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Age determination for segments of the North Anatolian Fault (NAF) northern branch by $^{234}U/^{230}Th$ dating of Soğucak (Yalova) range-front travertines, south Marmara, Turkey

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ABSTRACT

The Soğucak travertine occurrences developed along north segment of the North Anatolian Fault (NAF) in Yalova province, Marmara Region, Turkey. The range-front type travertines outcropping over an approximately 1 km^2 area with 20–40 m thickness are middle-thick bedded and back-tilted southward or horizontally. Lithology of the travertines includes physolite, stalactites-stalagmites, cave pearls, sharp pebble carbonate nodules, spherical-roller-intricate shapes and laminated banded travertines. Geochemical analysis was performed on six samples of the travertines. The samples showed high calcite composition (averagely 98%) and Mg carbonite content varying from 0.87 to 1.33%. The travertines were deposited by means of normal faults as indicated by structural and morphological relationship with active tectonics. $^{234}U/^{230}Th$ dating of the travertines provided an age range from 61.318 (±3.091) to 231.944 (±141.902) ka. Findings show that the travertine deposition and deployment of faults in the region occurred approximately at 231 ka, corresponding to Middle Pleistocene. Therefore, the age of both travertines and NAF was determined as Middle Pleistocene.

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1. Introduction

Travertines have played an important role in recent years especially in relation to active tectonic studies in the West Anatolian graben systems of Turkey. Investigations on travertines in West Anatolia were initiated by Altunel and Hancock (1993a, b), Altunel (1994) and Çakır (1996, 1999) and were continued by Özkul et al. (2002), Dilsiz et al. (2004), Altunel and Karabacak (2005), Uysal et al. (2007), and Selim and Yanık (2009). Studies related to active tectonics in the western part of Turkey are listed as follows. Temiz (2012) conducted a study about determining the age of the active Manisa Fault (West Turkey) reactivation by using U/Th dating method of carbonate precipitates. Similarly, De Filipps et al. (2012) investigated the growth of fissure ridge travertines from geothermal springs of Denizli Basin, western Turkey. Also, the comparison of the Quaternary travertine sites in the Denizli extensional basin based on their depositional and geochemical data was carried out by Özkul et al. (2013). Additionally, Brogi et al. (2014) studied the evolution of a fault-controlled fissure-ridge type travertine deposit in the western Anatolia extensional province with an example of the Çukurbağ fissure-ridge in Pamukkale, Turkey.

The study area in this paper is located in the southeast Marmara Region, NW Turkey near the village of Soğucak, which is 7 km from Yalova city, regional capital of Yalova province. The morphology of the region has an uplift area (Armutlu Peninsula) to the northwest, a depression area (İznik Lake) in the southeast and a northern segment of the southern branch of the North Anatolian Fault (NAF) in the southward and northern branch of the NAF in the Sea of Marmara (Gazioğlu et al., 2002) (Fig. 1). The travertine occurrences (hereafter called Soğucak travertines) are located between two active fault branches of the NAF, almost in the mid-section of the Armutlu Peninsula. The first objective of this study was to find the occurrence mechanism of the travertines and their relationship with the NAF and its segments by means of field and laboratory data on a regional scale. The second objective was to determine the

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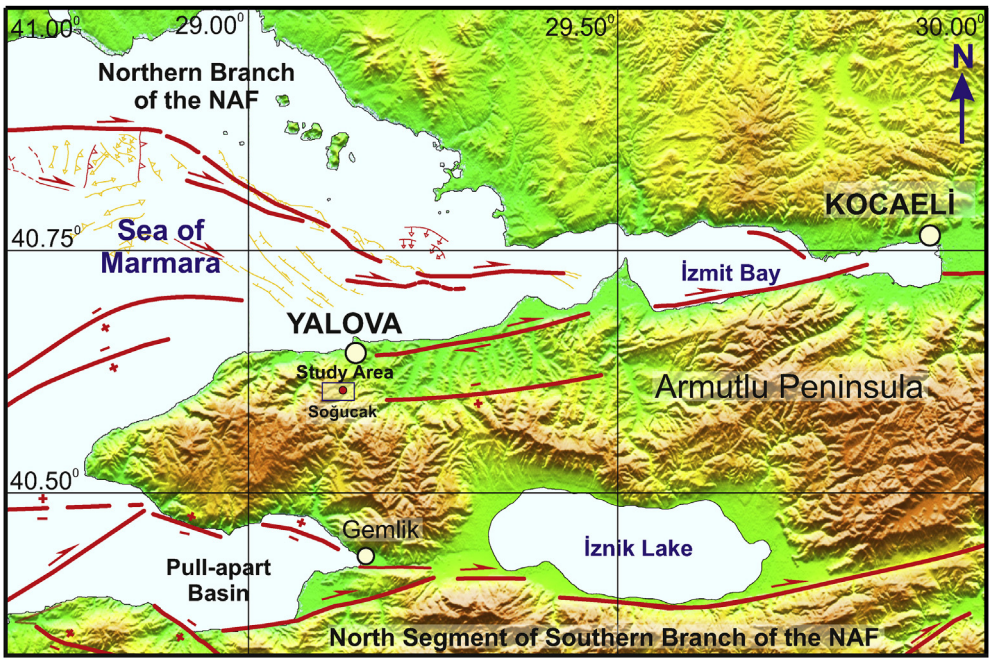


Fig. 1. Location map of study area showing north segment of southern branch and northern branch of the North Anatolian Fault (NAF) (İmren et al., 2001; Beyhan et al., 2009).

