10
15
700000
720000
740000
760000
780000
800000
820000
c
Offset length (m)
UTM Longitude (m)
d
scenario 3a
scenario 3b
Offset length (m)
UTM Longitude (m)

669

Figure 14. (a) Geometry of the fault section studied. (b) First order scenarios of horizontal slip distribution during past events. The last major event (light blue) is assumed to have ruptured all the segments. The penultimate (magenta) replicates this slip distribution. Alternative scenario 1b assumes a partly unpreserved, smaller slip (broken boxes) for the last major rupture. (c) Scenario 2 of horizontal slip distribution. The last rupture is assumed to have propagated in the east of the section studied and along segments F to H. The penultimate event propagated along the remaining segments and further west. The previous events (brown and orange) replicate these slip distributions. (d) Scenario 3 of horizontal slip distribution. The last ruptures propagated partially along the MNAF and neighboring systems. The antepenultimate event (brown) was a full MNAF rupture with a partly unpreserved smaller slip on segment A. Alternative scenario 3b assumes overlapping traces for the last ruptures on segment D.

The combination of the coseismic slip variation along strike, the epistemic uncertainty affecting offset measurements and the evolution of markers' morphology since the last event can limit the interpretation of COPD peaks as individual earthquakes (Lin et al., 2020; Reitman et al., 2019). Given that the last large earthquake along the MNAF happened before the 20th century and was not accurately documented at the time, we ignore the typical range of variation for the coseismic slip. The surface slip during 1999 Düzce and Izmit earthquakes on the NNAF show coefficients of variation (CoV) of 0.5-0.6 (Akyüz et al., 2002; Barka et al., 2002). Such values of CoV hardly enable to confidently recover more than one or two events or sequence of events from the COPD curve and estimate the associated slip values Therefore, higher COPD peak values and increments, which come with higher uncertainty, should be considered with caution. A couple of slip increments on segments B and E exceed 6.5 m (Table 4) and seem less realistic given the magnitudes typically observed for recent earthquakes and estimated for historical earthquakes in the Marmara region. Thus, we interpret those as being cumulative contributions of two or more smaller, distinct events.

The slip history per segment resulting from our offset analysis does not unambiguously unravel the past earthquakes succession along the MNAF. Alternative scenarios, with different numbers of earthquakes, locations, lengths of ruptures, can be proposed that account equally for these observations. Given the resolution of our satellite images and the uncertainties in our offset measurements, our analysis can hardly detect individual offsets below 2.5 m and thus slip events of Mw < 7. We cannot rule out that some smaller slip events were not resolved by our analysis, which would add some local variability of the slip distribution in the possible scenarios. The amount of slip involved in these events would logically be smaller as well, and so the uncertainties associated with them would not fundamentally change the proposed scenarios.

To assess the possible scenarios, we require independent constraints about the location, age and characteristics of past earthquakes along the MNAF. Fortunately, the seismicity of the MNAF region of the last two millennia is documented by significant written accounts (see e.g. Ambraseys, 2009), archeological evidence (Benjelloun et al., 2018, 2020) and a few paleoseismological investigations (see section 3). According to the slip rate estimates (sections 3 and 7.1), this time frame should correspond to a cumulative horizontal slip ranging between 6 and 10 meters. This includes between one and three COPD peaks, depending on segments.

7.3 Independent constraints on historical earthquakes along the MNAF

7.3.1 Historical seismicity

At least five destructive ruptures are documented in the historical seismicity catalogues for the eastern part of the MNAF (Ambraseys, 2002, 2009; Ambraseys and Finkel, 1991, 1995; Ambraseys and Jackson, 1998; Guidoboni et al., 1994; Fig. 2; Table S1). These events come with high uncertainties on their location and magnitude, and it is generally difficult to locate the ruptured fault from historical data only. Most of the information available relates to the cities of Iznik and Gemlik. Excluding the earthquakes documented on the NNAF, Iznik was destroyed by local earthquakes around 29-32 CE (M_s 7), in 121 CE (M_s 7.4), in 368 CE (M_s 6.8), and 1065 CE (M_s 6.8). The region of Gemlik was affected by the M_s~7.2 1419 CE earthquake, which may have originated from the SNAF system as no effect was reported in Iznik. A series of minor ruptures, with estimated magnitudes about 5, are known between 1855 and 1863, also felt in Gemlik and along the southern shore of Iznik Lake.

7.3.2 Archeoseismology

Through an archeoseismological study in Iznik, Benjelloun et al. (2020) evidenced three episodes of seismic damage in the city since the Roman period: (1) between the early 6th and late 8th century CE, (2) between the mid-9th and late 11th century CE, and (3) after the late 14th century CE. These episodes were associated with a minimal intensity of VIII (EMS-98) in Iznik, suggesting earthquakes of at least Mw 6. The modeling of a standing Roman obelisk north of the city ruled out the occurrence of Mw > 7.2 ruptures along the fault section south of Iznik since the 1st century AD.

7.3.3 Paleoseismology

Paleoseismological trenching works have documented mid-19th century events on segments A and C. On segment A, a penultimate event was identified between the 12th and 18th centuries CE, but was not seen in trenches located south of Iznik Lake. A possibly contemporaneous event was also documented between the 14th and 18th centuries in a trench west of Mekece. On segment C, one penultimate event was documented after the late 7th century CE, and two older events were identified before the mid-5th century CE in two trenches (see section 3, Fig. 2c). South of Iznik Lake, Erginal et al. (2021) reported a 50 cm high coseismic scarplet in beachrock deposits that they attributed to an 8th century rupture.

Other important constraints can be derived from the lake core recently studied by Gastineau et al. (2021). These sedimentary archives recorded the occurrence of several major earthquakes documented both on the NNAF and MNAF, among which the 29-32 CE, 121 CE, 1065 CE, and an 8th century CE event. The 1065 CE earthquake ruptured a sublacustrine fault trace identified within Iznik Lake, north of the onshore segment D. No event was recorded in these cores in the eight centuries following the 1065 CE earthquake, which strongly supports the absence of Mw > 6.5 events on the central segments of the MNAF after 1065 CE. However, the lack of earthquake recording after 1065 may be due to too low sedimentation rates in the lake in the last millennium, even for large events located farther than 20-30 km from the lake.

7.3.4 Synthesis

The events documented by at least two types of record, include the 29-32 (M_s 7), 121 (M_s 7.4), 1065 (M_s 6.8) and 1419 (M_s 7.2) CE historical earthquakes. The precise location of the 1419 CE earthquake is not well constrained, but the fact that it was not recorded in the Iznik Lake cores nor in trenches south of Iznik Lake, and that destructions were only reported in the region of Bursa, suggest that it did not extend east of Sölöz. To these we can add an 8th century event which affected the central MNAF segments south of Iznik Lake, and a 14th-18th century event attested by some damaged buildings in Iznik and one trench on segment E.

7.4 Analysis of COPD peak 1

In a first assumption (Fig. 14b, scenario 1a), COPD peak 1 can be interpreted as a large Mw 7.2-7.4 event rupturing the whole length of the studied fault. This first interpretation involves significant slip variations along strike, with slip values on the central segments C, D and E ~33% lower than on the other segments. The hypothesis of differential preservation across segments suggests another scenario (Fig. 14b, scenario 1b), with a more homogeneous slip of ~4 m along the studied section, only recovered on the central segments. Instead of decreasing slip on the central segments as in the scenario 1a, this scenario involves a maximum slip in the central area, which decrease towards both rupture tips. Given the higher structural complexity of this area, lower horizontal slip values are expected along the central segments. Therefore, scenario 1a can be considered more likely than scenario 1b. The favored historical candidate is the 1065 CE earthquake, which is the best documented event. However, this means that the magnitude of the 1065 CE earthquake, estimated at 6.8 by historical seismology studies, should be significantly raised, by at least 0.3 units. It also implies that the 1065 CE rupture identified in Iznik lake propagated along the onshore fault segments as well. In addition, the deformation of the obelisk north of Iznik does not support magnitudes over Mw 7.2 for events located south of Iznik, but might be accounted for with a more distant epicenter, located on the western or eastern segments

(Benjelloun et al., 2020).

