The Bekten Fault: the palaeoseismic behaviour and kinematic characteristics of an intervening segment of the North Anatolian Fault Zone, Southern Marmara Region, Turkey

Selim Özalp*, Akın Kürçer, Ersin Özdemir and Tamer Y. Duman
Department of Geological Research, General Directorate of Mineral Research and Exploration (MTA), Ankara TR-06800, Turkey

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The Bekten Fault is 20-km long N55°E trending and oblique-slip fault in the dextral strike-slip fault zone. The fault is extending sub-parallel between Yenice-Gönen and Sanköy faults, which forms the southern branch of North Anatolian Fault Zone in Southern Marmara Region. Tectonomorphological structures indicative of the recent fault displacements such as elongated ridges and offset creeks observed along the fault. In this study, we investigated palaeoseismic activities of the Bekten Fault by trenching surveys, which were carried out over a topographic saddle. The trench exposed the fault and the trench stratigraphy revealed repeated earthquake surface rupture events which resulted in displacements of late Pleistocene and Holocene deposits. According to radiocarbon ages obtained from samples taken from the event horizons in the stratigraphy, it was determined that at least three earthquakes resulting in surface rupture generated from the Bekten Fault within last ~1300 years. Based on the palaeoseismological data, the Bekten Fault displays non-characteristic earthquake behaviour and has not produced any earthquake associated with surface rupture for about the last 400 years. Additionally, the data will provide information for the role of small fault segments play except for the major structures in strike-slip fault systems.

**Keywords:** NW Anatolia; Southern Marmara; Bekten Fault; palaeoseismology

1. Introduction

Turkey is situated on the Alpine-Himalayan Earthquake Belt which is one of the most significant seismically active belts of the world. The Anatolian tectonic block (sub-plate) is being affected by converging plate movements that occur between the Arabian-African and Eurasian plates (e.g. Armijo, Meyer, Hubert, & Barka, 1999; Bozkurt, 2001; Jackson & McKenzie, 1984; Le Pichon, Chomat-Rooke, Lallemant, Noomen, & Veis, 1995; McKenzie, 1972, 1978; Şengör, 1979, 1980; Şengör, Görür, & Saroglu, 1985; Taymaz, Jackson, & McKenzie, 1991). As a result of this collision, the North Anatolian (NAF) and East Anatolian (EAF) transform faults have been formed. The Anatolian sub-plate is bounded to the north and east by these faults. The impingement started to move the sub-plate westward and resulted compression and uplifts near the Karlova triple junction in the Eastern Anatolia. As a result of anti-clockwise rotational movement of the Anatolian sub-plate in a westward direction four different neotectonic regions have been formed namely: (1) East Anatolian compressional region, (2) North Anatolian region, (3) Central Anatolian ‘ova’ region and (4) West Anatolian extensional region (Şengör et al., 1985).

The Biga Peninsula is located in a transitional belt between the NAF Zone and the West Anatolian Extensional Tectonic Regime (e.g. Barka, 1992; Barka & Kadinsky-Cade, 1988; Dewey & Şengör, 1979; Emre, Dogan, & Yildirim, 2012; Emre et al., 2013; Saroglu, Emre, & Kusçu, 1992; Şengör et al., 2005, Figure 1(a)). Recent tectonic deformation in the central and northern Biga Peninsula is mainly controlled by western extensions of the NAF (Figure 1(b)). Tectonic structures observed in this region are generally right lateral strike-slip faults within a broad restraining bend (Emre et al., 2013). Almost all of the faults show dextral strike-slip fault character and compose bending systems extending south as a concave geometry. The faults comprising the eastern limb of this bend extends NW-SE as a transtensional jog structure, while the faults at the western limb have tranpressional character extending NE-SW (Emre, Dogan, & Özalp, 2011; Emre et al., 2012). The reverse component has been observed at the palaeoseismological trench studies on Yenice-Gönen, Evcler, Sinekçi and Gündoğan faults which comprise the western limb with the Bekten Fault in the region (Çan et al., 2014; Duman, Çan, Olgun, Yavuzoglu, & Sömmez, 2014; Kop, Olgun, Çan, & Duman, 2013; Kürçer, Özalp, Özdemir, Uyanik, & Duman, 2013). The NAF is divided into two branches as northern and southern in Marmara region. Recent global positioning system measurements show that the plate movements in Marmara Region were principally accommodated along the northern branch of the NAF and these data suggest a velocity of 24 ± 1 mm/year on this branch (e.g. McClusky, Reilinger, Mahmoud, Ben Sari, & Tealeb, 2003; Reilinger et al., 2006). The southern branch of the NAF zone is less active with respect to the