age of the NAF in the region using the U/Th dating method. There are several studies related to U/Th dating of geological deposits in different locations of the world. Muhs et al. (1989) applied the uranium-trend dating method for the southern California marine terrace deposits. Sturchio et al. (1994) performed uranium-series age determinations by mass spectrometric methods for travertines and associated carbonate veins to date the last glaciation in the Northern Yellowstone Area, Wyoming-Montana. Díaz and Hernández-Enrile (2001) employed U/Th dating method for the terrace-mound, fissure-ridge, eroded sheets and range-front travertine deposits to characterize paleoseismic activity along an active oblique-slip Alhama de Murcia fault in Betic Cordillera, Spain. Temiz et al. (2009) applied U/Th dating of fissure ridge travertines from the Kırşehir region in Central Anatolia, Turkey and evaluated their structural relations and implications for the Neotectonic development of the Anatolian block. Sierralta et al. (2010) investigated uranium-series dating of travertine from Sütto and evaluated implications for reconstruction of environmental change in Hungary. Nuriel et al. (2012) presented results from a microstructural, geochemical, and geochronological study of calcite precipitates associated with striated fault planes from the Dead Sea fault zone in northern Israel by using U-Th dating of samples from three adjacent fault planes. Gao et al. (2013) studied the travertine deposits near the Rongma hot springs in northern Tibet, China by U-series dating.

The Soğucak travertines are range-front type travertine occurrences. Travertines located on the hanging walls of normal faults were named as “range-front travertines” by Chafetz and Folk (1984). Additionally, many banded travertine occurrences developed within the parent rock extending parallel to the strike of normal faults in the study area. Altunel and Hancock (1993a, b) interpreted these banded travertine occurrences as hot water springs depositing the range-front type travertine occurrences. In addition, there are also cold water springs at different points along the normal faults.

The NAF and its segments constantly deform the morphologic and geologic features in the southern Marmara sub-region (Gürbüz and Gürer, 2008; Gazioğlu et al., 2010; Selim and Tüysüz, 2013; Selim et al., 2013). The Soğucak travertine occurrences in segments of the NAF to the south of Yalova are evidence of active faulting in the Neo-tectonic period. İmren et al. (2001), Le Pichon et al. (2001) and Şengör et al. (2005) indicate that the age of the NAF in the Marmara Region is 200 ka, based on geological and stratigraphic data. For the first time, this study utilized U/Th dating to determine a specific age for the Yalova Fault of the NAF and at the same time reveals the occurrence mechanism of travertines in the region.

2. Geological setting

The structure, geology and morphology of the southeast Marmara Region present a mosaic of morphotectonic elements bordered by active faults. The region includes lithologically different rocks of the Palaeotectonic and Neotectonic periods (Yiğitbaş et al., 1999, 2004). The study area also contains various rocks from Mesozoic to Quaternary (Fig. 2). To the south of Yalova, the Neogene and Quaternary deposits overlay the Mesozoic basement unconformably (Fig. 3).

The basement rocks consist of metamorphic rocks with Mesozoic green schist facies and volcano-clastics (lava-tuff-agglomerate). The first cover unit (Yalova formation) on the basement rocks, with clear angular unconformity, is Upper Miocene-Pliocene pebble stone, sandstone, mudstone, marl and coal intercalation deposited in a lake-stream environment. The unit presents red, yellow and greenish colors with clear cross-bedding (Rückert-Ülkümen and Yigitbaş, 2007). The upper part of the unit mainly consists of sandstone, mudstone and marl sequence. This cover unit was deposited before the NAF and the age of the unit correlates with Late Miocene-Pliocene basins located in the west Anatolia Region (Gürer et al., 2003, 2006; Gürbüz and Gürer, 2009). The Aktoprak formation, consisting of white beige mid-thin bedded limestone and marl, overlies the Yalova formation conformably.

The Quaternary units consist of travertines, talus, alluvial fans and alluvium. The travertines cover an area of approximately 1 km^2. The Soğucak travertine is of white-beige color, mid-thick bedded of 20–40 m thickness, cavernous, and level or tilted to

