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Coastal Uplift along the Eastern Black Sea Coast: New Marine Terrace Data from Eastern Pontides, Trabzon (Turkey) and a Review

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ABSTRACT

An emerged, Quaternary, marine terrace sequence has been investigated near Trabzon, Turkey, along a ~20-km-long stretch of the coast of the southeastern Black Sea. The sequence includes seven principal marine terraces. The terraces are frequently compound and include up to three second-order marine terraces. The upper shoreline angles of the main terraces were found at the following maximum elevations above mean sea level: 3 ± 0.5 m (TH), 12 ± 3 m (T1), 36 ± 2 m (T2), 79 ± 9 m (T3), 120 ± 3 m (T4), 138 ± 10 m (T5), and 260 ± 25 m (T6). Fossil bivalves and gastropods from the TH, T1, T2, and T3 deposits have been dated by Electron Spin Resonance (ESR). The results show that the ages of the deposits from the TH, T1, T2, and T3 terraces are 5.141 ± 0.294 ka, 124.8 ± 26.0 ka, 292.5 ± 49.8 ka, and 407.998 ± 67.475 ka, respectively. Consequently, we correlate TH, T1, T2, and T3 to marine isotope stage (MIS) 1, 5e, 9, and 11, which correspond to ~5, ~123, ~321, and ~400 ka highstands, respectively. Estimated uplift rates deduced from the elevations of T1, T2, and T3 are 0.07 ± 0.05 , 0.10 ± 0.02 , 0.17 ± 0.03 mm/y or m/ka. These results show nonsteady, long-term uplift rates. Extrapolation of the oldest uplift rate (*i.e.*, determined on the highest dated terrace) shows that in the region of Trabzon, Turkey, coastal, positive, vertical deformations are recorded at ~2 Ma, which corresponds to the extrapolated age of the highest terrace in the sequence. Comparison with other sequences on the Black Sea coast reveals a rather weak uplift in this zone, which can be considered significative for the recent uplift of the Eastern Pontides.

ADDITIONAL INDEX WORDS: *Marine terrace, coastal uplift, Electron Spin Resonance, Eastern Pontides, Eastern Black Sea.*

INTRODUCTION

The emerged sequence of Quaternary marine terraces near Trabzon, Turkey, lies on the northern zone of the Eastern Pontides orogenic belt in a context of plate collision. In this zone, studies on marine terraces began as early as the 1940s (Ardel, 1943; Erol, 1952; Ertek and Aytac, 2001; Keskin, 2007; Solmaz, 1990; Yilmaz *et al.*, 1997, 1998, 2005). The sequence of paleoshorelines, which increase in altitude from a few meters up to 260 m in a short distance, has long been interpreted as a consequence of uplift (Ardel, 1943; Erol, 1952; Yilmaz *et al.*, 2005) but surprisingly, previous studies did not focus on determining uplift rates. Consequently, no estimation of the Quaternary uplift of the Eastern Pontides orogenic belt was proposed through coastal morphotectonic studies. The main purposes of this work are to (1) refine the geomorphological data on marine terraces in this zone, (2) correlate the marine

terraces's shoreline angle to the Pleistocene highstands through Electron Spin Resonance (ESR) dating of the terrace deposits, (3) calculate the average uplift rates, and (4) compare the average uplift rates of the Trabzon, Turkey, area with uplift rates calculated through similar studies at other sites along the Eastern Black Sea coast.

SETTINGS

Geodynamics

The Black Sea is located between the Eurasian plate in the north and the African–Arabian plates in the south, within the Anatolian sector of the Alpine–Himalayan orogenic system (Figure 1). Around the Black Sea, this orogenic system includes the Pontides, the Greater Caucasus, and the Crimean Mountains. Plate models (DeMets *et al.*, 1989) and recent geodetic data (Reilinger *et al.*, 1997; Smith *et al.*, 1994) indicate that in the surrounding region, northward-moving African and Arabian plates collide with the Eurasian plate. As a consequence, the Anatolian block moves westward. Within this tectonic framework, the present-day tectonics of the Black Sea has been a puzzle (Tari *et al.*, 2000). The Black Sea basin is

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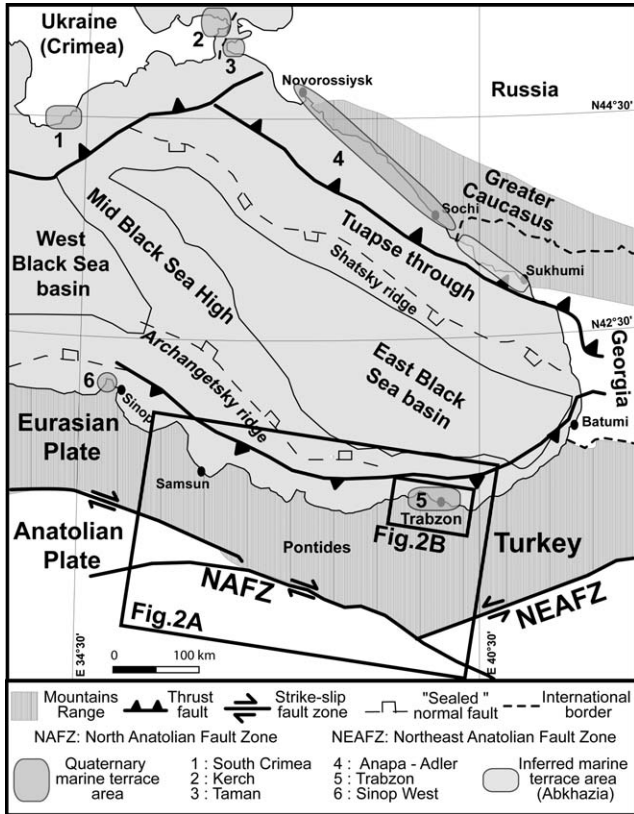


Figure 1. Geodynamical context of the Eastern Black Sea. Map sketch redrawn from Smith *et al.*, 1994; Reilinger *et al.*, 1997; and Tari *et al.*, 2000.

divided into two parts, the Western and Eastern basins, separated by the mid-Black Sea ridge (Figure 1). The origin of the Black Sea has long been discussed, and it has been proposed that the entire Black Sea was rifted starting during Aptian–Albian period (Görür, 1993), but the age of the rifting for the Eastern Black Sea is less well known (Spadini *et al.*, 1996). Following the closure of the Neotethys, the Black Sea began to close during the Eocene–Oligocene age, and the Eastern Black Sea continued to close from the Miocene to the present. Seismic activity within the circum-Black Sea has been low to moderate during the 20th century. The area studied lies in the Eastern Pontides (NE Turkey) orogenic belt, which extends along the southeastern coast of the Black Sea region. This belt is divided into three subgroups from north to south, depending on lithological assemblages and facies (Figure 2A) (Bektaş *et al.*, 1999; Eyüboğlu *et al.*, 2006). The fault zones are oriented NW–SE, E–W, and NE–SW (Figure 2A). The northern zone (the magmatic arc), including the study area, is characterized by a dominance of subduction-related, upper Cretaceous and Tertiary volcanic rocks and by upper Cretaceous and Eocene arc granites.