Another possibility is to propose earthquakes rupturing only a part of the studied MNAF section, with the central segments acting as a slip barrier (Fig. 14c, d). Following this hypothesis, COPD peak 1 would correspond to two different earthquakes. These earthquakes ruptured different sections of the fault, either adjacent (scenarios 2 and 3a) or overlapping (scenario 3b). The lower slip values on the central segments are associated with the termination of earthquakes. In this case, no significant slip variation appears along strike. The high slip values imply that the ruptured area during these earthquakes could be respectively extended west of Gemlik and east of the junction with the main NAF strand. This interpretation best accounts for the multiple events found in the different records of past seismicity. The 1065 CE earthquake is a favored candidate for the western and central segments. The historical seismicity of the east of the studied area is less documented, but the 14th-18th c. event found in the archeological and paleoseismic record is a possible candidate for the eastern rupture of this scenario.

7.5 Analysis of COPD peak 2 and implications for the long-term behavior of the MNAF

The increments between COPD peaks 1 and 2 suggest that the slip values of the last and penultimate events (or sequences of events) were comparable. Although the slip values estimated for the penultimate event come with higher uncertainties, they also suggest magnitudes as high as Mw 7.4±0.2. The lacustrine record documents at least two events in the first centuries CE (Gastineau et al., 2021). The historical catalogues include two candidates, in 29-32 CE and in 121 CE, with poorly constrained locations along the MNAF. Both events can be accounted for by interpreting peak 2 as two distinct ruptures (scenario 2, Fig. 14c). Given the uncertainties, a full MNAF rupture may also be proposed (scenarios 1 and 3, Fig. 14b and d).

The reconstructions of along-fault slip accumulation derived from systematic offset measurements have been associated to the development of earthquake recurrence models (Schwartz & Coppersmith, 1984; Zielke et al., 2015). In our case, given the large uncertainties, the successive increments on each segment cannot be unambiguously discriminated. Our dataset remains compatible with a “characteristic slip” behavior, as in scenarios 1 and 2 (Fig. 14b, c), where the earthquakes show recurring, similar slip distributions (see e. g. Klinger et al., 2011; Kurtz et al., 2018; Zielke et al., 2010). In scenarios 1a and 2, the horizontal cumulative slip on segments C, D and E is 25-35% lower than on the other segments for the last two events. This cumulative slip deficit on the central segments produces a higher apparent slip rate variation along-strike. The interpretations of scenario 3 depart from the characteristic slip model, as the proposed distributions of the last events differ from the previous one, which resembles a variable slip model.

The Late Quaternary slip accumulation along the MNAF seems dominated by large events with comparable per-segment slip increments. This corresponds to the synoptic model of Zielke et al. (2015), which also considers the occurrence of smaller ruptures contributing marginally to the overall slip accumulation. The 8th century CE event reported south of Iznik Lake (Erginal et al., 2021), and the 19th century CE earthquakes reported in Gemlik (Özalp et al., 2013) may illustrate these features. Future trenching work is needed to document the timing of earthquakes and to judge between both models.

7.6 Possible interactions between the NAF strands for the historical period

In all the scenarios discussed, we can propose that the eastern MNAF has experienced two major sequences of ruptures in the last two millennia. These historical sequences correspond to large magnitude events, with amounts of slip ranging between 3.2 and 6.2 m. Most of the deformation was produced during intervals of high seismic activity, separated by longer quiescent periods (1000-1500 years). This can be compared to the rupture history of other strike-slip fault systems such as the San Andreas and Dead Sea faults (Lefevre et al., 2018; Rockwell et al., 2014). This long recurrence time contrasts with the historical behavior of the NNAF (Fig. 2), and is consistent with a slip rate ~5 times smaller on the MNAF. In the final part of this discussion, we replace our propositions of past rupture history in the wider frame of the eastern Marmara region.

The last sequence of high seismicity along the MNAF, whatever the scenario considered, seems to occur between the 11th and 18th centuries, while the northern strand of the NAF along the Izmit Gulf (between 29.2° and 30.3°E) knew a period of lower seismic activity (Fig. 2b). The 1065 CE earthquake was preceded by a major event on the NNAF in 1063 CE. However, it mainly affected the western part of the Marmara region, with no significant damage reported east of Constantinople (Ambraseys, 2009). Between the 14th and 18th centuries, only one major earthquake is known for the eastern Marmara region in 1509 CE (M~7.2). The Gulf of Izmit was likely affected by this earthquake (Klinger et al., 2003), but the contemporary historical records do not account for heavy damage farther east (Ambraseys, 2001b). After this earthquake, a quiescence period is reported for the Marmara region between 1509 and 1719 CE (Ambraseys & Jacskon, 2000; Pondard et al., 2007; Rockwell et al., 2009).

By contrast, the southern strands of the NAF were marked by a significant seismic activity in the east of the Marmara Sea. After the 1065 CE earthquake on the MNAF, this activity seems to restart in the early 15th century CE. It includes the 1419 CE earthquake which affected the Bursa region, and the event proposed between the 14th and 18th centuries CE along the eastern segments of the MNAF (scenarios 2 and 3). This earthquake may have propagated across the junction with the main NAF strand. The junction zone does not present any significant step-over, but only an azimuth change of ~20°. The 1967 CE earthquake propagated across this junction between the main NAF and the NNAF, with a similar azimuth difference. Therefore, a symmetrical rupture between the main NAF and the MNAF is not unrealistic. A trenching study carried out by Palyvos et al. (2007) in the Mudurnu valley, located a few kilometers east of the junction with the main NAF strand, identified at least two events younger than 1394 CE. The authors have suggested that some of these ruptures may have propagated across of the junction along the MNAF. Analogous alternations of active and quiescent phases between adjacent fault strands have been previously identified on the San Andreas fault system in relation to the San Jacinto fault (Lozos, 2016; Onderdonk et al., 2018). In the case of the NAF in the Marmara region, the investigation of older sedimentary records of past earthquakes on the different strands might help to better document this behavior and check for earlier occurrences of it.

8 Conclusion

By combining field observations and the analysis of high-resolution satellite images, we have demonstrated that the segments constituting the MNAF in the southeast of the Marmara region have been significantly active during the Holocene. The fault displays morphological features typical of strike-slip deformation, associated locally with a smaller vertical component. We collected 114 measurements of horizontally offset markers, providing evidence for large, repeated earthquakes along the MNAF. Through a statistical analysis of the offsets, we particularly documented at least two major surface-rupturing earthquakes whose deformation was preserved in the landscape. They are characterized by coseismic horizontal displacement ranging from 3.2 to 6.2 m, which indicates moment magnitudes ranging between 7.2±0.2 and 7.4±0.2 according to empirical scaling laws. Some of these events may have ruptured the whole eastern MNAF section along more than 100 km. Although smaller earthquakes also happened in the past, our analysis may not resolve accurately their frequency due to the data uncertainties and preservation issues. According to the historical catalogues of seismicity and paleoseismological studies, the last large events documented along this fault strand possibly happened in 1065 CE, or between the 14th and 18th centuries CE along the eastern segments. These intervals correspond to a period of relative quiescence along the NNAF segments located east of the Marmara Sea. We estimated a late Holocene horizontal slip rate of ~4.3 mm/yr on the central MNAF segments, in agreement with previous estimates. Since the last large events, the eastern MNAF segments may have therefore accumulated stress equivalent to 1-4 m of horizontal deformation. Therefore, the current level of stress may be enough to generate a significant earthquake, comparable or larger than a 1065 CE type rupture, which caused important damage in Iznik. The activity of the secondary strands of the NAF should not be neglected in terms of slip history and should be considered into any seismic hazard assessment.