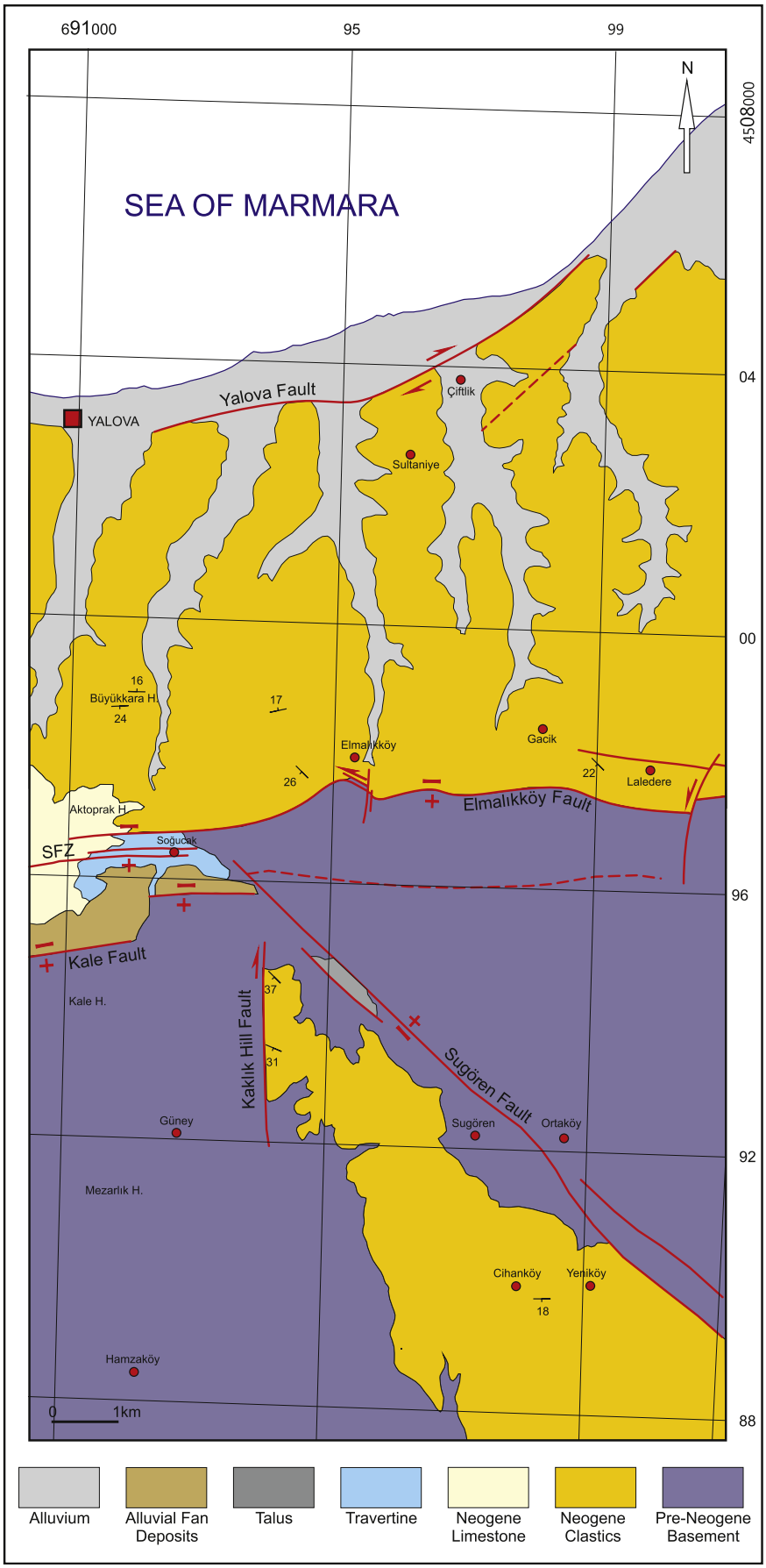


Fig. 2. Simplified geologic map of study area. SFZ: Soğucak Fault Zone.