*Corresponding author. Email: selim.ozalp@mta.gov.tr

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northern branch. In the study area which is located in the western continuation of the southern branch, dextral and extensional slip rates are suggested as varying 0.9–6.8 mm/year and 0.8–5.5 mm/year, respectively (Aktug et al., 2009; Ergintav et al., 2014; Flerit, Armijo, King, & Meyer, 2004; Meade et al., 2002; Reilinger et al., 2006).

In this study, data related to the active tectonics, palaeoseismological features and kinematic characteristics of the Bekten Fault are presented. Though it located
in the YGF, SF and EF segments, and is a smaller structure than these faults, the Bekten Fault is considered important as it plays key role in the kinematic behaviour and rupture processes in the area. The Late Quaternary palaeoseismic history of Bekten Fault will contribute to our understanding of the seismic hazard of the region and elucidating the role which small fault segments play in neotectonics of the region except for the major structures in strike-slip fault systems.

2. The Bekten Fault

The Bekten Fault is a NE-SW trending oblique reverse fault with minor dextral strike-slip component and located in the Yenice-Gönen (YGF), Sarıköy (SF) and Evciler (EF) faults extending sub-parallel. The Bekten Fault, which was mapped as the Neotectonic period fault by several researchers (Gürer, Sangu, & Özburan, 2006; Saroglu et al., 1992; Siyako, Bürkan, & Okay, 1989), was first named by Emre et al. (2011) and mapped as an active fault in detail. Microseismicity, tectonomorphological structures and palaeoseismological data indicate recent activity on the Bekten Fault. The presence of fault scarps proves repeated large earthquakes occurred on the fault in the Holocene.

The Bekten fault, is one of the structures within the restraining bend in the dextral strike-slip fault zone appears in north of Yenice (Çanakkale). The fault is located between the YGF (67 km long), SF (66 km long) and EF (46 km long), extending sub-parallel to those faults. It is 20 km long, an oblique reverse fault with minor dextral strike-slip active fault and strikes N55°E (Figure 2). The mapped extent of the fault is 2 km from the YGF in southwest and 7 km from the SF at its north-eastern end. The Bekten Fault is divided into two sections, ‘western’ and ‘eastern’. These two sections are separated by a 1 km wide left stepover. The two sections overlap ~1.5 km near the Bekten (Figure 2). The western section is 16 km long and strikes N55°E. To the north of the left stepover, the fault trend deviates 5° towards north and continues 4 km striking N50°E south of Sofular.

The western fault section brings units of different ages into fault contact (Figure 3). The southern fault-bound block consists of Upper Palaeozoic metamorphic rocks of the Kalabak group. The northern fault-bound block is composed of Upper Permian (?)-Triassic metaclastic rocks of the Karakaya Complex (Duru, Pehlivan, Okay, Şentürk, & Kar, 2012). The strike of the fault changes to N60°E in southern parts of Davutköy and makes nearly 4 km bend to the south. The northern fault-bound block includes the basin in which Bekten plain developed and is filled by Plio-Quaternary terrestrial deposits. Holocene fault scarps are present where the fault crosses the Bekten plain. The southern fault-bound block contains lithologies of the Karakaya Complex (Figure 4(a)). The western section of the fault cuts the Karakaya Complex at the south of Bekten village and fault scarps are preserved there (Figure 4(b)–(d)), where is near the left stepover. The eastern fault section is observed within Upper Palaeozoic metamorphic units of the Kalabak group (Torasan formation) (Figures 3 and 4(d)). The fault continues 2 km within Oligo-Miocene granitoids.

