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Late Cenozoic polyphase deformation and basin development, Kütahya region, western Turkey

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The Neogene–Quaternary succession in the Kütahya region is of importance in the neotectonic evolution of western Anatolia because the strata contain clear evidence of compression and extension. During the early-middle Miocene, N–S compression/transpression as well as NE–SW- and NW–SE-oriented oblique conjugate faults formed. NE–SW-oriented horsts and grabens developed, controlled by the dominant NE–SW faults. The Seyitömer and Sabuncupınar grabens were filled primarily by terrestrial clastic sedimentary and volcanic rocks. At the end of the middle Miocene, the graben fill was locally folded and reverse faulted, reflecting reactivation of compression. Between the late Miocene and the middle Pliocene, the region underwent erosion and lacustrine sediments accumulated in topographic lows. Between the middle and late Pliocene, compression in the region was again reactivated and basal units were thrust over the pre-upper Pliocene units. The late Plio-Quaternary marked the onset of N–S extension and development of the NW–SE-oriented Kütahya Graben, co-genetic equivalents of which are common throughout western Anatolia. This study indicates that tectonic evolution of western Anatolia involved multiple stages of contraction and extension.

Keywords: late Cenozoic compression; extension; transpression; graben; oblique faulting; reverse faulting; western Anatolia

Introduction

Western Anatolia underwent N–S extension during the Plio-Quaternary period. Although interplay of the late Cenozoic compression/extension has been reported for the region, the evidence of this transition has not been quantified. It was previously proposed that the region has been undergoing (1) continuous N–S extension beginning in the late Miocene to the present day (McKenzie 1972; Şengör and Yılmaz 1981; Şengör 1987), (2) continuous N–S extension beginning in the late Oligocene to the present day (Seyitoğlu and Scott 1991; Seyitoğlu et al. 1992, 2004; Işık et al. 2003), (3) N–S extension interrupted by a period of compression or quiescence beginning in the Miocene (Koçyiğit et al. 1999; Bozkurt 2001; Bozkurt and Sözbilir 2004; Purvis and Robertson 2004; Beccaletto and Steiner 2005; Bozkurt and Rojay 2005; Çiftçi and Bozkurt 2009; Ersoy et al. 2010), or (4) late Oligocene–Miocene N–S compression followed by Plio-Quaternary N–S extension (Sarıca 2000; Yılmaz et al. 2000; Gürer et al. 2001, 2003, 2006, 2009; Gürer and Yılmaz 2002; Gürer et al. 2002, 2004; Ring et al. 2003; Koçyiğit 2005; Kaymakçı 2006; Hasözbek et al. 2010; Gürbüz et al. 2012).

In this article, we focus on the Kütahya region, located in the western part of the Anatolian Peninsula, to better describe the compression/extension transition, because this region hosts large Neogene–Quaternary outcrops, folding and thrust faults, and horst and graben systems (Figures 1 and 2).

Specifically, we focused on determining the (1) provenances of the basin fills, (2) fault kinematics of the basin development, (3) parameters that controlled the initiation of the basins, (4) tectonic regime(s) that control(s) the evolution of the basins, and (5) relationships among the basins. In order to find answers to these questions, we conducted a 2-year field work study between 2007 and 2009, during which detailed geological mapping of an area of 13 quadrangle sheets was generated and new stratigraphic and structural data were developed. In Figure 2, a simplified geological map of our work shows the major late Tertiary–Quaternary units in relation to the structural setting of the Kütahya region.

During Neogene–Quaternary time, different tectonic processes produced a network of fault systems and several basins filled with terrestrial sediments. This fault network is dominated by NE and NW orientations (Figure 2). A detailed analysis for mesoscale fault geometry and kinematics was conducted to determine the deformation history of the Plio-Quaternary Kütahya basin.
**Geological setting**

The Kütahya region is an area where continental and oceanic basement rocks, young magmatic rocks, and sedimentary rocks are observed together (Figure 3). All these rocks can mainly be classified into two groups: basement rocks and cover rocks.

**Basement rocks**

In Kütahya and its surrounding area, two different rock groups exist in the basement. They are schist and marble groups, representing the continental rocks, and green-schist and blueschist metamorphites, representing the oceanic rocks.