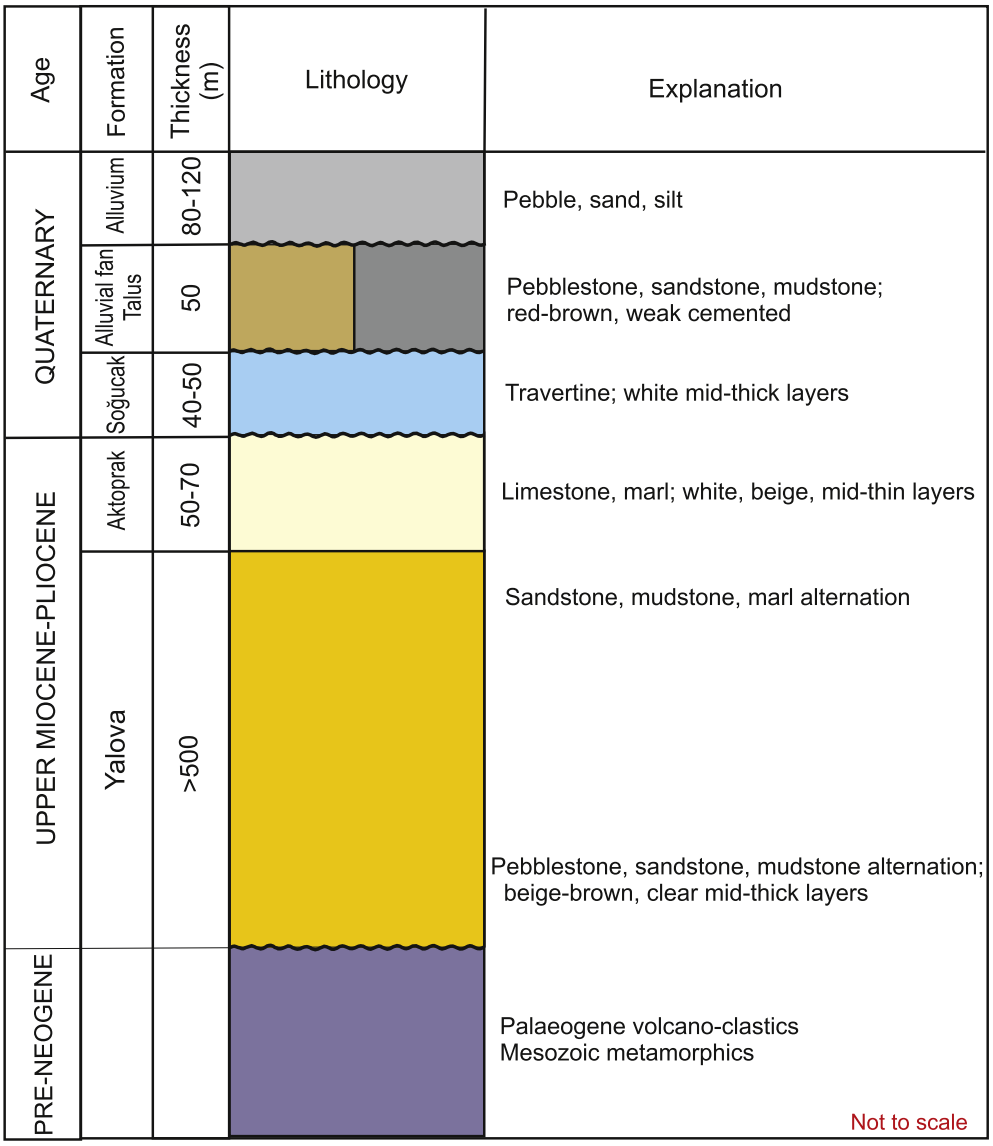


Fig. 3. Generalized stratigraphic column of study area.

the south. The strike of the travertine is N75W with 50° NE dipping. Travertine occurrences show a deposition parallel to the NAF in Soğucak village located in the south of Yalova and deposited in the Kale Fault as a front-range type travertine. The fault morphology is clearly seen to the south of the travertines. This fault verges on the basement rocks with Neogene and Holocene travertine units (Fig. 4).

The Soğucak travertine was deposited in the form of physolite, stalactites-stalagmites, cave pearls, angular pebbles, carbonate nodules, spherical-roller-intricate shapes or laminated travertines. Stratigraphy of the study area is represented by talus and alluvial fan products of the active tectonism dominant in the region. The talus seen on the hanging wall of the Sugören Fault has a red color with the matrix and rock fragments varying from 10 to 30 cm in length. Alluvial fan units, on the other hand, consist of almost level, weakly-cemented and poorly-graded red and brown pebble stone, sandstone and mudstone. Alluvium, consisting of gravel, sand and silt-size grains, is the topmost unit in the study area. The talus and clastics are cemented at the bottom of the travertines, while the clastics gradually decrease toward the upper levels.

3. Neo-tectonic features of Soğucak travertine

The study area is located in a region affected by high seismic activity caused by fault planes developed in the Neo-tectonic period. The main structural features in south Yalova province and its surroundings are products of the Neo-tectonic period. The NAF having a right lateral offset mechanism is one of the products and is affected by an extension regime running NNE-SSW in the south Marmara (Selim, 2004). These structural elements are Neo-tectonic indications in the study area and its vicinity. There were conjugate fault systems running in NW-SE and NE-SW directions in the Late Miocene-Pliocene deposits before the Neo-tectonic period (Yiğitbaş et al., 2006). The morphology of the study area and its vicinity was shaped particularly by the NAF and its segments.

The Sugören Fault extends NW-SE and the Kaklık Tepe Fault runs in a N-S direction in the study area. The Soğucak Fault Zone (SFZ), a NAF segment allowing travertine deposition with an E-W direction, intersects the Yalova, Kale and Elmalıkköy faults (See Fig. 2). The Sugören Fault, located to the southeast of the travertines, is a normal fault of approximately 10.5 km in length

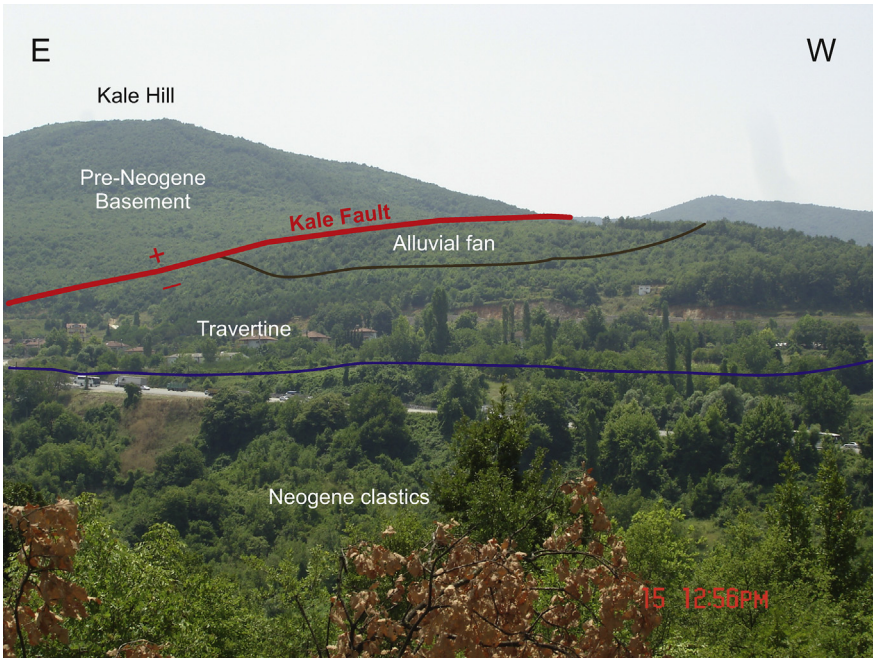


Fig. 4. View from Kale Fault between basement rocks and Soğucak travertines.

extending along the valley. The Elmalıkköy Fault is a strike-slip fault approximately 14.5 km long. The SFZ breaks up into more than one segment to the west of the study area around Soğucak village and gains an en echelon structure. Several notable hot and cold springs on the same lineament are located in the fault zone. A thermal spring with water temperature of 20° C on the segment extending to the south of Soğucak village stands in a field. There are also hot springs at Yalova city on the continuation of the fault zone. Lying to the north of the village, there are also cold and hot water springs on the other segment of the fault line (Fig. 5a).