Data Availability Statement

The bathymetric map of Marmara was made available by the EMODnet Bathymetry project (https://www.emodnet.eu/bathymetry), using the EMODnet Bathymetry portal (EMODnet Bathymetry Consortium, 2016, EMODnet Digital Bathymetry [DTM], DOI: 10.12770/c7b53704-999d-4721-b1a3-04ec60c87238) funded by the European Commission Directorate General for Maritime Affairs and Fisheries. The large-scale topography of the study area was obtained from the Shuttle Radar Topography Mission 1 Arc-Second Global (DOI:10.5066/F7PR7TFT). The bathymetry of İznik Lake was provided by and can be obtained from the Turkish General Directorate of Hydraulic Works (DSI). Pleiades imagery is available for purchase from Airbus industry (https://www.intelligence-airbusds.com/en/8692- pleiades). The full offset retro-deformation dataset and a vector file of the fault map are available on the Zenodo repository (Benjelloun et al., 2021) [open access]. The maps of Figures 5 are from Google Earth satellite imagery. The diagrams of Figures 6, 7, 8 and 14 were prepared using the Matplotlib 3.3.0 package for Python (https://matplotlib.org/; Hunter, 2007). All websites were last accessed in January 2021. Supporting Information for this article includes a detailed explanation of the marker quality score determination, a list of historical earthquakes in the area of interest, a summary of paleoseismic trenching works done in the area, the offset measurement data, and supplementary figures on the vertical slip markers south of Iznik Lake, some field examples of Quaternary faulting, and the automatic fault discretization procedure.

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Figure 1.

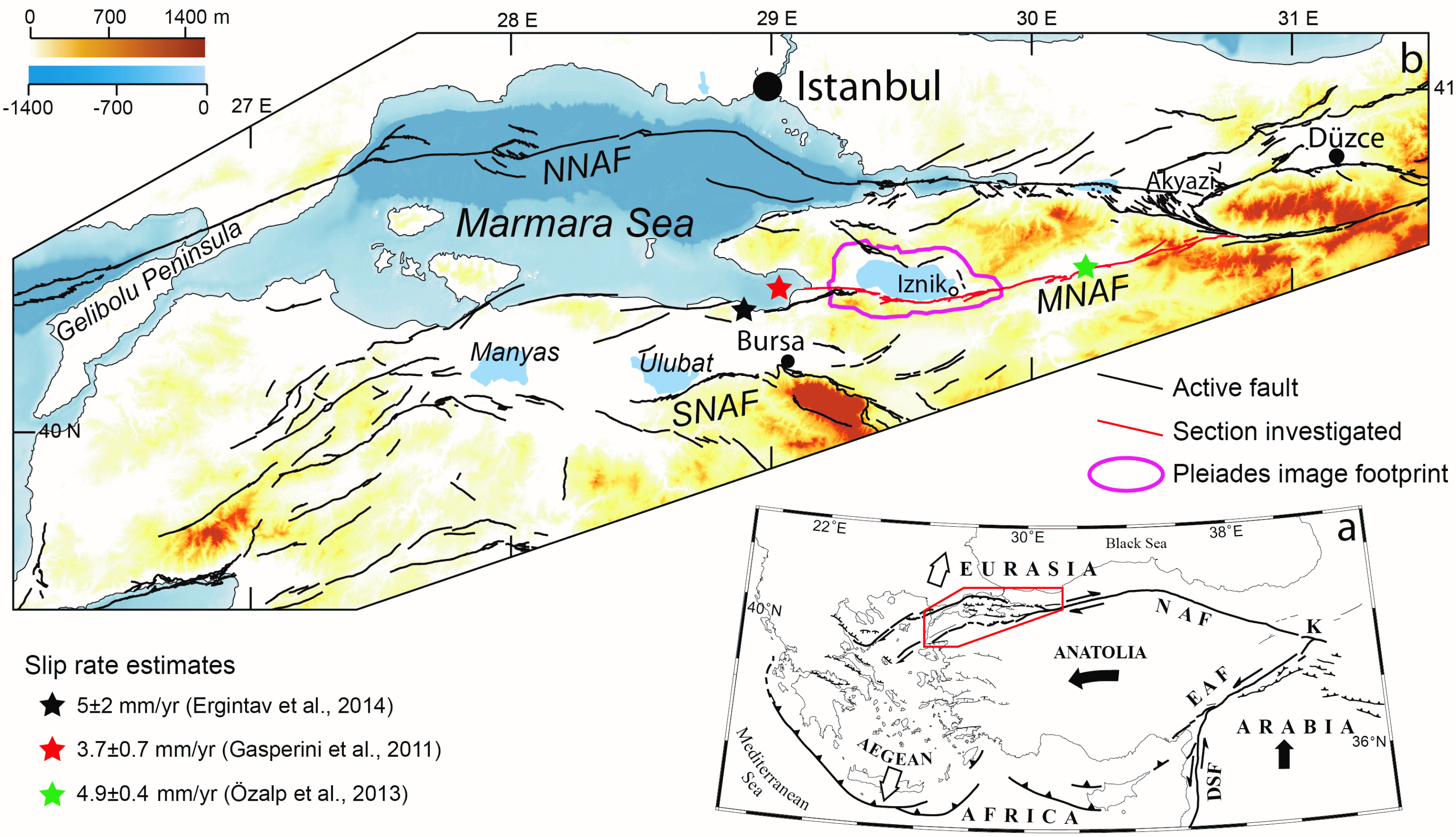

0
700
1400 m
-1400
-700
0
28 E
29 E
30 E
31 E
27 E
41 N
40 N
b
Istanbul
NNAF
Marmara Sea
Gelibolu Peninsula
Düzce
Akyazi
Iznik
MNAF
Bursa
Manyas
Ulubat
SNAF
Active fault
Section investigated
Pleiades image footprint
a
22°E
30°E
38°E
Black Sea
40°N
36°N
EURASIA
NAF
K
ANATOLIA
EAF
ARABIA
AEGEAN
Mediterranean Sea
AFRICA
DSF
Slip rate estimates
5±2 mm/yr (Ergintav et al., 2014)
3.7±0.7 mm/yr (Gasperini et al., 2011)
4.9±0.4 mm/yr (Özalp et al., 2013)

Figure 2.

29°E
30°E
40°40'N
40°20'N
Topography
2500
300
150
0 m
NNAF
Izmit Gulf
IZMIT
AKYAZI
IZNIK
Iznik Lake
GEMLIK
MEKECE
GPB
MNAF
BURSA
SNAF
a
Year CE
1894
1719
478
358
181
b NNAF
1065
368
121
29-32
c MNAF
1419
d SNAF
km

Figure 3.

29°E
30°E
N
Samanli Mts
Geyve-Pamukova Basin
Geyve
Karadere
Olukdere
Sakarya river
MNAF
Karatekin
Mekece
Iznik
Gölyatagi
Kocadere
Kirandere
Gemlik
Sölöz
Katirli Mts
0
20
40 km
a
40°35'N
40°25'N
N
A
B
C
D
E
F
G
H
Iznik Lake
Mekece stepover
Sölöz bend
b

Figure 4.