The evolution of the Eastern Black Sea basin has been controlled by subsidence (Görür *et al.*, 1993; Nikishin *et al.*, 2003; Yılmaz *et al.*, 1997). Görür *et al.* (1993) and Yılmaz *et al.* (1997) emphasized that Pontides underwent regional subsidence and local uplift. Nikishin *et al.* (2003) proposed that the

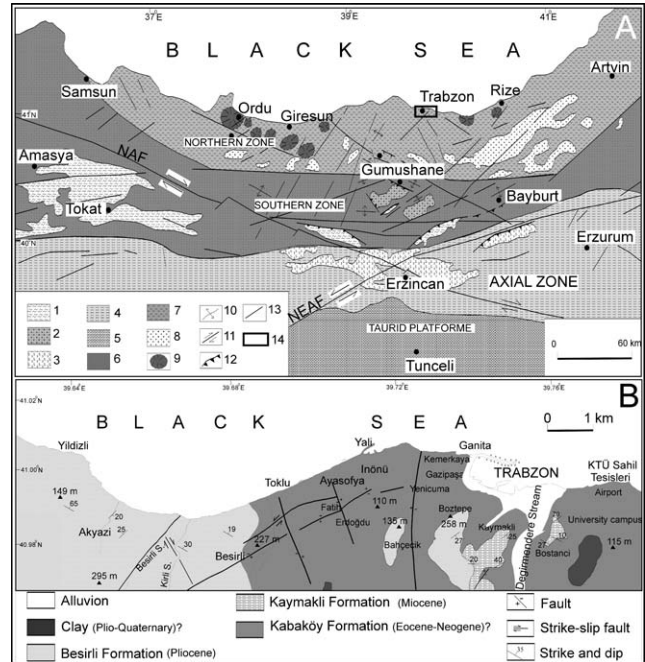


Figure 2. Geology of the Eastern Pontides and Trabzon, Turkey, area. (A) Main tectonic features and tectonic zones of the Eastern Pontides: (1) Paleozoic metamorphic basement, (2) paleozoic granites, (3) serpentinite, (4) undifferentiated Mesozoic and Cenozoic rocks, (5) platform carbonates, (6) primarily Mesozoic sedimentary rocks, (7) Cretaceous and Eocene arc volcanics, (8) Upper Cretaceous and Eocene arc granites, (9) caldera or dome, (10) orthogonal drape and drag folds, (11) fault, (12) thrust fault, (13) normal fault, and (14) study area. Abbreviations: NAF = North Anatolian Fault, NEAF = Northeast Anatolian Fault (*per* Eyüboğlu *et al.*, 2006). (B) Geological map of the study area.

regional compression, folding, and thrusting started during the late Eocene–Oligocene, and the general uplift of the recent mountains that surround the Black Sea began nearly 10 million years ago. In the Transcaucasus and Turkish regions, large-scale uplift of the mountains started during the Oligocene, but an acceleration of the deformation started during the Late Sarmatian (~10 Ma) (Milanovsky, 1968, 1991). Milanovsky (1968, 1991) also suggested that in the Eastern Black Sea basin, tectonic subsidence rate were 70–80 m/Ma, 20–30 m/Ma, and 85 m/Ma during the Late Cretaceous–Eocene, the Oligocene–Miocene, and the Plio–Quaternary, respectively.

Geology

In the study area (Figure 2B), six different units (excluding marine terraces) are distinguished (Yılmaz *et al.*, 1998): (1) the Upper Cretaceous–Paleocene Bakirköy Formation, (2) the Eocene–Neogene Kabaköy Formation, (3) the Miocene Kaymakli Formation, (4) the Pliocene Besirli Formation, (5) the Pliocene–Quaternary clays, and (6) the Quaternary alluvium. All units are briefly described in the next paragraph.

The Bakirköy Formation is composed of Upper Cretaceous–Paleogene age sandy limestone, red biomicrite, and marl intercalation (Eyüboğlu *et al.*, 2006). The Cenomanian to early the Tertiary period, especially the Eocene, is characterized by

the evolution of the sedimentary rocks in the southern zone and represented by dense volcanic activity in the northern zone. The Neogene (Mio–Pliocene) volcanic activity that formed the Bakirköy Formation cut all units in the region. The Miocene Kaymakli Formation overlies these volcanic rocks and was first described as Pontian clays by Özsayar (1971). This formation contains sandy, clayey siltstone. The Pliocene Besirli Formation is an outcropping near the seashore and is represented by basaltic and andesitic agglomerate, tuff, claystone–sandstone–marl intercalations, coarse-grained sandstone, loosely cemented conglomerate, and breccias. The Pliocene Besirli Formation and the Eocene–Neogene Kabaköy Formation (Yilmaz *et al.*, 1998) are uncomfortably overlaid by the Quaternary marine terraces and alluvium.

Quaternary Sea-Level History of the Black Sea

Throughout geological time, the Black Sea experienced major sea-level changes, accompanied by environmental modifications, such as geomorphological reshaping (Panin and Popescu, 2007).

The Pleistocene epoch was characterized by alternations between a flow-type and a semiclosed water body. In a broad sense, marine transgressions occurred during the interglacials, whereas during the glacial periods, the basin became a flow-through, brackish water body (Algan *et al.*, 2007). During the Quaternary glaciations and delectation, the induced sea-level fluctuations endowed the restricted channels of the Bosphorus and Dardanelle with the power to control the Black Sea’s connection to the Mediterranean Sea (Panin and Popescu, 2007). When global sea level dropped below the Bosphorus sill, the water level in the Black Sea varied according to regional conditions, independent of those in the World Ocean (Panin and Popescu, 2007). One important consequence of these lowstands was the interruption of Mediterranean inflow to the Black Sea, which, lacking any saline contribution gradually became a giant brackish to freshwater lake (Panin and Popescu, 2007). As noted by Zubakov (1988), the number and ages of glacial–interglacial cycles in continental Europe are identical to the climatic cycles in the Black Sea and Mediterranean Sea. During marine events, Mediterranean mollusks penetrated into the Black Sea and up to the Azov Sea (*e.g.*, Zubakov, 1988). Thus, the fluctuations of the Black Sea levels were effectively controlled by the global climate changes, with the higher sea levels corresponding to the increased inflow of water during the milder and wetter interstadial episodes and the lower levels occurring during the colder and drier stages (Arslanova, Dolukhanov, and Gei, 2007). For example, during the Last Interglacial (marine isotope stage [MIS] 5), eustatic rise in sea level allowed saline Mediterranean water to penetrate the Pontic basin (Panin and Popescu, 2007). This phase, locally named the Karangatian, introduced marine conditions that lasted about 60 ka (from 125 to ~65 ka BP). Marine terraces of this age (see “Marine Terraces” below) have been found around the Black Sea basin at elevations as high as 10 m on the Kerch and Crimea peninsulas (Panin and Popescu, 2007; Zubakov, 1988) and up to 48 m along the Caucasus coast because of the tectonic uplift (Nesmeyanov, 1995).