The SFZ continues east in an approximately E-W direction and cuts into the left lateral strike-slip Elmalıkköy Fault. Here, the fault zone extends between the Quaternary and basement units in the west and between the Late Miocene-Pliocene and basement units in the east. The Yalova Fault parallel to the SFZ is a young segment of the NAF, with a NE-SW or E-W strike being the contact surface

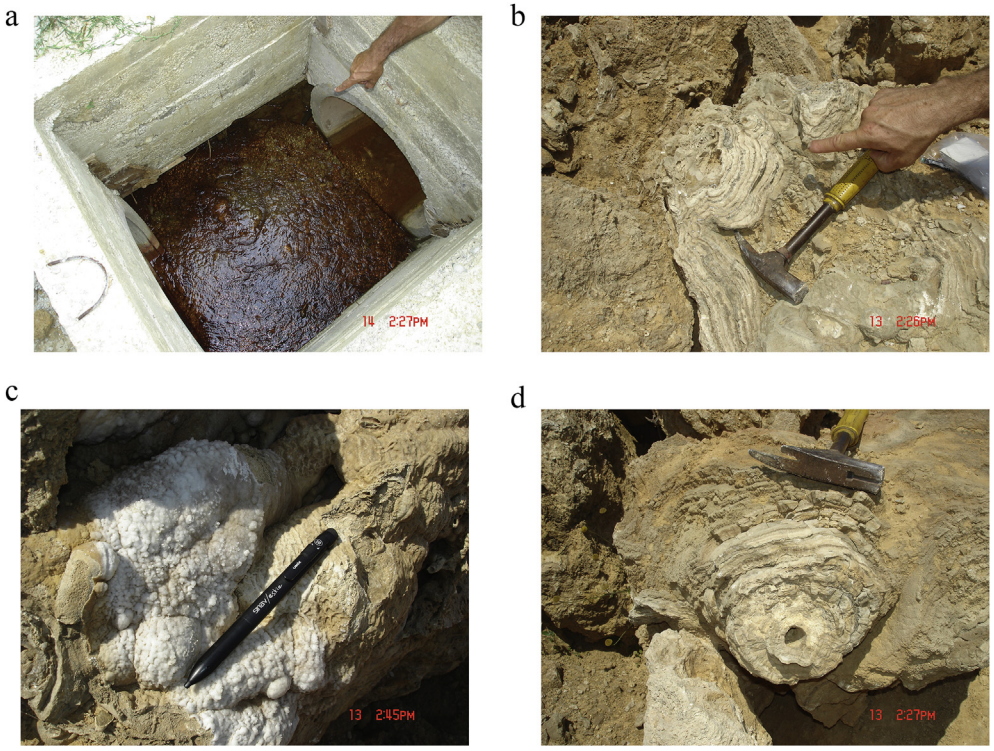


Fig. 5. Field views of travertines. a) Precipitation by hot water spring, b) Banded travertine occurrences, c) Well-crystallized, hard and solid-structured travertines, d) Hollow tubes composed of aragonite needle botryoids.

between the alluvium and Upper Miocene-Pliocene units in the northernmost part.

The Soğucak travertine occurrences were deposited along the Kale Fault and SFZ. The en echelon structure of the fault zone caused hot water outflows in many locations and the spread of the travertine over an approximately 1 km^2 area. The Soğucak travertine deposited on the fault zone crossing Soğucak village has a wide extension on the hanging wall of the fault. The front-range travertines contain cavities approximately 3 cm in length and 2 cm in width occupied by level travertine laminations near the fault (south of Soğucak village). These are banded travertine occurrences (Fig. 5b). Hot water seepages depositing travertines in front of the fault planes extend along the entire length of the fault. Dipping of the bedded front–range travertines is parallel to the slope on which the travertine was deposited. Travertines located to the south of Soğucak village are almost level. However, some of the bedded front–range travertines on the hanging wall have 17° dipping towards the fault. These beds gained an inclination towards the back probably due to the activity of the fault. The travertines to the north of the village are tilted towards the south, according to the en echelon structure of the fault zone. The Soğucak travertines are the only travertine occurrences related to the NAF in the Marmara Region and no kinematic data could be obtained because the travertines are covered by alluvial fan deposits.

4. Methods

Petrographic and geochemical analyses of the travertines deposited by the hot springs at Soğucak were carried out to define the depositional facies along segments of the NAF. The six samples collected from the travertines were examined under a polarizing microscope and defined according to their macroscopic and microscopic properties. Chemical analyses were performed in the Geological Department, geochemistry research laboratory (İTÜ-JAL) of Istanbul Technical University. The rock samples were ground to a fine powder form and effectively homogenized for bulk chemical analyses of quantitative major elements (Ca, Mg, Si, Fe, Al) and then analyzed by Bruker S-8 Tiger type XRF analyses of glass disc prepared with lithium tetraborate flux except for Na and K. LOI (Loss on Ignition) was added to the results to keep the whole mass amount. The elemental composition of the Soğucak travertine is presented in Table 1.