3. Seismicity

The Biga Peninsula and the surrounding region experienced significant earthquake activity in the historical period (Table 1, Figure 5). Historical earthquake catalogues reveal that 21 destructive earthquakes occurred between AD 200 and 1900 in the study region (Ambraseys, 2002,
The earthquakes are generally concentrated in Çanakkale, Erdek, Biga and Bandırma regions. Until this study, none of them were associated with Bekten Fault. However, there are some instrumental events which can be generated by the Bekten Fault (Figure 6). One of them is the 22 March 1953 of Ms. 4.2. Its epicentre (40.00 N – 27.30 E, Kalafat et al., 2011) corresponds to the left stepover between the east and west fault sections and has a shallow focal depth of 26 km. During the instrumental period, the largest event occurred in the region is the 18 March 1953 Yenice-Gönen earthquake of Ms. 7.2 with depth, 10 km, which is also one of the most destructive ones in Turkey (Ambraseys, 1988; Belindir, 2008; Herece, 1990; Ketin & Roesli, 1953; Kürçer et al., 2008; Pinar, 1953). The epicentre of the earthquake (39.99 N – 27.36 E) is estimated as at 7 km SE of Bekten by Kalafat et al. (2011). Based on the time and location relation with the 1953 events, it may conclude that the YGF segment may induce and trigger a moderate earthquake on the Bekten Fault to the north.

4. Palaeoseismological studies

4.1. Bekten trench site

Bekten trench site, which was selected by aerial photograph analyses, tectonomorphological structures (Figure 4(a)–(c)) and geological observations (Figure 4(b)), is located at ~1 km SW of Bekten in an area where Quaternary deposits outcrop (Figures 2 and 4(c)). The fault in this area is quite morphologically distinctive with a 1-km long fault scarp and aligned topographical saddle structures.

The micro topography of the Bekten trench site was surveyed using a Total Station. The survey data were used to develop a site map with a 20 cm contour interval (Figure 7). Two trenches were excavated perpendicular to fault scarp and parallel to each other and vary between 2 and 4 m in depth. A 1-m horizontal and vertical grid was established on the trench walls and photographs of the gridded trench walls were taken. The photographs were used to develop trench wall photomosaics. Logging was completed on the photomosaics at a scale of 1:20. Earthquake event horizons were defined on logs using tectonostratigraphical relationships. Sampling for charcoal and organic material was carried out in order to develop a numerical age chronology of the trench stratigraphy. Nine samples were analysed by AMS-14C (radiocarbon) method at BETA Analytic laboratories in Miami (Florida, USA).

The trench excavation site corresponds to NE-SW trending, 100-m long, 75-m wide topographical saddle (Figures 4(c) and 7). In this area, Triassic metamorphic units of the Karakaya Complex are observed at higher elevations and stratigraphic positions than the north side of the fault, where fine clastic alluvial late Pleistocene and Holocene fan deposits outcrop. The trench exposed Triassic metamorphic rocks faulted over Pleistocene-Holocene alluvial fan deposits due to oblique displacements on the Bekten Fault. South of the excavation site the surface of the hanging-wall block is eroded and the
The face of fault scarp is northward facing. The trench was excavated below the top of the scarp in an area where scarp derived sediments (colluvium) has accumulated (Figure 4(c)).

4.2. Trenches

Trench-1 (T-1) was excavated perpendicular to the direction of Bekten Fault (N40°W). The 32 m long and 5 m wide T1 varies between 2 and 3.5 m in depth (Figures 4(c) and 7). We present the 10 m of the T1 exposure to summarise the deformation style and fault characteristics. All units and earthquake events are observed well on the east wall of T1, therefore, we present only the east wall data. Except for the Karakaya Complex near the trench bottom, 10 units which are alluvial fan and channel deposits and colluvial deposits are observed in the trench exposures (Figure 8). In general, meta-serpentine (unit1) which is observed only near the southern end of the western fault section, and meta-sandstone, meta-tuff and chlorite schist are the bedrock units in the trench.