The sea level during the Black Sea’s history has been rather

complicated and heavily discussed; there is still little consensus on the Black Sea variations in level, and different scenarios have been proposed to explain the evolution of the Black Sea since the Last Glacial Maximum (*e.g.*, Giosan, Filip, and Constatinescu, 2009; Hiscott *et al.*, 2007; Pirazzoli, 1991; Ryan and Pitman, 1999). The main conclusion in the latest review (Panin and Popescu, 2007) on this subject is that more extensive studies are needed to fill the remaining gaps in our knowledge about Late Pleistocene and Holocene sea-level changes. It must be pointed out here, that our study concentrated on the highstands of the Black Sea and the sea-level history of the Black Sea during the interglacials is not controversial. All authors, to our knowledge, agree on the connection of the Black Sea to the Mediterranean Sea through the Marmara Sea.

The maximum rise in the Black Sea (3–5 m above current level) took place 3.5–4 ka ago during the Subboreal period (Panin and Popescu, 2007). At this time, the so-called Old Black Sea terrace was formed (Panin and Popescu, 2007). A rapid lowering of the water level by –5 to –8 m followed, coeval with the first Greek colonization of the Black Sea coast. A new, short-lived ingression of the sea to a stand of +1 to +3 m then occurred. By about the 10th century AD, the level of the Black Sea experienced a decline of 1–2 m, then a slow rise, which continues today (Panin and Popescu, 2007).

In any case, most researchers agree that (1) all fauna encountered in the marine terrace deposits of the Trabzon area are characteristics of saline water (James Nebelsick, personal communication), (2) the ages provided by ESR dating on fossil bivalves and gastropods yield ages very close to the well-known, worldwide, Quaternary sea-level highstands, and (3) in the Black Sea, sea levels during past interglacials are not controversial. Authors agree on a connection of the Black Sea to the Mediterranean Sea through the Marmara Sea (see above). Therefore, we conclude that the marine terrace of the Trabzon area can be correlated to worldwide, major highstands.

METHODS

Marine Terraces

On uplifting coasts, marine terrace sequences are sometimes represented by flights of terraces up to hundreds of meters above mean sea level (Better Bull, 2008). Each terrace corresponds to a gently seaward dipping erosional or depositional platform backed by a relict sea cliff. The shoreline angle (*i.e.*, the intersection of the relict platform and the relict sea cliff) provides a good approximation of the location and elevation of a former shoreline and hence a relative sea level (Bull, 1985; Pedoja *et al.*, 2008). Most researchers now view marine terraces as being formed during the separated highstands of interglacial stages, which are correlated to marine oxygen-isotopic stages. The total displacement of the shoreline, relative to the age of the associated interglacial stage, allows us to calculate the mean uplift rate (Lajoie *et al.*, 1986) through the following classical equation: $U = (E - e)/A$, where U is the total uplift rate of each marine terrace, E is the present-day elevation of the marine terrace, e is the eustatic sea level of the considered MIS, and A is the age of the marine terrace

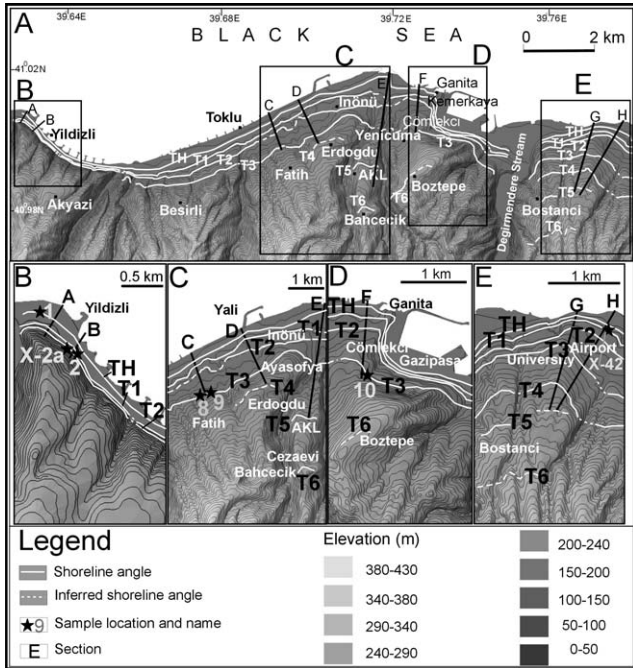


Figure 3. Marine terrace sequence in Trabzon, Turkey. The contour line is at 10-m intervals. (A) General repartition. (B) Zoom-in view of Yildizli. (C) Zoom-in view of Yali. (D) Zoom-in view of Ganita. (E) Zoom-in view of the Trabzon Airport area.

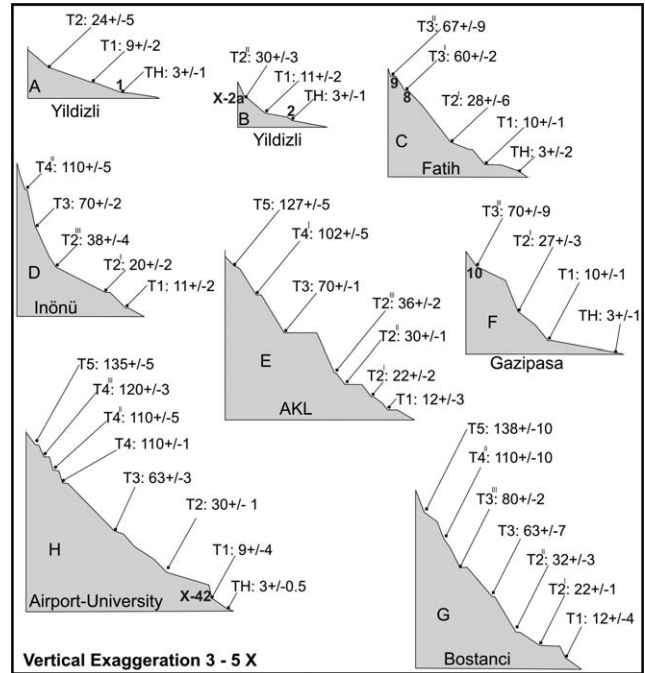


Figure 4. Altitudes of the marine terraces along the Trabzon, Turkey, coast. All altitudes are given as above mean sea level (amsl). See Figure 3 for the location of transect.

corresponding to the age of the MIS considered for the carving of the shoreline angle. In other word, dating of the marine terrace deposits allows discrete correlation to an interglacial stage, the latter being itself correlated to an MIS (see, e.g., Lajoie *et al.*, 1986).