The U/Th dating analyses for the present study were carried out in the Université du Québec à Montréal (Canada) according to methods outlined in Ivanovich and Harmon (1992), Mallick and Frank (2002), Temiz et al. (2009, 2011 and 2013). The samples for $^{234}U/^{230}Th$ dating analysis were collected from well-crystallized, hard and solid-structured travertines in the SFZ (Fig. 5c). Six samples were taken from the study area to conduct U-series age determination analysis. All samples presented realistic age data as a result of dating tests (Table 2). The location of the samples is as follows: 1 lowermost (4496176 N - 692418 E), 3B (4496150 N - 692484 E), 5 north of the fault (4496563 N - 692556 E), T-17 banded travertine (4496141 N - 692471 E), 18-B

Table 1
Chemical properties of range-front type Soğucak travertine samples.

	T-17	1	T-21	3B	5	18-B
$CaCO_3$	98,67	98,33	99	98,39	98,11	98,99
$MgCO_3$	0,87	1,31	0,85	1,33	1,25	0,91
SiO_2	2,14	1,31	0,80	1,14	0,41	0,48
Fe_2O_3	0,31	0,25	0,12	0,15	0,50	0,26
Al_2O_3	0,70	0,77	0,33	0,45	0,18	0,20

Table 2
Age data obtained by U/Th dating method.

Sample	^{238}U ppm	±	^{232}Th ppm	±	$^{234}U/^{238}U$	±	$^{230}Th/^{234}U$	±	$^{230}Th/^{238}U$	±	$^{230}Th/^{232}Th$	±	Calculated uncorrected age (ka)	Err.	Corrected age (ka)	Err.
Sample 1[a] Lower most +	0.1329	0.0001	0.1829	0.0019	1.5185	0.0116	0.9903	0.0155	1.5037	0.0210	3.3390	0.0600	253.958	13.565	231.944	141.902
Sample 3B*	0.1783	0.0001	0.0897	0.0001	1.5713	0.0112	0.7632	0.0072	1.1993	0.0083	7.2840	0.0710	137.558	2.627	129.174	9.970
Sample 5[a] North of the fault	0.2518	0.0012	0.0626	0.0016	1.6402	0.0104	0.4683	0.0133	0.7681	0.0214	9.4450	0.3560	65.536	2.469	61.318	3.091
Sample 18-B[a] fault plane	0.1784	0.0001	0.0384	0.0003	1.5598	0.0123	0.7775	0.0093	1.2127	0.0119	7.2100	0.2200	142.525	3.496	139.014	5.435
Sample T-17[a] banded travertine	0.2063	0.0011	0.0967	0.0001	1.5705	0.0153	0.8276	0.0113	1.2997	0.0138	8.4700	0.1170	160.678	4.960	153.149	13.466
Sample T-21[a] foot wall of fault	0.1804	0.0001	0.0359	0.0001	1.5560	0.0122	0.7585	0.0073	1.1803	0.0080	18.1030	0.1650	136.273	2.719	132.994	4.081

Correction in which the U-Th isotopic composition of the detrital contamination is arbitrary estimated, in a manner resembling the one used by Ludwig and Paces (2002). Specifically, we used ^{232}Th as an index and assumed a typical crustal Th/U ratio, with $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ activity ratios near secular equilibrium.
In this model, the isotope and the activity ratios used for detrital contamination were $(^{232}Th/^{238}U) = 1.21 \pm 50\%$, $(^{234}U/^{238}U) = 1 \pm 10\%$ and $(^{230}Th/^{238}U) = 1 \pm 10\%$.
[a] Samples requires correction for detritus.

fault plane (4496280 N - 691300 E) and T-21 footwall of the fault (4496375 N - 691525 E) (Fig. 6).

5. Results

5.1. Petrographic and geochemical properties

The travertines are range-front travertine occurrences composed of aragonite needle botryoids. A banded structure is common texturally; however, tubular-shaped travertines are also seen as indicators of the deposition system. The apron and channel facies are floored by hollow tubes composed of aragonite needle botryoids (Fig. 5d). Polarizing optical microscopy (POM) showed the distribution of organic matter (dark areas) and mineral phases (light granules) associated with solids collected from different parts of the spring. The travertine on the hanging wall of the SFZ is composed entirely of calcite. Mg carbonate content varying from 0.87 to 1.33% is consistently low in the higher-temperature facies.

5.2. $^{234}U/^{230}Th$ dating results of carbonate precipitations

Tectonic activities played an important role during the carbonate precipitation of the Soğucak travertine. The Soğucak travertine occurrences originated tectonically were deposited as a range-front travertine type in the SFZ. The SFZ has normal fault geometry and suggests syn-depositional faulting related to extensional tectonics. In recent studies on travertine age determination, $^{234}U/^{230}Th$ disequilibrium and α-spectrometry techniques have been used to determine the age of travertines numerically (Harmon et al., 1980; Blackwell and Schwarcz, 1986; Eikenberg et al., 2001; Temiz et al., 2011, 2013). The samples for this study were taken from the different levels of the travertines. The 1 lowermost sample was taken from the lowermost levels of the travertine. The 3B sample was taken from the topmost banded and pebbly level of the travertine. The sample numbered 5 was taken from the low levels of the travertine located in the hanging wall of the SFZ. The T-17 sample was taken from the upper banded level of the travertine. The 18-B sample was taken from the middle levels of the travertine located in the footwall of the SFZ. The T-21 sample was taken from the low levels of the travertine located in the hanging wall of the SFZ. The age of the samples taken from Soğucak travertine was calculated to be from 61.318 (±3.091) to 231.944 (±141.902) ka. This time interval geologically corresponds to Middle Pleistocene. It is deduced that the age of the travertines and age of the active Yalova segment of the NAF are the same. The travertine occurrences were deposited by means of the NAF segment. Thus, the age of the travertines and NAF segment can be interpreted as Middle Pleistocene in the study area (Fig. 7).