There are observed many northward overlapping faults similar to the recent tectonic deformation style which is seen especially between 8th and 12th meters of the T1 in both units. However, these faults were assessed as old structures because there had been no data related to their ages. Between 6th and 8th meters of the T1, it is clearly seen that Triassic aged units belonging to the basement to the south were reverse faulted over Late Pleistocene-Holocene deposits to the north (Figures 8...
and 9). The oldest unit that can be observed north of the fault is unit 3 which is formed by maroon-red, fine gravel and coarse sand. Two charcoal samples taken from unit indicate the age of this unit is 29800 BC and 15960 BC. Unit 6 unconformably overlies unit 5. Radiocarbon analysis of a charcoal sample taken from upper portion of the unit 5 yielded an age of AD 640 and AD 680. Based on these data, there is ~16,300-year hiatus between units 5 and 6 (Table 2). Unit 7 which is a white-coloured colluvium unconformably overlies unit 6 north of the fault and unit 2 within the fault zone. This unit overlies unit 6 and the event horizon (event 3) which represents the oldest surface faulting that can be observed on trench walls. Analysis of the charcoal sample indicates the age of unit 7 is AD 890–1020. This unit is unconformably over lain by unit 8 which is composed of greenish grey, fine pebbly sand and has the characteristics of an alluvial channel deposit. The unit is observed on both sides of the fault and consists of material eroded from older units. Two charcoal samples taken from unit 10 yielded ages between AD 1660 and AD 1020. Three fault splays associated with the penultimate event (event 2) cut unit 10 south of the main fault trace. These three splays are truncated by unit 11 which unconformably overlies unit 10. Unit 11 consists of pale brown-yellow-coloured colluvial sand with rare angular gravel (Figure 8). A charcoal sample taken from unit 11 yielded an age of AD 1300–1420. Unit 11 is faulted by event 1 which is observed along an erosional unconformity. Units 11 and 12 are observed below unit 5. Unit 5 is then overlain by unit 10 which is observed only in a limited area in the fault zone. Unit 10 is yellowish green, sand and gravel, and has the characteristics of an alluvial channel deposit. The unit is observed on both sides of the fault and consists of material eroded from older units. Two charcoal samples taken from unit 10 yielded aged between AD 890–1020 and AD 1020–1170. Three fault splays associated with the penultimate event (event 2) cut unit 10 south of the main fault trace. These three splays are truncated by unit 11 which unconformably overlies unit 10. Unit 11 consists of pale brown-yellow-coloured colluvial sand with rare angular gravel (Figure 8). A charcoal sample taken from unit 11 yielded an age of AD 1300–1420. Unit 11 is faulted by event 1 which is observed on both trench walls. Unit 11 is overlain by unit 12 (modern soil). Unit 12 is the surficial unit and is unfaulted where it buries the fault tip (Figure 8). Radiocarbon analysis of a charcoal sample collected from the bottom of unit 12 suggests the material was deposited AD 1660–1880 (Table 2). On the west wall of the T1, a similar stratigraphy is observed below unit 5. Unit 5 is then overlain by unit 10 along an erosional unconformity. Units 11 and 12 are also observed in similar relationships (Figure 9).

T2 was excavated at nearly 8 m east of the T1 on the fault scarp in order to confirm the stratigraphy and events observed in the T1 (Figures 4(c), 7 and 10).
Figure 5. Historical (see Table 1 for numbers) and Instrumental (Kalafat et al., 2011) period earthquakes on the Active Fault map (Emre et al., 2013) of the Biga Peninsula and its vicinity. The focal mechanism solutions with 1 and 2 are taken from 1. McKenzie (1972) and 2. Taymaz et al. (1991), respectively.

Figure 6. Instrumental period earthquakes on the study area and its vicinity (Kalafat et al., 2011).
The 8-m long, 4-m wide trench was oriented N40°W, perpendicular to the strike of the Bekten Fault, and had a maximum depth of 2 m.

4.3. Interpretation of the events

According to tectonostratigraphical relationships observed on the trench walls, a total of three faulting events were observed. The fault geometry and deformation structures indicate that each event has both strike-slip fault with reverse component. In the Bekten trenches, a fault parallel trench was not excavated as reverse displacements appear, and the likelihood of observing a piercing point to determine lateral displacements seemed unlikely. So, the strike-slip component of total fault displacement is undetermined.

The trace of the most recent event (E1) can easily be seen on both walls of the trench. The fault trace cuts all stratigraphic units except the modern topsoil (unit 12) (Figures 8 and 9). Unit 11 is the youngest unit which is cut by the fault and unit 12 overlies the fault. Based on the numerical ages of these units, the E1 event could have occurred between AD 1420 and 1660 (Figure 11). The E1 may be correlated with the 1737 historical event, which locates on the SF showed with number 11 in Table 1 and Figure 5.