The best-represented terrace worldwide is the one correlated to the Last Interglacial maximum (MIS 5e) (Hearty and Kindler, 1995; Johnson and Libbey, 1997; Pedita *et al.*, 2006a, 2006b, 2006c, 2008). The age of MIS 5e is astronomically fixed to range from 130 to 116 ka (Kukla *et al.*, 2002) but is demonstrated to range from 134 to 113 ka in Hawaii and the Barbados, with a peak from 128 to 116 ka on tectonically stable coastlines (Muhs, Simmons, and Steinke, 2002; Shackleton *et al.*, 2003). In our calculations, we used a mean of 123 ± 11 ka. Older marine terraces well represented in worldwide sequences are those related to MIS 9 (303–339 ka) and 11 (362–423 ka) (Imbrie *et al.*, 1984). For MIS 9 and 11, we used a value of 321 ± 18 ka and 400 ± 20 . Compilations show that the sea level was 3 ± 3 m higher during mean isotope substage (MISS) 5e, MIS 9, and MIS 11 than at present and -1 ± 1 m, compared to the present level, during MIS 7 (Hearty and Kindler, 1995; Zazo, 1999). Consequently, MIS 7 (180–240 ka) (Imbrie *et al.*, 1984) marine terraces are less pronounced and sometimes absent (Zazo, 1999). Because the elevations of these terraces are higher than the uncertainties in paleo-eustatic sea levels for the Holocene and Late Pleistocene, these uncertainties have no effect on the overall interpretation.

Field surveys and geological and geomorphological study of the marine terraces on the Trabzon coast (Figures 3, 4, and 5)

were carried out between 2004 and 2008. The marine terraces were named TH for the Holocene terrace and T1, T2, T3, T4, T5, and T6 (from lowest to highest) (Figures 3, 4, and 6) for the Pleistocene terraces. Elevations of the shoreline angle of the marine terraces were determined using a Global Positioning System (GPS), altimeter measurements, and ArcGIS software. All altitudes are given in meters above mean sea level (amsl) with an associated margin of error, which depends mainly on shoreline preservation. The vertical and horizontal distribution of the highest terraces and the associated deposits are not always well identified in the field or on aerial photographs. Consequently, in some cases, Geographic Information System (GIS) mapping was used to determine the distribution and elevation of marine terraces (Figures 3 and 4). Mollusk shell samples, mainly bivalves and gastropods fragments, were collected from deposits in TH, T1, T2, and T3 marine terraces for dating. As noted before, all the fauna identified are characteristics of saline water. The fauna is present as fragments, with the exception of T2 and T3 deposits, where we found *Chione* sp. (T2) and *Mytilus* sp. and *Ostrea* sp. (T3).

ESR Dating

During the past 20 y, the ESR method has improved considerably in dating littoral deposits (coral reefs, barrier beach systems, and aeolianites) (Jonas, 1997). The ESR ages of Quaternary mollusk shells not only enable the chronological differentiation of the MIS 1, 5, 7, 9, 11 but also, sometimes, the substages of the main interglacials MIS 5a, 5c, 5e, 9, and 11

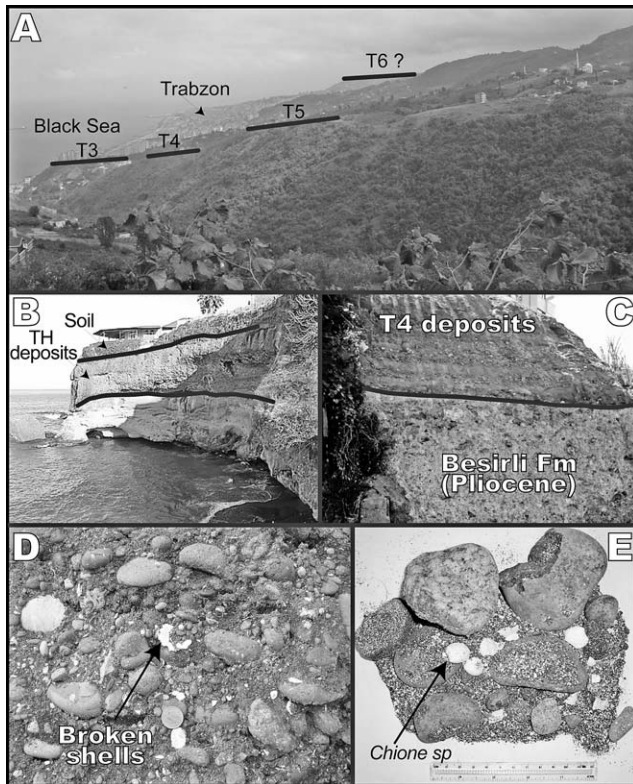


Figure 5. Illustration of the marine terraces on the Trabzon, Turkey, coast. (A) Interpreted panorama. Photo taken west of Trabzon city. (B) Detail of the Holocene terrace in Ganita. (C) Marine terrace T4 deposits overlying the Pliocene Besirli formation in Erdogdu. (D) Details of the *in situ* Holocene marine deposits on the TH terrace in the Yildizli area. Note the typical marine terrace deposits consisting of boulders and broken shells in a sandy matrix. (E) Details of the T2 terrace deposits as studied in the laboratory.

(Schellmann and Radtke, 2000; 2004) (Table 1). The temporal resolution of ESR dating on mollusk shells is within a mean age error of 10–15% or less (Schellmann *et al.*, 2004). To calculate the ESR age of mollusk shells, two parameters are needed: the equivalent dose and the total dose or annual dose rate (Tables 2 and 3). The equivalent dose is calibrated by construction of so-called growth curves. The total dose combines the cosmic dose rate and the β and γ doses from the potassium (K), thorium (Th), and uranium (U) concentrations in the sediment and the α , β , and γ doses from the U concentrations in the mollusk shells. All ESR measurements were carried out at the Geography Department, University of Cologne, and performed with a Bruker 400 ESP spectrometer, using the multiple aliquot additive method for the equivalent dose determination (see Tables 2 and 3). The radionuclide content of K, Th, and U was determined by inductively coupled plasma mass spectroscopy (ICP-MS) to calculate the annual dose rate. Equivalent doses were calculated using the FITSIM software program, and all ESR ages calculated by DATA 7 program. The ESR age is calculated dividing the equivalent dose rate by the total dose rate (Table 1).

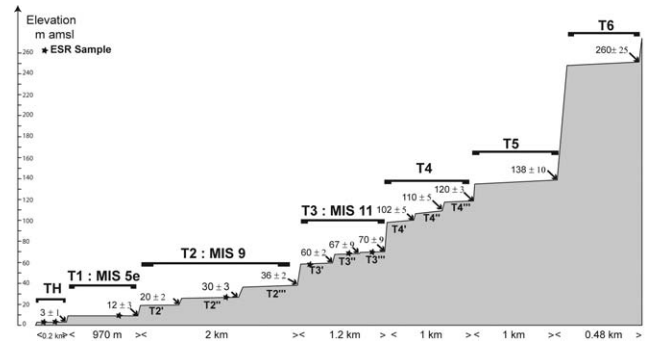


Figure 6. Synthetic marine terrace sequence of the Trabzon, Turkey, area.