6. Discussion

Occurrence of travertines is closely related to active fault zones (Barnes et al., 1978). Fluids reaching the surface due to faults deposit travertines. At the same time, travertine occurrences reflect signs of fault activity and the Neo–tectonic period. Indications from the Neo–tectonic period are clearly seen in the study area. Many destructive and damaging earthquakes occurred in the historical and instrumental periods in Yalova and its vicinity. The

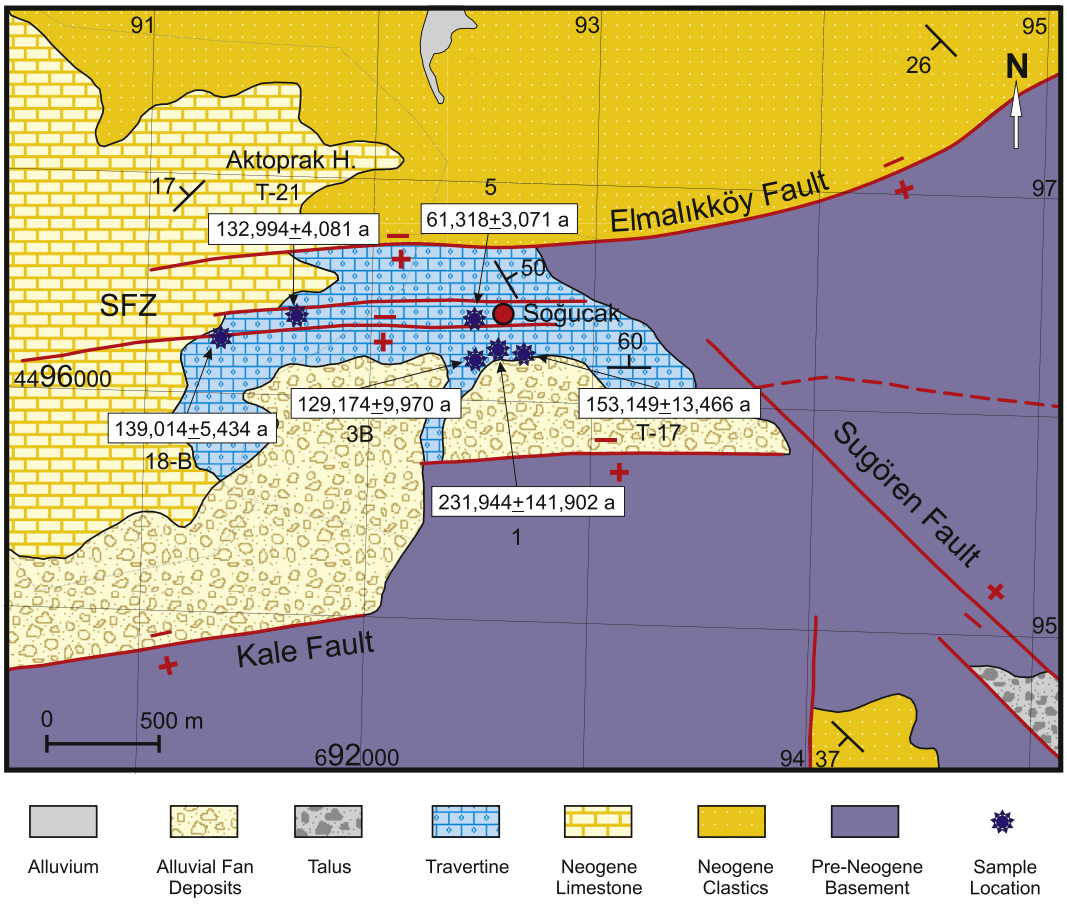


Fig. 6. Sample locations on map displaying detailed geology and travertine spread. SFZ: Soğucak Fault Zone.