Evidence for the penultimate event (E2) is best exposed on the east trench wall in the form of multiple...
Figure 8. (a) Photo mosaic of T1 eastern wall without interpretation. (b) Log of T1 eastern wall.
sub-parallel fault branches (Figures 8 and 9). Faults displace and deform unit 10 and are overlain by unit 11. Radiocarbon age constraints on unit 10 and 11 indicate the E2 event occurred between AD 1170 and 1300 (Figure 11). According to historical earthquake records, a large earthquake occurred in 1354 Earthquake in Gelibolu region (Table 1, Figure 5).

Evidence of the antepenultimate event (E3) is observed on both walls of the T1 (Figures 8 and 9). On the west wall, three bifurcating fault branches cut units 4 and 5 and are buried by unit 10. Whereas, on the east wall the youngest faulted unit is unit 6. The fault traces are buried by unit 7. Radiocarbon age constraints on units 6 and 7 indicate the E3 occurred between AD 680
Table 2. Radiocarbon dates on samples recovered from Bekten trenches.

| Sample no. | Laboratory no. (BETA) | Stratigraphic unit | Sample material | Measured radiocarbon age (BP) | $\delta^{13}$C (‰) | Conventional radiocarbon age (BP) | Calibrated age range (2σ) | 95% probability |
|------------|-----------------------|--------------------|-----------------|-------------------------------|-----------------|---------------------------------|---------------------------|-----------------|
| BEK-EC-14  | 365978                | Unit 12 (modern soil) | Charred material | 190 ± 30                      | −26.0           | 170 ± 30                        | AD 1660–1700              | AD 1660–1700 |
| BEK-WC-01  | 365979                | Unit 11 (sand)      | Organic sediment | 560 ± 30                      | −23.6           | 580 ± 30                        | AD 1300–1370              | AD 1300–1370 |
| BEK2-WC-01 | 365983                | Unit 10 (sand-gravel) | Charred material | 890 ± 30                      | −22.7           | 930 ± 30                        | AD 1020–1170              | AD 1020–1170 |
| BEK-EC-04  | 365970                | Unit 10 (sand-gravel) | Charred material | 1080 ± 30                     | −25.2           | 1080 ± 30                       | AD 890–1020               | AD 890–1020 |
| BEK-EC-10  | 365974                | Unit 7 (colluvium)   | Organic sediment | 1070 ± 30                     | −24.2           | 1080 ± 30                       | AD 890–1020               | AD 890–1020 |
| BEK-EC-11  | 365975                | Unit 6 (clay)        | Organic sediment | 1350 ± 30                     | −24.3           | 1360 ± 30                       | AD 640–680                | AD 640–680 |
| BEK-EC-05  | 365971                | Unit 5 (sandy silt)  | Organic sediment | 14590 ± 60                    | −23.7           | 14610 ± 30                      | BC 15980–15690            | BC 15980–15690 |
| BEK-EC-09  | 365973                | Unit 3 (sand)        | Organic sediment | 23800 ± 120                   | −24.2           | 23810 ± 120                     | BC 26780–26450            | BC 26780–26450 |
| BEK-EC-08  | 365972                | Unit 3 (sand)        | Organic sediment | 27470 ± 150                   | −23.3           | 27500 ± 150                     | BC 29800–29430            | BC 29800–29430 |

Note: Ages reported by radiocarbon laboratory based upon the Libby half-life (5570 years) for 14C.
Figure 10. (a) Photo mosaic of T2 western wall without interpretation. (b) Log of T2 western wall. See Figure 8 for unit descriptions.

Figure 11. Probability distribution of calibrated 14 C ages (Table 2) obtained from radiocarbon dates (BP) using OxCal 3.10 software (Bronk Ramsey, 1998) for Bekten trench site samples.
and 890 (Figure 11). Except the 460, 464 and 543 historical events suggested located in Erdek area (Figure 5), no reported earthquakes occurred during this time in the historical record close to the Bekten Fault (Table 1, Figure 5).

The timing of three historical earthquakes obtained in Bekten trenches almost coincide with reported historical earthquakes in catalogues. The time intervals of earthquakes traced in trenches and the 1737, 1354 and 543 events reported in the historical catalogues are remarkable. This situation makes us consider that Bekten Fault might have been triggered as a result of the large earthquakes that occurred on major active fault segments in and around the Biga Peninsula.