RESULTS

Marine Terrace Sequence of the Trabzon Region

A well-developed marine terrace sequence in the Trabzon region has been studied in detail. The sequence has seven main terraces, but they are frequently compound: two or three “second-order” terraces, separated by small, intermediate shoreline angles. In total, there are as many as 13 terraces, including the second-order ones (Figures 3, 4, and 6). The sequence can be described as two narrow, low-lying terraces (TH and T1) overlooked by higher compound levels (T2, T3, T4, T5, and T6) (Figure 6). Although the highest terraces (T4, T5, and T6) are distinguishable in the study area (in Bahcecik, Erdogdu, Yenicuma, and Boztepe sectors) (Figures 3 and 4), they have been strongly affected by (1) fluvial processes, (2) pedogenetization, and (3) anthropization (mainly farming).

In the Trabzon area, marine terrace deposits are composed of less than 2 m of sand, clay, pebbles, blocks, and boulders, mostly composed of sedimentary and volcanic rocks (andesite and basalt) from the substratum (the Pliocene Besirli Formation and Eocene–Neogene Kabaköy Formation). These deposits contain common fossil bivalves and gastropods, whole or broken. They are overlaid by brownish–dark brownish soil. Deposits are very similar from one terrace to another.

The TH terrace is well observed in the Yildizli and Ganita district (Figures 3A, 3B, 3D, 4, 5B, and 5D). It is present along an ~3-km stretch of coast between Yildizli and Akyazi and ~2 km between the towns of Trabzon and Kemer kaya. In this zone, the marine terrace is ~0.2 km wide, and its shoreline angle is present at an altitude of 3 ± 1 m (Figure 6). In two outcrops located on the Yildizli point, we sampled fossil seashells for ESR dating (samples 1 and 2 in Figure 3B, laboratory numbers K-5339 and K-5341). A general view of the TH in Ganita is provided in Figure 5B, and an example of an *in situ* deposit of TH is provided in Figure 5D.

The T1 terrace is clearly recognizable and observable in the Yildizli, Yali, and Bostanci areas and in the area of the Trabzon Airport (Figures 3A–E and 4). The T1 is present along a 6-km stretch of coast between Yildizli and Besirli and along a 4-km stretch of coast between the city center and the airport. Its shoreline angle is present at a maximum altitude of 12 ± 3 m amsl (Figure 6), and the terrace is nearly 1 km wide. In an

Table 1. Chronostratigraphical interpretation of the dated marine terraces in the Trabzon, Turkey, area.

| Location | Sample | Latitude | Longitude | Elevation (m) | ESR age (ka) | MIS or MISS assigned to the terrace |
|----------------|--------|----------------|----------------|---------------|------------------|-------------------------------------|
| Fatih | 8 | 39°42'19.20" N | 41°0'3.22" E | 60 ± 2 | 407.998 ± 67.475 | 11 |
| Fatih | 9 | 39°42'20.20" N | 40°59'58.67" E | 67 ± 9 | 416.150 ± 92.669 | 11 |
| Gazipasa | 10 | 39°43'41.57" N | 41°0'12.02" E | 70 ± 9 | 395.099 ± 30.830 | 11 |
| Yildizli | X-2a | 39°37'15.65" N | 41°0'30.65" E | 30 ± 3 | 292.5 ± 49.8 | 9 |
| KTÜ Sahil Tes. | X-42 | 39°46'39.48" N | 41°0'3.81" E | 12 ± 3 | 124.8 ± 26.0 | 5e |
| Yildizli-DSİ | 2 | 39°37'33.58" N | 41°0'26.84" E | 3 ± 1 | 5.141 ± 294 | 1 |
| Yildizli-DSİ | 1 | 39°37'31.59" N | 41°0'26.00" E | 3 ± 1 | 5.008 ± 533 | 1 |

Abbreviations: MIS = marine isotope stage, MISS = marine isotope substage, ESR = Electron Spin Resonance, KTÜ = Karadeniz Technical University, Tes.

outcrop located near the airport, we sampled some fossils seashells for ESR dating (sample X-42 in Figure 3E, laboratory number K-5312 in Table 2).

The T2 terrace is best observed in Yildizli, Degirmendere, the Trabzon Airport area, İnönü, Fatih, and around the Trabzon Stadium. The T2 is present along a 7-km-long stretch of coast between Trabzon and Toklu and also along a 4-km stretch of coast between the Trabzon Airport and the city center (Figures 3A–E and 4). This terrace is generally ~2 km wide. The T2 is a compound terrace that includes three second-order terrace: T2', T2'', and T2''' (Figure 6). From GIS data (Figures 3 and 6), we calculated that the shoreline angles of T2', T2'', and T2''' are, respectively, at 20 ± 2 , 30 ± 3 , and 36 ± 2 m, and we consider the highest shoreline angle (36 ± 2 m) as characteristic of the T2 marine terrace. In an outcrop located on the Yildizli point, we sampled fossils seashells for ESR dating (sample X-2a in Figure 3A, laboratory number K-5311 in Table 2) and recognized bivalves, such as *Chione* sp. (for an example of the T2 deposits, see Figure 5E).

The T3 terrace is well observed in Yenicuma, Ayasofya, Fatih, İnönü, Gazipasa, AKL, and Degirmendere sectors (Figures 3A and C–E). The terrace is present along a 5-km stretch of coast between Toklu and Cömlekci and along a 4-km stretch of coast between Trabzon Airport and Degirmendere. Similar to T2, T3 is a compound terrace that includes at least three second-order marine terraces: T3', T3'', and T3'''. The T3', T3'', and T3''' terraces were calculated to be at altitudes of 60 ± 2 , 67 ± 9 , and 70 ± 9 m, respectively, by GIS and field measurements (Figure 6). In section F, the T3''' shoreline angle was measured at the maximum altitude of 80 ± 2 m amsl (Figure 4). In three outcrops, two near Fatih and one near Gazipasa, we sampled some fossil seashells for ESR dating (samples 8–10 in Figures 3C and D, laboratory numbers K-5335, K-5336, and K-5347 in Table 3).

The T4 terrace is well observed in Bahcecik, Besirli, Yenicuma, and Erdogdu (Figures 3A, C, and E). It is present along an 8-km stretch of coast between Besirli and the Karadeniz Technical University campus. In this zone, the T4 is 1 km wide. Similar to T2 and T3, T4 is a compound terrace that includes at least three second-order marine terraces: T4', T4'', and T4''' (Figure 6). The shoreline angle of T4' is present at 102 ± 5 m in section H. The shoreline angles of T4'' and T4''' were found, respectively, to be at 110 ± 5 m and 120 ± 3 m in section H (Figures 4 and 6). A photograph of the T4 deposits (Figure 5C) shows it to be lying uncomfortably on the Besirli Formation.

The T5 terrace is well observed in the Bostanci, AKL, and Bahcecik districts (Figures 3A, C, and E). It is present along a 5-km stretch of coast between the Bahcecik and Bostanci districts, where it is ~1 km wide. The shoreline angle of the T5 has been measured at 127 ± 5 m amsl in section E. Based on GIS analysis, the shoreline angle of the T5 is present at 138 ± 10 m in section G and at 135 ± 5 m amsl in section H (Figure 4).