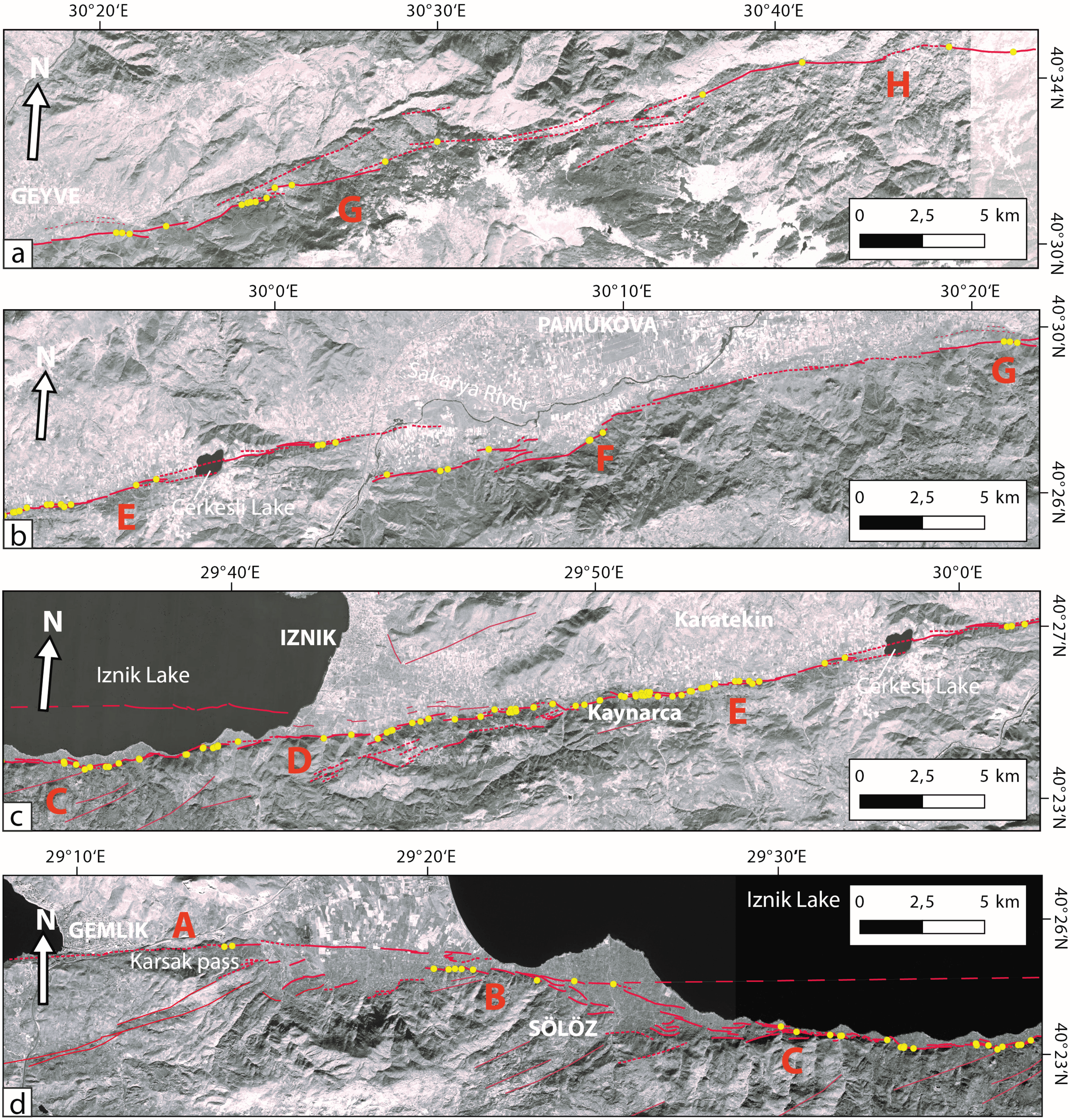

30°20'E
30°30'E
30°40'E
40°34'N
40°30'N
N
GEYVE
G
H
0 2,5 5 km
a
30°0'E
30°10'E
30°20'E
40°30'N
40°26'N
PAMUKOVA
Sakarya River
N
Çerkesli Lake
E
F
G
0 2,5 5 km
b
29°40'E
29°50'E
30°0'E
40°27'N
40°23'N
N
IZNIK
Iznik Lake
Karatekin
Kaynarca
Çerkesli Lake
C
D
E
0 2,5 5 km
c
29°10'E
29°20'E
29°30'E
40°26'N
40°23'N
Iznik Lake
N
GEMLIK
A
Karsak pass
B
SÖLÖZ
C
0 2,5 5 km
d

Figure 5.

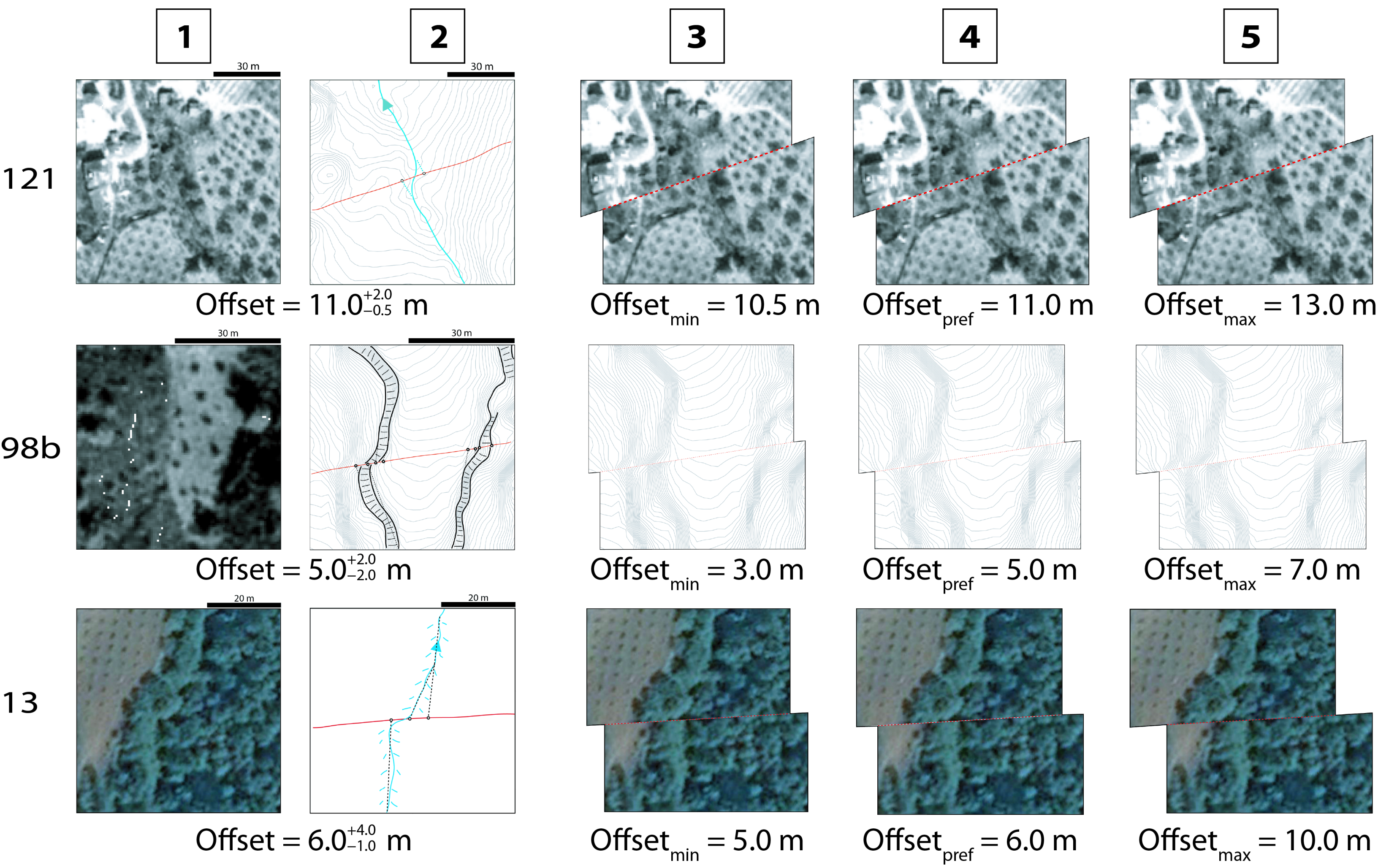
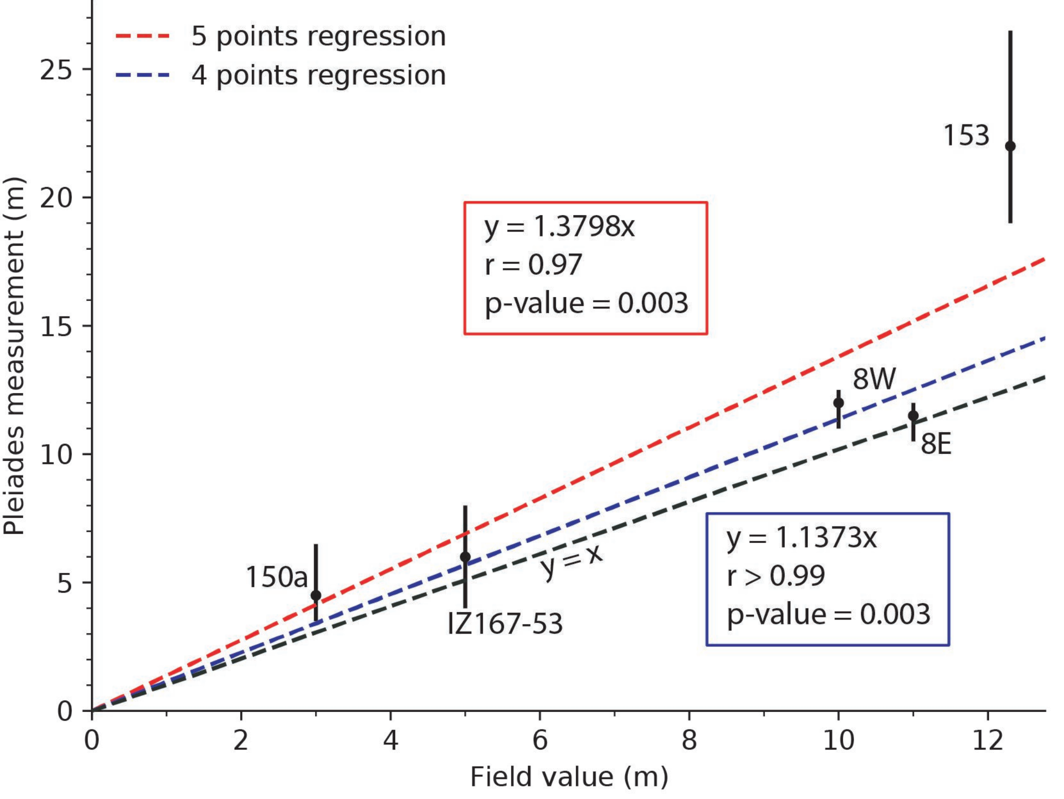