Being a product of the low-grade regional metamorphism, these schist and marble groups represent the passive continental margin of the Toride-Anatolide platform facing the north and are called the Afyon Zone (Okay 1984). Typically reflecting a shelf environment, these rocks consist of metasandstone, metaquartzite, metabasite, and marble, which are 1500 m thick and developed across the green-schist facies as a result of metamorphism. Derived from the İzmir-Ankara Suture in the north and thrusted onto the rocks of the Afyon Zone in the south, serpentinized peridotite and ophiolite-greenschist rocks were defined as the Tavşanlı Zone (Okay 1981). Detailed descriptions of the basement units are beyond the scope of this article.

**Cover rocks**

**Beke Formation**

This unit is exposed across the northwest section of the study area. At the bottom, it starts with red, brown, yellowish, and grey-coloured block and gravel-sized rough clasts with weak sorting. The gravels are weakly to moderately rounded. Grains are mostly derived from ophiolitic rocks at the base of the succession and from different origins of rocks, such as schist, quartzite, marble, and granitoid, up to the middle levels. Up to the upper level, the succession typically continues with sandstone, mudstone,
and marl intercalation. Sandstone is generally observed in brown, yellowish, and grey colours and is moderate to well sorted. Unconformably, the Beke Formation overlies the Tavşanlı Zone basement rocks at the base and it rests conformably on the Tunçbilek Formation. The thickness of the unit is 75–150 m. Geometric, lithologic, and structural properties of the succession reflect the sedimentation across the alluvial fan and high-energy fluvial environment.

In previous studies, the age of the unit was presented as the lower Miocene (Şengüler 1999), the middle Miocene (Baş 1983), and the middle to late Miocene (Kaya 2009). The lower Miocene age was considered to be appropriate in this study due to its stratigraphic position.

Tunçbilek Formation

The unit mainly consists of pebblestone, sandstone, siltstone, marl, mudstone, rarely tuff, and limestone intercalated with coal seams. The pebblestone comprises middle to well-rounded polygenic grains with weak sorting. The sandstone and siltstone layers are of a yellowish-reddish colour, well consolidated, and thin to medium bedded. The mudstone levels are initially replaced by marl and then further up with limestone due to the increase in the carbonate ratio. The succession develops symmetric and asymmetric ripple marks, scour-and-fill structures, and load moulds. The uppermost levels of the Tunçbilek Formation consist of pebbles and sand containing limestone and clayey limestone strata. Part of it is siliceous limestone, which is of a lower thickness (20 m) and spread. The maximum outcrop around Bozcahüyük is of limestone.

The unit spreads over a broad area across the Seyitömer Graben and its surroundings. Lignite beds exist in two different levels. The greenish-grey-coloured laminated marl located above the coal bed has a high bitumen content. The 5–30 m-thick bituminous marl layers in the Seyitömer region hold reserves of up to 480 million tons (Şengüler et al. 1982). The thickness of the lower coal bed across the Seyitömer lignite basin can reach up to 16 m and that of the upper coal bed up to 10 m. The Tunçbilek Formation is a transition above the Beke Formation at the base and shows angular unconformity with the Çokköy Formation at the top.

Particularly, the clay-, marl-, and coal-containing strata of the Tunçbilek Formation comprise spores and pollens, leaf traces, ostracoda fossils, and mammal fossils. In previous studies, the age of the unit was presented as the lower-middle Miocene (Yavuz et al. 1995; Yavuz 1999, 2001; Çelik et al. 2004a, 2004b; Yavuz-İşık 2007; Akkiraz et al. 2012), the middle-upper Miocene (Kaya 2009), and the upper Miocene (Arslan 1979; Baş 1983; Özcan 1986; Akyol and Akgün 1990; Çelik 1999). Kaya (1993) discovered a new mammal fauna in part of the lower coal bed of the Seyitömer lignite layers. Kaya (1993) defined Begetherium grimmi (Heissig 1976) and, for the first time in Turkey, Moropus elatus Marsh, and based on this fossil, proposed the end of the middle Miocene (late Astarician) as the age. Radiometric ages of the samples from the
Domaniç-Tunçbilek (Kütahya) region, outside the study area for volcanic rocks, which are intercalated with the upper layers of the succession (Baş 1983), suggest that the unit is of the lower-middle Miocene. Based on this data, the age of the formation is considered to be of the lower-middle Miocene.

Lithology of the unit reflects facies characteristics and a fossil containing a lacustrine environment. The fact that
some parts of the sediments are siliceous can be attributed to the effect of volcanism that took place simultaneously with the sedimentation.