The T6 terrace is clearly observed in Boztepe, Bostanci, Bahcecik, and Cezaevi districts (Figures 3A, C, D, and E). It is present along a 6-km stretch of coast between Bahcecik and Bostanci. Based on GIS analysis and field survey, the shoreline angle of the T6 is present at an altitude of 260 ± 25 m (Figure 6).

Dating and Chronostratigraphical Interpretation

Fossil bivalves and gastropod were collected from the deposits of TH, T1, T2, and T3 to obtain geochronological measurements through the ESR method. Two samples collected in the TH deposits in the Yildizli area gave corrected ESR ages of 5.008 ± 0.533 ka and 5.141 ± 0.294 ka (Figure 3B; Table 3). Consequently, we correlated TH to the Holocene (MIS

Table 2. Dosimetric parameters and Electron Spin Resonance (ESR) ages obtained from marine shells.

| Laboratory No. | Sample No. | K (ext) (%) ¹ | Th (ext) (ppm) ¹ | U (ext) (ppm) ¹ | U (int) (ppm) ¹ | Water Content (%) | Depth (m) | Total Dose Rate ^{2,3} | | |
|----------------|------------|--------------------------|-----------------------------|----------------------------|----------------------------|-------------------|-----------|--------------------------------|---------------------|---------------------------|
| | | | | | | | | Gy/ka | D _e (Gy) | ESR Age ⁴ (ka) |
| K-5312 | X-42 | 0.63 | 2.57 | 2.41 | 1.48 | 15 ± 10 | 4.5 ± 1 | 0.977 ± 0.08 | 121.9 ± 23.2 | 124.8 ± 26.0 |
| K-5311 | X-2a | 0.74 | 4.55 | 1.4 | 1.43 | 10 ± 5 | 0.2 ± 0.1 | 1.230 ± 0.08 | 359.9 ± 56.7 | 292.5 ± 49.8 |

¹Uncertainties on ICP-MS analyses of U, Th, and K are taken to be ±1%.

²The total dose combines the cosmic dose rate; the β and γ doses from the K, Th, and U concentrations in the sediment; and the α, β, and γ doses from the U concentrations in the shells. Sample thickness was 4–5 mm, the thickness removed was 0.4–1 mm (age calculation with β-attenuation).

³D_e = equivalent dose (calculated via the program FIT-SIM [R. Grün]).

⁴Ages were calculated via the program DATA 7 (R. Grün).

Table 3. *Dosimetric parameters and Electron Spin Resonance (ESR) ages obtained from marine shells.*

| Laboratory No. | Sample No. | Th (ppm) ¹ | U (ppm) ¹ | K (%) ¹ | Thickness (mm) | Water content (%) | Depth (m) | D _e ² (Gy) | ESR Age ³ (ka) |
|----------------|------------|-----------------------|----------------------|--------------------|------------------|-------------------|-----------|----------------------------------|---------------------------|
| K-5335 | 8 | 5.68 | 1.06 | 0.63 | 1.28/0.84 (0.44) | 7 | 10 | 463.51 ± 69.91 | 407.998 ± 67.475 |
| K-5336 | 9 | 2.72 | 0.76 | 0.45 | 1.46/1.15 (0.31) | 4 | 0.3 | 463.51 ± 69.91 | 416.150 ± 92.669 |
| K-5337 | 10 | 2.93 | 0.72 | 0.68 | 1.26/1.10 (0.16) | 8 | 0.25 | 379.72 ± 12.49 | 395.099 ± 30.830 |
| K-5339 | 1 | 3.77 | 0.83 | 1.33 | 1.20/0.96 (0.24) | 12.59 | 8–8.5 | 5.02 ± 0.47 | 5.008 ± 533 |
| K-5341 | 2 | 3.93 | 0.83 | 1.33 | 1.18/1.02 (0.16) | 8.92 | 9 | 5.35 ± 0.16 | 5.141 ± 294 |

¹Uncertainties on ICP-MS analyses of U, Th, and K are taken to be ±1%.

²D_e = equivalent dose (calculated *via* the program FIT-SIM [R. Grün]).

³Ages were calculated *via* the program DATA 7 [R. Grün].

1) (Table 1). Sample X-2a, taken from the T1 deposits, gave an ESR age of 124.8 ± 26.0 ka (Figure 3B; Table 2). Consequently, we propose to correlate this well-preserved marine terrace to the Last Interglacial maximum (MISS 5e, 123 ± 11 ka) (Table 1). Sample X-42, collected from T2' deposits in the university area (Figure 3E), gave an ESR age of about 292.5 ± 49.8 ka (Table 2). This result leads us to propose a correlation of the upper shoreline of T2 with MIS 9 (303–339 ka) (Table 1). Samples 8, 9, and 11, taken from T3', T3'', and T3''' deposits, yielded ESR ages of 395.099 ± 30.830 ka, 407.998 ± 67.475 ka, and 416.150 ± 92.669 ka, respectively. Consequently, we propose to correlate the highest T3 shoreline angle with MIS 11 (362–423 ka) and probably with an early substage of this complex interglacial period.

DISCUSSION

Uplift Rates and Extrapolation

Because the maximum rise in the Black Sea (3–5 m above current level) took place 3.5–4 ka ago, during the Subboreal, and given the present elevation of the TH, we did not calculate the uplift rate for this period. In other words, the elevation of the TH can be explained by eustatic variation alone.

The uplift rate for each dated Pleistocene shoreline was calculated using parameters shown in Table 4. The T1, T2, and T3 altitudes and age lead us to determine uplift rates of 0.07 ± 0.05 , 0.10 ± 0.02 , and 0.17 ± 0.03 mm/y or m/ka for MIS 5e, 7, and 9, respectively (Table 4, Figure 7). The low elevation of the terraces, the uncertainties about the duration, and the eustatic sea level of Last Interglacials (Siddall *et al.*, 2006) create a notable margin of error, particularly for the T1 terrace (Table 4). Nevertheless, mean value reflects the sequence morphostratigraphy, *i.e.*, two low, well-preserved terraces below higher, compound levels (T2, T3, T4, T5, and T6). Therefore, the variation in the mean uplift rate can be considered representative of the evolution of the deformation. A slight decrease was observed. Relationships were observed

between marine terrace development and nonsteady, long-term uplift rates, more drastically in Futuna (Neef and McCulloch, 2003), and, more recently, in Chile (Saillard *et al.*, 2009). Generally these variations are interpreted as pulses of tectonic activity.

Nevertheless, to have an approximation of the duration of the uplift, we extrapolated the T3 uplift rates, the oldest uplift, to propose “ages” for the oldest terraces (T4, T5, and T6). As stated in a recent synthesis (Siddall *et al.*, 2006), we consider eustatic sea levels older than MIS 11 to be similar to those present now. This means that the actual altitude of the shoreline corresponds roughly to its displacement (Figure 7). Following that idea, the highest shoreline angles of the three upper marine terraces were carved during the following time intervals: 680–910 ka (T4), 750 ka to ~1.1 Ma (T5), and 1.4–2.1 Ma (T6). As a preliminary result, we propose that the entire marine terrace sequence in the Trabzon region is from the Quaternary period.