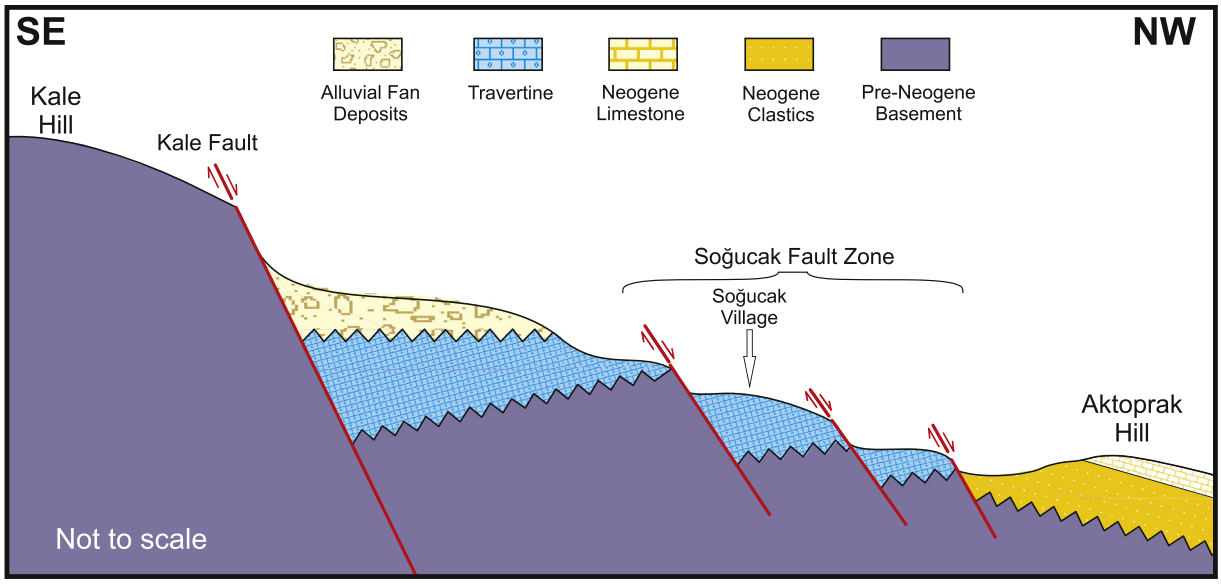


Fig. 7. Occurrence model of range-front type Soğucak travertine.

historical period earthquakes happened specifically in the years of 120 or 128 AD, 358, 477 or 480, 557, 989, 1344, 1509, 1719, 1754, 1766, 1878 and 1894 (Ambraseys and Finkel, 1991). The 1912, 1963 and 1999 earthquakes took place during the instrumental period. The area is still under significant seismic risk due to the NAF and its segments.

The SFZ crossing Soğucak village is one of the NAF segments. The structurally-laminated, cavernous and banded Soğucak travertine occurrences deposited on the SFZ are proof of the active fault zone. At the same time, hot and cold water seepages precipitating the travertines extend on the same lineament. On the other hand, beds of travertines tilted toward the south indicate that the normal faults in the SFZ are still active. Tilted and deposited travertines on the fault plane suggest that tectonic activity continued during and after travertine deposition.

The North Anatolian Fault (NAF) has an approximate length of 1200 km and borders the Anatolian Plate to the north and is a right lateral strike–slip fault (Ketin, 1948; Barka, 1992). This fault, constituting a border between the Eurasian and Anatolian plates, is a transform fault. The NAF splays into north and south branches in the Marmara Region. The study area is located on the northern branch of the NAF and its segments. Several fault zones with approximate E-W strike and right lateral strike–slip have developed and intersected the NE–SW and NW–SE extending faults that existed before the NAF (Yiğitbaş et al., 2006). Morphologically, these activities created E-W extending uplift areas in the region due to the young faults. These two branches are the source of seismic activity in the region. According to GPS measurements, the southern and northern branches of the NAF move distinctly. An annual movement of 24–25 mm for the northern branch was calculated by Armijo et al. (2002). The six samples taken from the Soğucak travertines were tested using U/Th dating. U/Th data indicated that the travertines were deposited during a time period between 61 ka and 231 ka, which corresponds to the Middle Pleistocene geological time interval. Related studies examining the initiation age of the NAF in the Marmara Region were carried out by İmren et al. (2001), Le Pichon et al. (2001) and Şengör et al. (2005); where the age of the fault in the region was given as 200 ka, which is the closest predicted age to the U-series data. For the first time, the age of the northern branch of the NAF was determined based on the results of U/Th dating by this study. According to U/Th data, the age of the Soğucak travertine was obtained as 231.944 ± 141.902 ka from the 1 lowermost sample (lowermost level), 153.149 ± 13.466 ka from the T-17 sample (upper level) and 129.174 ± 9.970 ka from the 3B sample (topmost level). Other two samples, numbered 5 and T-21, taken from the hanging walls of the SFZ crossing the travertines E-W direction yielded age data of 61.318 ± 3.091 ka and 132.994 ± 4.081 ka respectively. On the other hand, 18-B sample taken from the footwall of the SFZ gave age of 139.014 ± 5.435 ka. According to these dating data, deposition of travertine occurrences started 231.944 ± 141.902 ka and continued until 61.318 ± 3.091 ka. Furthermore, it is manifested that the north segment formed by the NAF in the study area has been active for 231 ka. As a result, the activity along the northern branch of the NAF started in Middle Pleistocene in the Marmara Region. Field observations, U-series data and tectonic evidence clearly support this.

7. Conclusions

This study investigated the occurrence mechanisms of the Soğucak travertines and determined the age of the travertines using U/Th dating. The Soğucak travertine occurrences located on north segment of the NAF in the south of Yalova province are evidence of active faulting in the Neo-tectonic period and were deposited as physolite, stalactites-stalagmites, cave pearls, angular pebbles, carbonate nodules, spherical-roller-intricate shapes or laminated travertines. The Soğucak travertines are range-front type occurrences composed of aragonite needle botryoids. The six samples collected from the travertine occurrences were examined under a polarizing microscope and defined according to their macroscopic and microscopic properties. A banded structure is common texturally but tubular-shaped travertines are also seen as indicators for the deposition system.

The Soğucak travertines were deposited in front of the fault planes with en echelon morphology. Hot water, including travertine precipitations, reached the surface along fault discontinuities and the travertines were precipitated on the hanging walls of the normal faults. Deposition of the travertines was in a level position, tilted towards the fault planes and the south in the Kale Fault and SFZ. No travertine occurrence was observed beyond the SFZ.

The age of the samples taken from Soğucak travertine is calculated to be from 61.318 (±3.091) to 231.944 (±141.902) ka. It is

inferred that the age of the travertines and the active Yalova segment related to the NAF are the same throughout the region. Ages of the travertines and NAF segments are interpreted as Middle Pleistocene in the study area - the Marmara Region - because the travertine occurrences were deposited by means of segments related to the NAF in Yalova province.

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