1
2
3
4
5
121
30 m
30 m
Offset = 11.0$^{+2.0}_{-0.5}$ m
Offset$_{min}$ = 10.5 m
Offset$_{pref}$ = 11.0 m
Offset$_{max}$ = 13.0 m
98b
30 m
30 m
Offset = 5.0$^{+2.0}_{-2.0}$ m
Offset$_{min}$ = 3.0 m
Offset$_{pref}$ = 5.0 m
Offset$_{max}$ = 7.0 m
13
20 m
20 m
Offset = 6.0$^{+4.0}_{-1.0}$ m
Offset$_{min}$ = 5.0 m
Offset$_{pref}$ = 6.0 m
Offset$_{max}$ = 10.0 m

Figure 6.

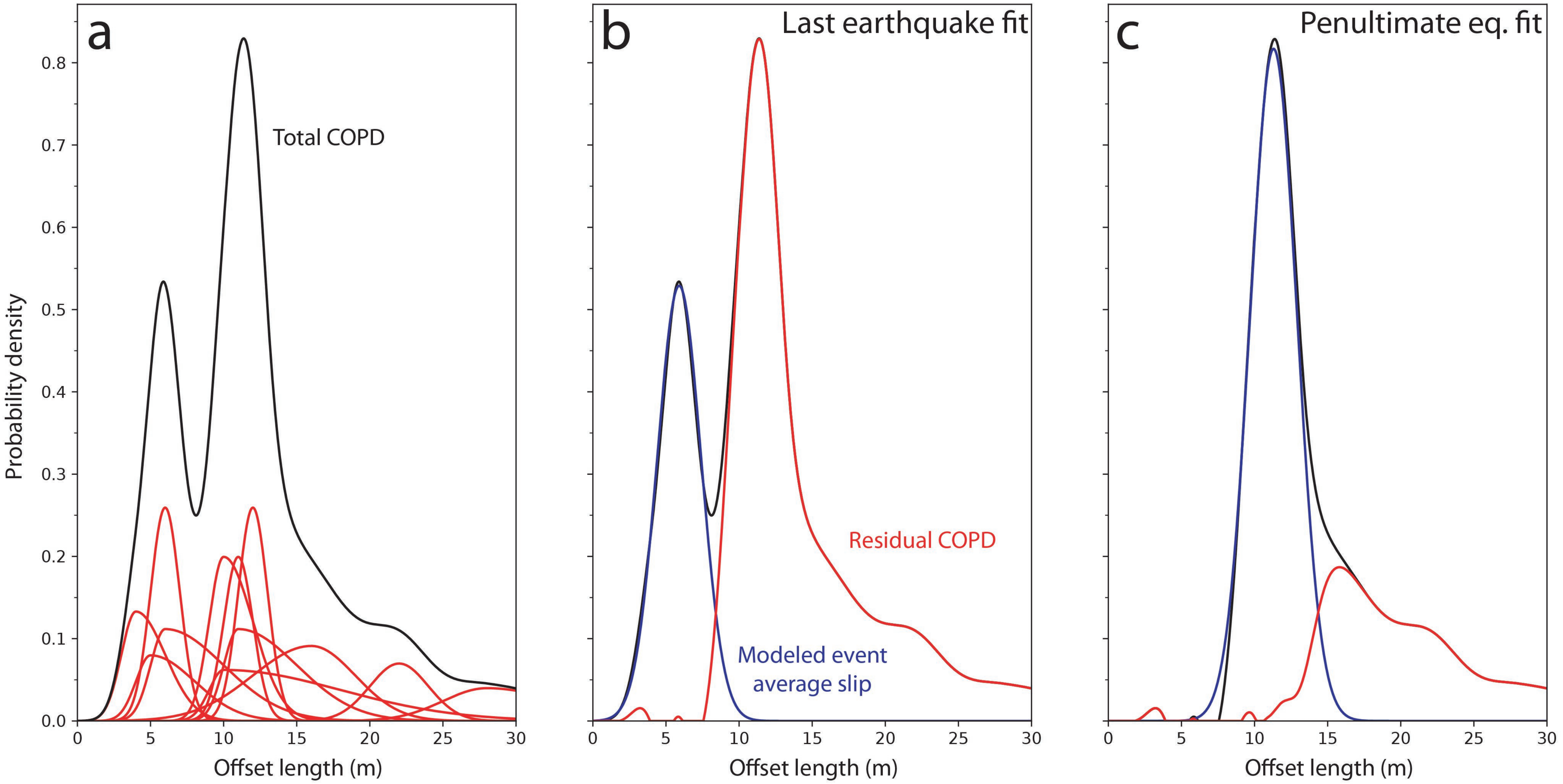


5 points regression
4 points regression
y = 1.3798x
r = 0.97
p-value = 0.003
y = 1.1373x
r > 0.99
p-value = 0.003
y = x
153
8W
8E
150a
IZ167-53
Pleiades measurement (m)
Field value (m)
0
5
10
15
20
25
0
2
4
6
8
10
12

Figure 7.

20 km
N
a
Iznik Lake
A
B
C
D
E
F
G
H
b
Offset length (m)
UTM Longitude (m)
c
Offset length (m)
3
3
3
2
4
3
3
2
2
4
8
6
7
14
3
3
5
4
Cumulative offset probability density (different scales between segments)

Figure 8.



a
Total COPD
b
Last earthquake fit
Residual COPD
Modeled event
average slip
c
Penultimate eq. fit
Probability density
Offset length (m)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
5
10
15
20
25
30

Figure 9.