Given that finding, the observed uplift has been rather slow in comparison to other orogenic belts: in the Caucasus (see below and Table 5) or in Morocco, on the sea side of the Atlas range (Meghraoui *et al.*, 1998). In Morocco, north of Agadir, the MIS 5e terrace is found at elevations ranging from 18 to 28 ± 1 m amsl. Following the calculation we used for the Eastern Black Sea, we calculate a maximum uplift rate of 0.20 ± 0.05 mm/y or m/ka.

Origin of the Uplift

The marine terrace in Trabzon reveals a rather slow, Quaternary uplift of the southeastern Black Sea shore. From our point of view, these deformations have to be related to the Pontides orogenesis. More precisely, in the studied area, three distinctive lineaments, trending NE–SW, NW–SE, and E–W (Figure 2A), are present and are probably responsible for the uplift of the marine terrace sequence. At this stage, it must be pointed out that these faults are not directly observed in the

Table 4. *Measured shoreline angles and calculated uplift rates for marine terraces T1, T2, and T3.*

| Terrace | MIS | E (m) | | A (ka) | | e (m) | | D (m) | | U (mm/y, m/ka) | |
|---------|-----|-------|-----|--------|-----|-------|-----|-------|-----|----------------|------|
| | | E | MoE | A | MoE | e | MoE | D | MoE | U | MoE |
| T1 | 5e | 12 | 3 | 123 | 11 | 3 | 3 | 9 | 6 | 0.07 | 0.05 |
| T2 | 9 | 36 | 2 | 321 | 18 | 3 | 3 | 33 | 5 | 0.1 | 0.02 |
| T3 | 11 | 70 | 9 | 400 | 20 | 3 | 3 | 67 | 12 | 0.17 | 0.03 |

Abbreviations: MIS = marine isotope stage, MoE = margin of error.

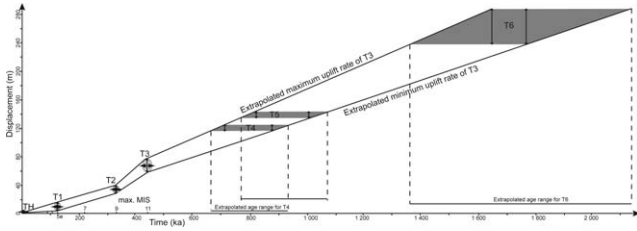


Figure 7. Graphic representation of the uplift rates deduced from the marine terraces along the Trabzon, Turkey, coast.

field because of urbanization and vegetation, but they are seen on aerial photos and geomorphological maps. We suggest that the marine terrace of Trabzon reveals the vertical motion rates of active faults and, more particularly, of the northern fault; however, at this stage in our knowledge, we can not exclude the possibility that the uplift is caused by local compression associated with a restraining bend in the eastern segment of the North Anatolian Fault. To improve upon our hypothesis, other geomorphic markers need to be studied directly to the south of our study area. In a broad sense, we propose that the primary cause of the uplift is the local compression associated with the convergence of the African–Arabian plates with the Eurasian plate. The variation in the uplift rates may be a consequence of tectonic pulses during the ongoing Eastern Pontides orogenesis.

Comparison with Other Marine Terrace Sequence along the Eastern Black Sea Shore

Other studies of marine terraces have been conducted along the Eastern Black Sea coast (Figures 1 and 8). Marine terrace sequences have been studied in Russia and in the Ukraine (Nesmeyanov, 1995; Papin and Popescu, 2007; Zubakov, 1988), where the deformations are related to the Caucasus orogenesis. On the Black Sea shore of Turkey, a sequence was briefly described on the western part of the Sinop Peninsula, where it is related to the Central Pontides orogenesis (Figures 1 and 8) (Ertek and Aytaç, 2001).

To compare the deformation rates of these different zones, we propose to calculate the homogeneous uplift rates deduced from the marine terrace correlated to the Last Interglacial maximum. Consequently, we use the same values for e and A (see the equation in the “Methods” section). In other words, we propose to establish the Eemian (or Karangatian) marine terrace as tectonical benchmark, as has already been done in Italy (Antonioli *et al.*, 2006; Bordini and Valensise, 1998). In this synthesis, we excluded data from the Marmara Sea (Yaltırak *et al.*, 2002) that corresponds to a different geodynamical context. In fact, this zone has complicated, active tectonics, influenced by the escape of the Anatolian block, the northward motion of the African plate, and the Aegean extension, leading to a global extensional regime (*e.g.*, Tari *et al.*, 2000).

The results of these calculations are presented in Figure 8 and Table 5. Around the Eastern Black Sea, altitudes of MIS 5e

shoreline angles range from 6 ± 2 mm/a to 48 ± 3 mm/a in the Taman Peninsula and the Tuapse Loo area, respectively (Table 5). Consequently, uplift rates deduced from the elevation of the MIS 5e terrace range from 0.02 ± 0.04 mm/a to 0.37 ± 0.08 mm/a (Figure 8; Table 5). The most striking result is that the Trabzon marine terrace sequence reveals one of the weakest uplifts of the Eastern Black Sea shore (0.07 ± 0.06 mm/a for MIS 5e). At a regional scale, the highest coastal uplift rates are found on the coasts bordering the Greater Caucasus and the Central Pontides (Sinop Peninsula). The greatest variability is observed on the coasts bordering the Greater Caucasus, where the marine terrace sequence is defined by arching (Nesmeyanov, 1995). This fact should be interpreted as the difference in the intensity of orogenesis between the Greater Caucasus and the Eastern Pontides. No marine terrace sequences have been described, to our knowledge, in the Lower Caucasus (*e.g.*, near Batumi in Figure 1), and data are lacking in Abkhazia (Figures 1 and 8). In other words, studies of the Quaternary coastal uplift of the Eastern Black Sea are still in the preliminary stages, and more work has to be done (by us or other geologists) to complete the puzzle and to provide a coherent, regional interpretation.

CONCLUSION

- (1) A Pleistocene marine terrace sequence borders the Eastern Black Sea in the vicinity of Trabzon, Turkey, at elevations ranging from 3 ± 1 m up to 260 ± 25 m. The ESR dates on *in situ* shells extracted from shallow marine deposits at key localities show that these sediments accumulated between MIS 11 and the Holocene, with the best-developed successions occurring during the interglacial oxygen isotopic stages 11, 9, 5e, and 1. Older terraces are present and have extrapolated ages corresponding to the Early Pleistocene (2 Ma).
- (2) The ages of the raised terraces and shoreline deposits document that the southeastern Black Sea shore, north of Northeast Anatolian Fault Zone, has been experiencing maximal regional uplift of 0.017 ± 0.03 mm/y or m/ka. We propose that this local uplift owes its origin to the Pontides orogenesis as a consequence of the convergence of the African–Arabian plate with the Eurasian plate.
- (3) Comparison of the uplift rates in the Trabzon area with other places around the Black Sea shows that the vertical reaction of this portion of coast is quite limited. The Caucasus orogenesis seems to have had more of an effect on the Quaternary coastal deformation than on the Pontides orogenesis.
- (4) The Quaternary shoreline displacements around the Black Sea in general, and eastern Turkey in particular, are still poorly known. New ESR data allow us to revise and reinterpret, in one place, the literature on this topic, taking into account only those markers that allow precise estimates of the altitude and age of the sea-level highstands. Several sequences of Quaternary marine terrace, with associated deposits, can be observed along the Black Sea coast of Turkey and need further attention to refine our knowledge of the Pontides orogenesis in