4.4. Structural data

Slip data were measured on fault planes which were observed on trench walls in order to investigate Bekten fault kinematics. Kinematic indicators like slickenlines or groove marks were preserved in relatively soft sediments such as clay and silt on the fault plane between units 2 and 5. These structures which are clearly observed on east wall of trenches 1 and 2 were measured (Figure 12(a) and (b)). These data show that part of the fault has been subjected to similar tectonic deformation over multiple events. FaultKinWin 6.6.3 software was used for fault plane analyses which consists of the method suggested by Marrett and Allmendinger (1990) [software developed by Allmendinger, Cardozo, and Fisher (2012) for the analysis of fault plane data], and the result obtained is presented in the form of a focal mechanism solution (Figure 12(c)).

A total of three slip indicators were measured in the trench exposures. The data indicate maximum and minimum horizontal stress directions of (SHmax) N47°W-S47°E and (SHmin) N80°E-S80°W. The focal mechanism solution based on the slip indicators suggests that the fault is oblique slip with reverse component (Figure 12(c)).

5. Discussion and conclusions

This article is the first investigation carried out related to the palaeoseismic history of the Bekten Fault. Morphological features, palaeoseismological data and radiometric dating reveal Holocene activity of the fault.

The presence of large earthquakes occurred during historic time were revealed due to age and stratigraphic data obtained during trenching studies. Three earthquakes which caused surface rupture have been defined within last 1300 years along the Bekten Fault. According to the 14C ages, the antepenultimate event (E3) occurred between AD 680 and 890, penultimate event (E2) occurred between AD 1170 and 1300 and the most recent event (E1) occurred between AD 1420 and 660. These data suggest the Bekten Fault displays non-characteristic earthquake behaviour and has not produced any earthquake resulting in surface rupture for about the last 355–595 years.

Considering kinematical data measured on fault planes exposed in the trenches, the Bekten Fault is located in area which is under NW-SE compression. The focal mechanism solution (Figure 12(c)) obtained from
the trenches are similar to the focal mechanism solution of the 3 March 1969 Earthquake (Kalafat et al., 2011; 40.08 N–27.50 E, Ms: 5.8, depth: 6 km) which occurred on a similarly oriented structure in close proximity (Figure 5). Focal mechanism solutions of this earthquake interpreted as reverse faulting which NW block over SE block along a NE striking fault plane in the NW-SE compression area (Kocaefe, 1982; McKenzie, 1972; Taymaz et al., 1991). The epicentre of this earthquake located on the Atıçoba Fault north of the YGF (Gürer et al., 2006; Kalafat et al., 2011; Taymaz et al., 1991) (Figure 5). The Atıçoba Fault, where is located at 15 km north-east of Bekten Fault and extends sub-parallel between YGF and SF, is an 18 km long, right lateral strike-slip fault with reverse component (Emre et al., 2013). The 3 March 1969 earthquake is considered to have occurred as a result of strain accumulation on the Atıçoba Fault after the 18 March 1953 Yenice-Gönen earthquake. It is possible that a similar stress transfer between the Bekten Fault and YGF is occurring. Each earthquake along SF, YGF and EF could increase stress on Bekten Fault induce earthquakes as likely occurred between the 18 March 1953 Yenice-Gönen Earthquake and the 22 March 1953 Bekten Earthquake (Ms: 4.2). This earthquake likely occurred as an induced event as a result of the increase in stress due to rupture of the nearby YGF segment.

The Bekten Fault has produced moderate to large earthquakes forming surface ruptures during the last 1300 years and has the potential to produce strong earthquakes in the future. The large earthquakes at each occurrence on the major YGF, SF and EF segments, strain accumulation may have transferred on the Bekten Fault in the region. Accordingly, earthquake can occurred caused to rupture on the Bekten fault concurrently with earthquakes or later. Consequently, depending on palaeoseismological findings why Bekten Fault has short and much recurrence interval can be explained.

The palaeoseismological data obtained from the Bekten Fault, when assessed with results from nearby fault structures, especially from the YGF, SF and EF segments, will contribute significantly to our understanding of the fault kinematics, strain partitioning and slip rates in the Biga Peninsula and Southern Marmara region in Holocene time and provide insight to the seismic hazard of the region.

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ORCID
Selim Özalp https://orcid.org/0000-0002-6755-4206

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