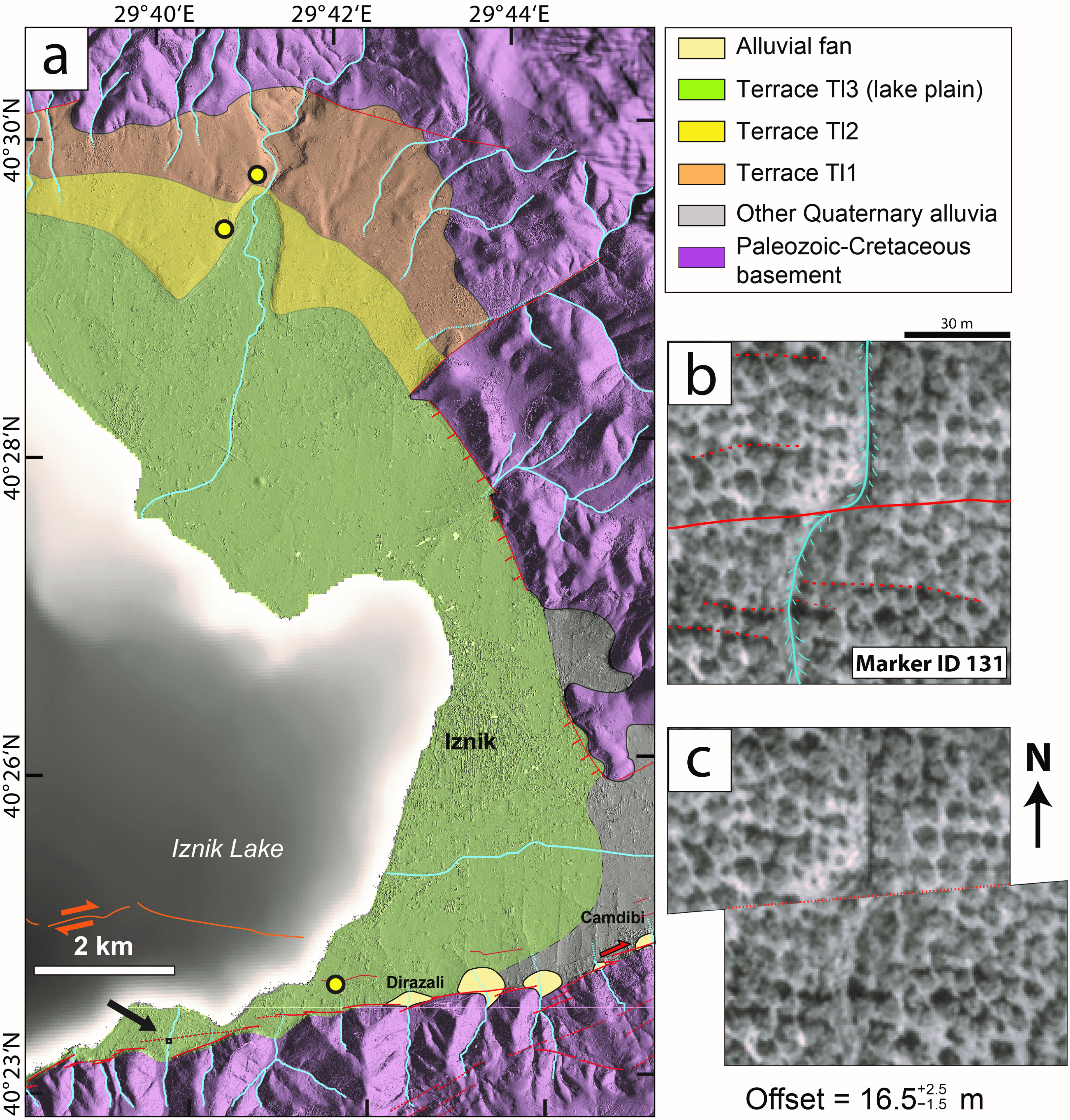
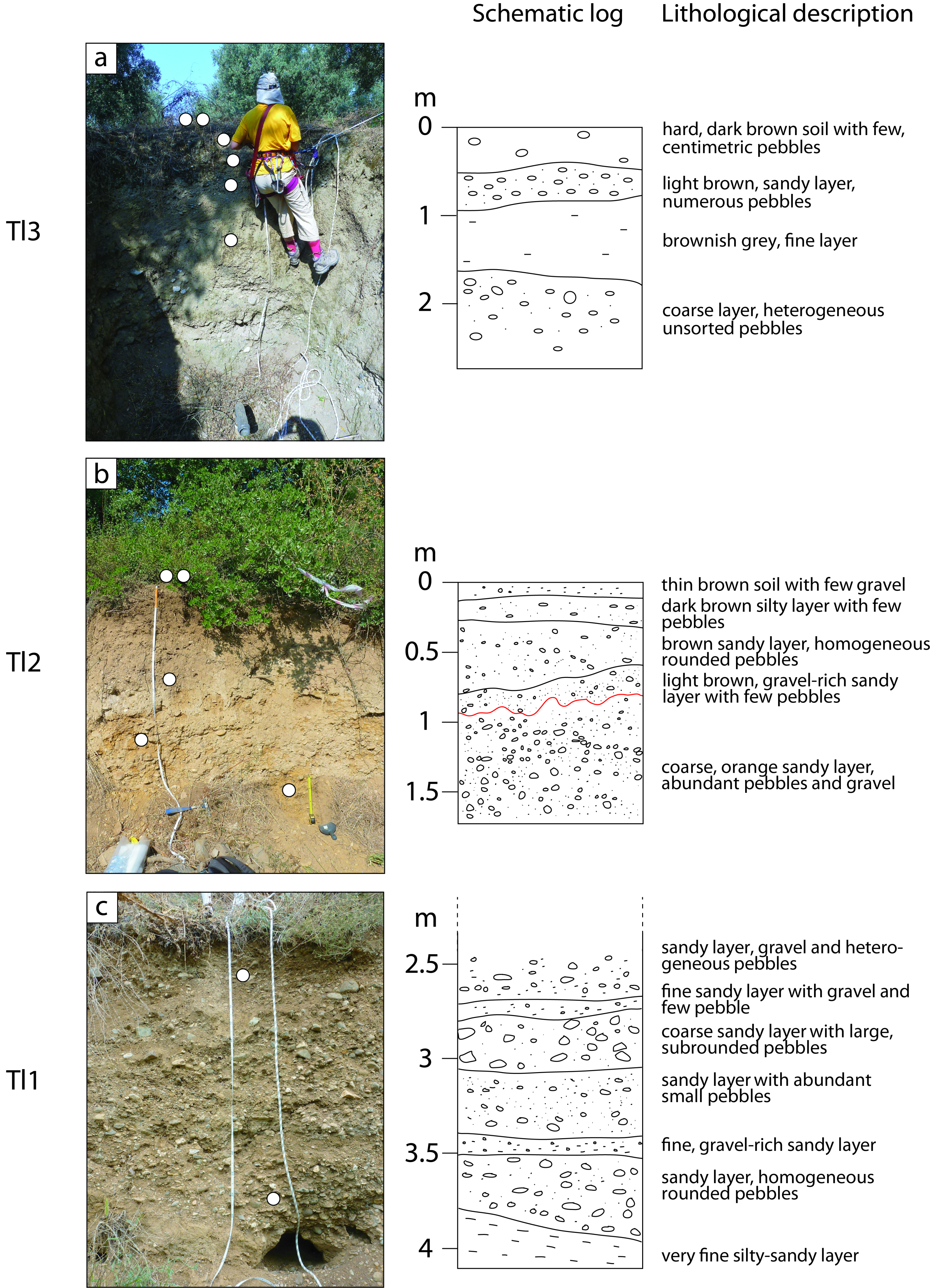
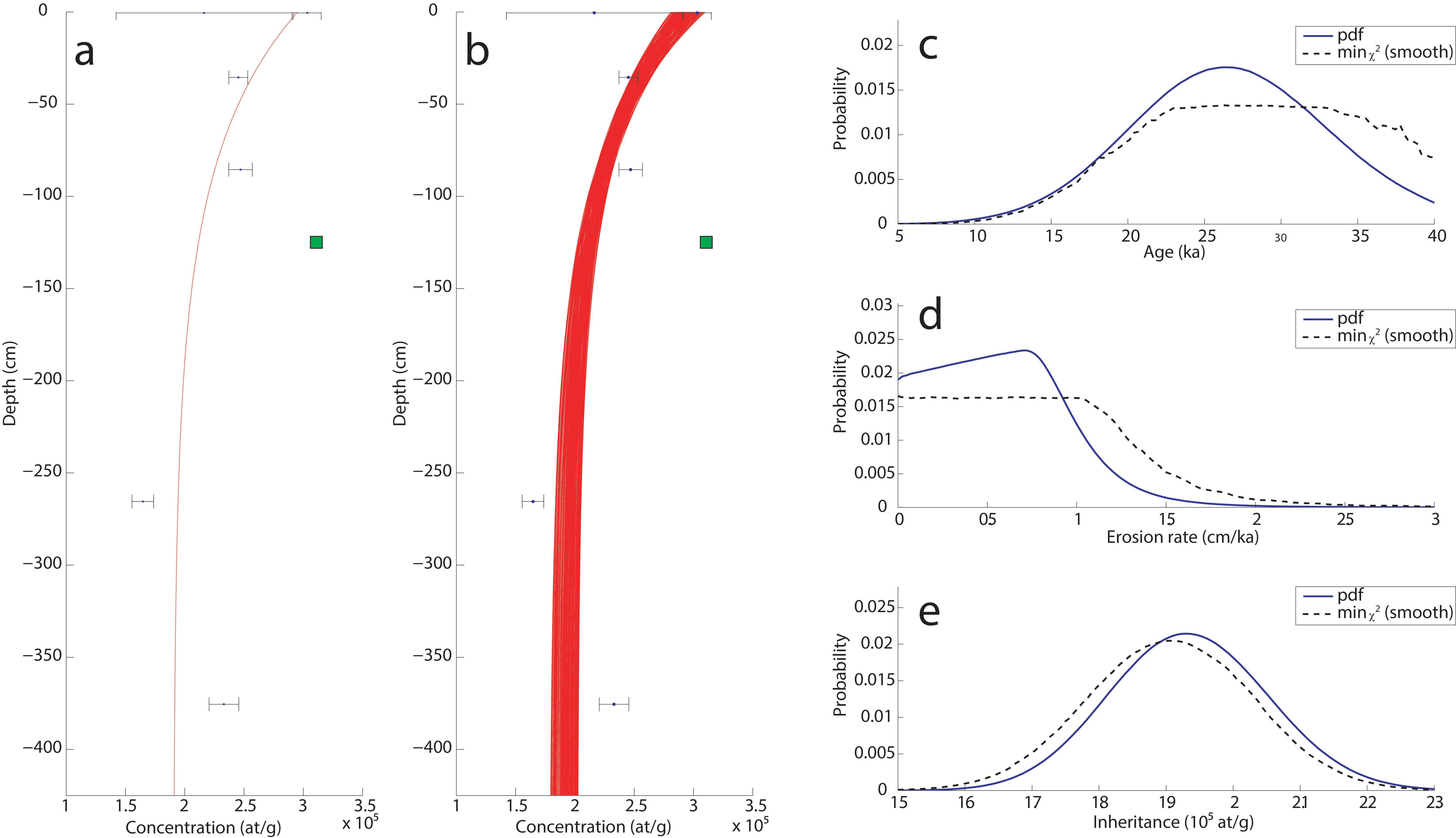