Table 5. Synthesis on MIS 5e terraces along the Eastern Black Sea coast.

| No. | Country | Latitude | | Longitude | | Name | No. of Sequences Described | Length of Coastal Stretch (km) | Min. Dimension of the Sequences (km) | Max. No. of Palaeoshoreline | Max. Altitude of Sequence | Max. Altitude of MIS 5e with MoE (m amsl) | Chronostratigraphy | Uplift Rates | | Dating Method | Dating performed on | Reference |
|-----|---------|----------------|----------------|----------------|----------------|------------------|----------------------------|--------------------------------|--------------------------------------|-----------------------------|---------------------------|---|------------------------------|--------------|------|---------------|---------------------|--------------------------------------|
| | | 1 | 2 | 1 | 2 | | | | | | | | | Rate | MoE | | | |
| 1 | Ukraine | 44°28'0.00" N | 44°28'0.00" N | 34°7'0.00" E | 34°7'0.00" E | Crimea | 1 | 30 | ng | 4 | 10 | 10 | Holocene, MIS 5e | 0.06 | 0.05 | * | * | Panin & Popescu, 2007 |
| 2 | Russia | 45°22'0.00" N | 45°22'0.00" N | 36°28'0.00" E | 36°28'0.00" E | Kerch | 3 | 30 | ng | 4 | 16 | 10 | Holocene, MIS 5e | 0.06 | 0.05 | U/Th | Shells | Panin & Popescu, 2007; Zabakov, 1988 |
| 3 | Russia | 45°10'52.89" N | 45°10'52.89" N | 36°38'51.74" E | 36°38'51.74" E | Taman | 3 | 58 | ng | 4 | 16 | 6 | Holocene, MIS 5e | 0.02 | 0.04 | U/Th | Shells | Panin & Popescu, 2007; Zabakov, 1988 |
| 4 | Russia | 44°53'28.23" N | 44°30'3.48" N | 37°19'29.04" E | 38°7'33.69" E | Anapa-Gelendzhik | 5 | 91 | ng | 7 | 175 | 25 | MIS 5e and lower Pleistocene | 0.18 | 0.08 | Fauna | shells | Nesmeyanov, 1995 |
| 5 | Russia | 44°22'46.38" N | 44°22'46.38" N | 38°22'53.13" E | 38°22'53.13" E | Pshadsk | 6 | 28 | ng | 7 | 175 | 22 | MIS 5e and lower Pleistocene | 0.15 | 0.06 | Fauna | shells | Nesmeyanov, 1995 |
| 6 | Russia | 44°18'49.45" N | 44°18'49.45" N | 38°42'1.10" E | 38°42'1.10" E | Dzhulgga | 8 | 30 | ng | 6 | 210 | 30 | MIS 5e and lower Pleistocene | 0.22 | 0.09 | Fauna | shells | Nesmeyanov, 1995 |
| 7 | Russia | 44°0'3.91" N | 44°0'3.91" N | 39°11'22.13" E | 39°11'22.13" E | Tuapse-Loo | 1 | 60 | 3 × 1.2 | 6 | 135 ± 10 | 48 | MIS 5e and lower Pleistocene | 0.37 | 0.08 | Fauna | shells | Nesmeyanov, 1995 |
| 8 | Russia | 43°35'53.94" N | 43°35'53.94" N | 39°42'59.43" E | 39°42'59.43" E | Sochi | 7 | 11 | ng | 9 | 120 | 27.5 | MIS 5e and lower Pleistocene | 0.20 | 0.06 | Fauna | shells | Nesmeyanov, 1995 |
| 9 | Russia | 43°25'31.16" N | 43°25'31.16" N | 39°55'15.80" E | 39°55'15.80" E | Adler | 6 | 10 | ng | 3 | 120 | 20 | MIS 5e and lower Pleistocene | 0.14 | 0.08 | Fauna | shells | Nesmeyanov, 1995 |
| 10 | Turkey | 41°0'21.62" N | 41°0'0.48" N | 39°37'52.88" E | 39°46'10.31" E | Trabzon | 1 | 12 | 5 × 3 | 7 | 260 ± 25 | 12 | Holocene, MIS 5e, 9, 11 | 0.07 | 0.06 | ESR | Shells | This study |
| 11 | Turkey | 42°5'24.48" N | 42°5'24.48" N | 34°57'4.40" E | 34°57'4.40" E | Sinop West | 1 | ng | ng | ng | 40 | 40 | MIS 5e | 0.30 | 0.09 | * | * | Ereke & Aytaç, 2001 |

Abbreviations: MIS = marine isotope stage, No. = number, MoE = margin of error, Min. = minimum, Max. = maximum.

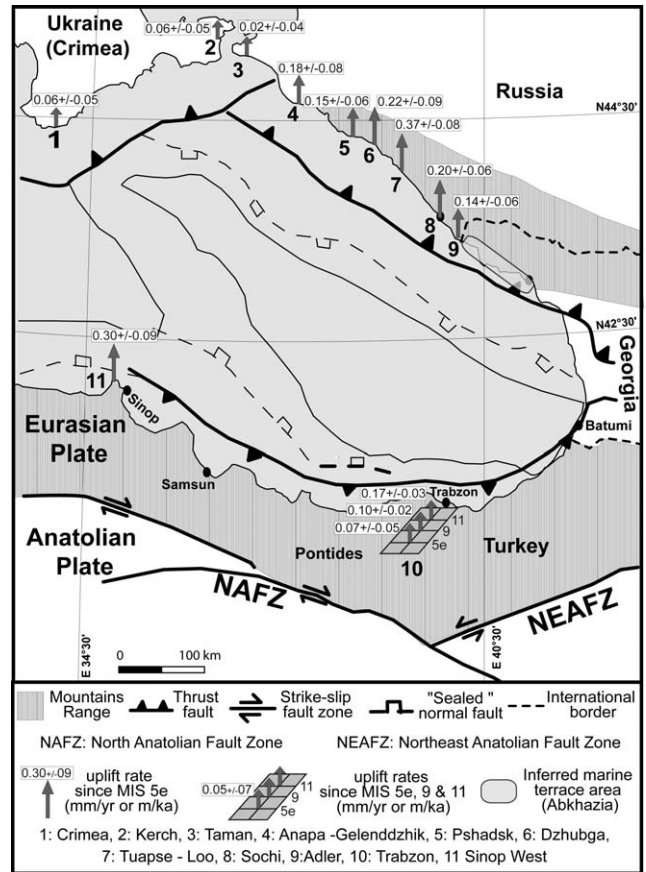


Figure 8. Structural framework and coastal uplift along the Eastern Black Sea Coast.

particular, and the Quaternary coastal deformation in general.

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