a
29°40'E
29°42'E
29°44'E
40°30'N
40°28'N
40°26'N
40°23'N
Iznik
Iznik Lake
2 km
Camdibi
Dirazali
Alluvial fan
Terrace Tl3 (lake plain)
Terrace Tl2
Terrace Tl1
Other Quaternary alluvia
Paleozoic-Cretaceous basement
30 m
b
Marker ID 131
c
N
Offset = $16.5^{+2.5}_{-1.5}$ m

Figure 10.



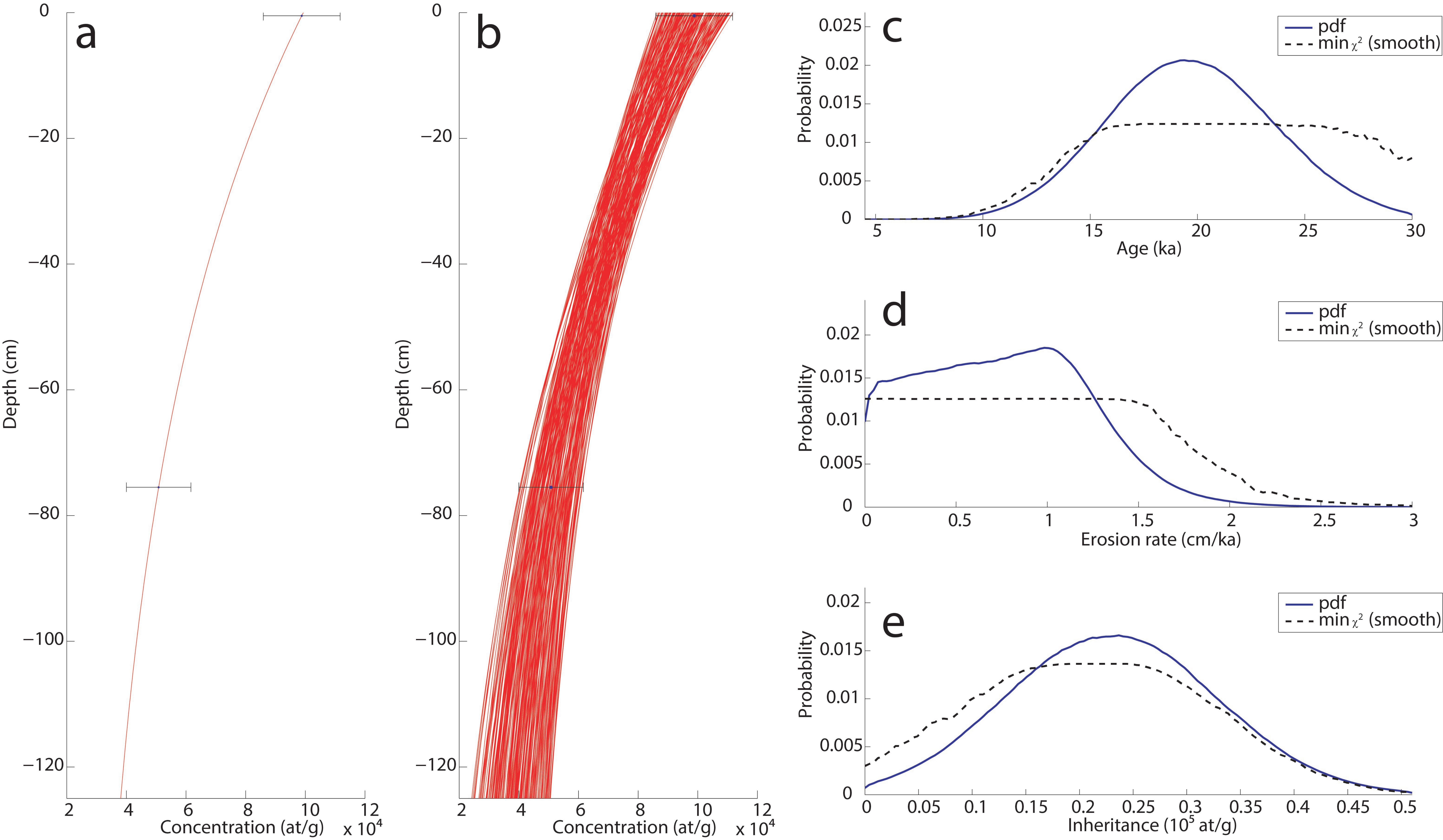
Schematic log
Lithological description
a
Tl3
m
0
1
2
hard, dark brown soil with few, centimetric pebbles
light brown, sandy layer, numerous pebbles
brownish grey, fine layer
coarse layer, heterogeneous unsorted pebbles
b
Tl2
m
0
0.5
1
1.5
thin brown soil with few gravel
dark brown silty layer with few pebbles
brown sandy layer, homogeneous rounded pebbles
light brown, gravel-rich sandy layer with few pebbles
coarse, orange sandy layer, abundant pebbles and gravel
c
Tl1
m
2.5
3
3.5
4
sandy layer, gravel and hetero-geneous pebbles
fine sandy layer with gravel and few pebble
coarse sandy layer with large, subrounded pebbles
sandy layer with abundant small pebbles
fine, gravel-rich sandy layer
sandy layer, homogeneous rounded pebbles
very fine silty-sandy layer

Figure 11.



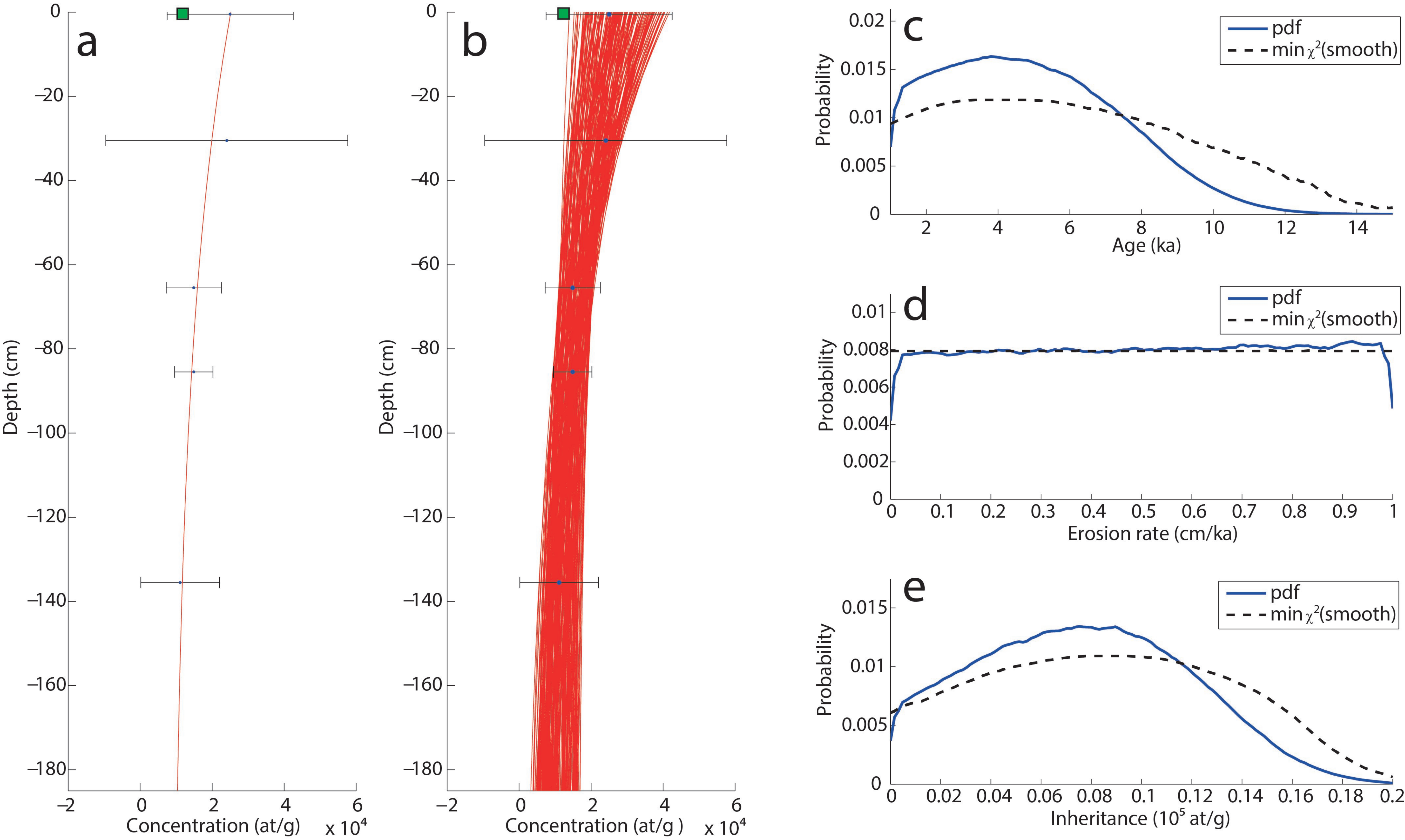
a
b
c
d
e
Depth (cm)
Concentration (at/g)
x 10^5
0
−50
−100
−150
−200
−250
−300
−350
−400
1
1.5
2
2.5
3
3.5
Probability
Age (ka)
Erosion rate (cm/ka)
Inheritance (10^5 at/g)
pdf
min χ^2 (smooth)

Figure 12.



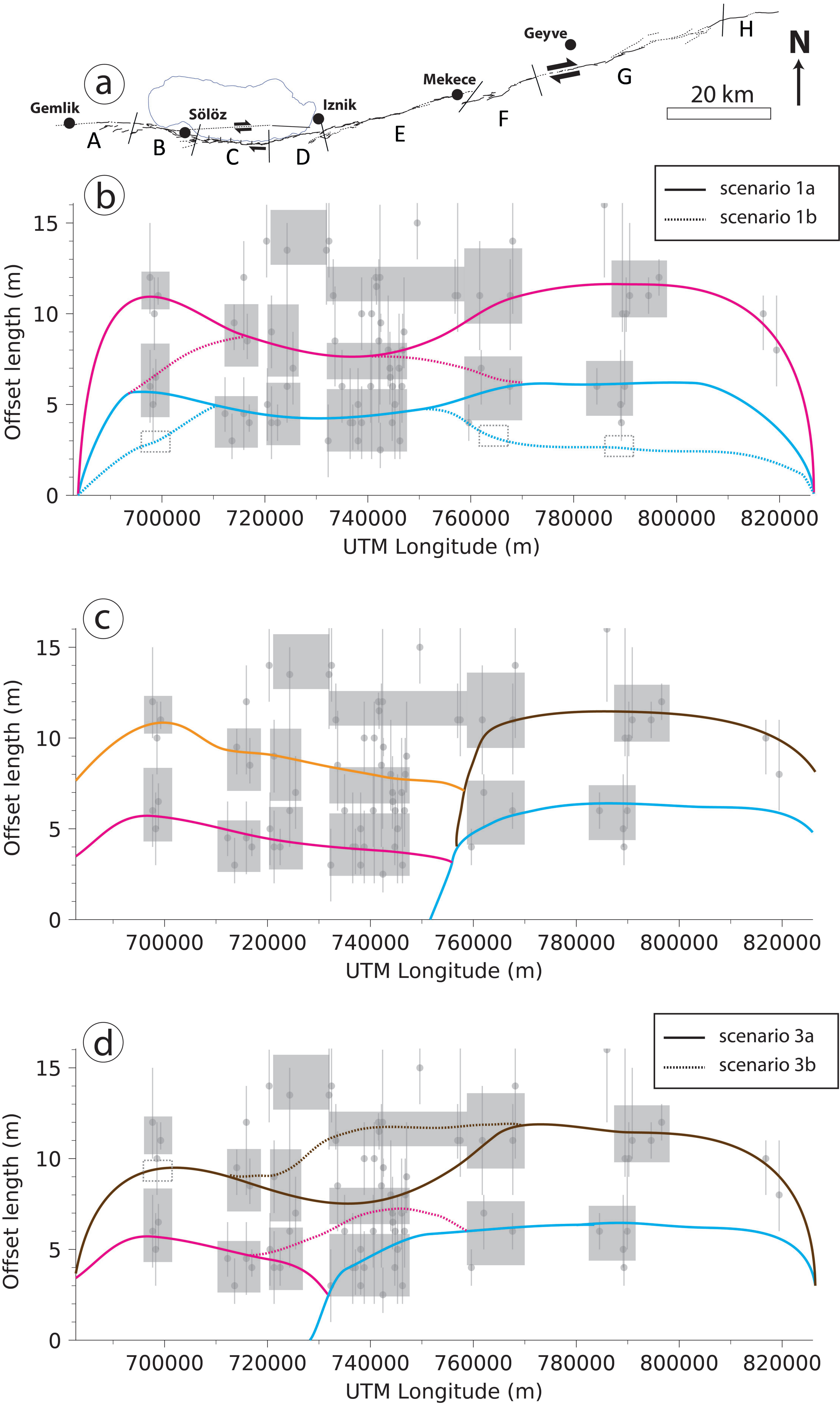
a
b
c
d
e
Depth (cm)
Concentration (at/g)
x 10^4
Probability
Age (ka)
Erosion rate (cm/ka)
Inheritance (10^5 at/g)
pdf
min χ² (smooth)

Figure 13.



a
b
c
d
e
Depth (cm)
Concentration (at/g)
x 10^4
Concentration (at/g)
Probability
Age (ka)
Erosion rate (cm/ka)
Inheritance (10^5 at/g)
pdf
min χ²(smooth)

Figure 14.



a
Gemlik
Sölöz
Iznik
Mekece
Geyve
A
B
C
D
E
F
G
H
20 km
N
b
scenario 1a
scenario 1b
c
d
scenario 3a
scenario 3b
Offset length (m)
UTM Longitude (m)
0
5
10
15
700000
720000
740000
760000
780000
800000
820000