Çayca Tuff
The unit dominantly consists of felsic pyroclastic rocks, mainly containing white and yellow coloured tuff, and includes sediment interbedded in thin levels across some strata. Being thick stratified and massive in some places, the unit is exposed in white and beige colours, easily discernible. It mostly comprises pumice tuffs (pumice fall) and lithic tuffs. Pumice fall tuffs are apparently stratified and mainly contain pumice and volcanic ash. Tuffs are white, yellowish, greyish, pinkish, and beige coloured. The unit hosts claystone and sandstone in some places, sporadic agglomerate levels, and intercalations comprising lapilli and pumice particles, whose thickness does not exceed a few metres (Arık and Temur 2003). Agglomerate, observed in beige and light grey colours, contains pyroclastics with a diameter up to 15 cm and pebbles and blocks derived from the basement rocks.

Outcropping over a considerably broad area between the Kütahya and Eskişehir provinces, the tuffs are primarily observed across the Sabuncupınar Graben within the study area. Across the Sabuncupınar Graben and the surrounding area, the tuffs rest nonconformably on the high-grade metamorphic rocks of the Tavşanlı Zone.

The unit is intercalated with the Tunçbilek Formation in the northwest of the Sabuncupınar Graben. The average thickness of the unit is 300 m.

In this region: Sickenberg et al. (1975) discovered the middle Miocene-aged Tragulidae; Heissig (1976), the middle Miocene-aged Begertherium grimmi fossils; Yalçınlar (1983), Alicornops simorrense fossils aged at the end of the middle Miocene; and Saraç (2003), again the middle Miocene-aged Tragulidae and Rhinoceritidae fossils. However, radiometric dating studies on the tuffs around Soğca, where the fossils were discovered, indicate the lower-middle Miocene (Besang et al. 1977). Based on these data, the age of the Çayca Tuff is considered to be of the lower Miocene to middle Miocene.

The Çayca Tuff indicates the beginning of widespread magmatic activity in the region. Accordingly, volcanic activities developed in two phases across the study area. The first formed the Çayca Tuff and the second the Kızılkaya volcanics.

Kızılkaya volcanics
Lava and pyroclastics mainly comprising andesite, basaltic andesite, and olivine basalt are typical with their reddish-brown, reddish-green, and blackish colours.

Lava is observed as a flow structure or dome above the tuffs at the base and above the sediments in some places. Lava is covered by sediment in some places where it is exposed around the Kütahya–Eskişehir roadway. The maximum thickness of the unit is 100 m. These volcanic rocks, outside the study area (Domaniç-Kütahya), cut the Tunçbilek Formation of the lower-middle Miocene age and cover the Çayca Tuff. At the point of contact of the lava and tuff, in some places there is a 10–15 cm-thick red- and brown-coloured baked zone. Across these levels, the lava has a blocked and pebbled appearance encircled with a tuff matrix. Up to the top is black-coloured, very vesicular basalt that contains more gas space than rock and has a very rough, irregular, and pocked exterior. Part of this unit is composed of pyroclastic levels. Generally having a latitic and andesitic composition, these levels are often, particularly in the upper levels, intercalated with pyroclastic fall deposition units originating from felsic volcanism. The upper levels of the pyroclastic fall deposition and flow units are composed of latitic, andesitic, and, less frequently, dacitic thin lava layers and intercalated flow breccias and lahars levels. The lahars levels comprise pebbles and blocks in a sediment or tuff matrix containing medium to coarse-sized, well-rounded, and spherical particles.

Sunder (1979) defined the lavas around Sarıkaya, located in the west of Kırka (Seytigazi, Eskişehir) and in the east of the study area, as quartz latite and phonolithic olivine tephrite. Sunder (1979) established the age of quartz lattes, which he stated originated from calc-alkaline-characterized volcanism, to be 19.6 million years and of the phonolithic olivine tephrites, which he stated originated from alkaline volcanism, to be 17.2 million years. Innocenti et al. (2005) defined the lava samples from around İğdekpınar, located at İlica junction on the Kütahya–Eskişehir roadway, as a product of calc-alkaline volcanism with basaltic andesitic composition and established the age of calc-alkaline volcanism to be 16–21 million years. Based on these studies, the age of the unit is considered to be of the lower-middle Miocene.

Lithologic and stratigraphic characteristics of the unit suggest that, during the early-middle Miocene period, volcanic activities existed in several phases across the region producing intermediate volcanic products and that there were lakes around these volcanic output centres. Across and at the near vicinity of the NW–SE- and NE–SW-oriented faults, on which the volcanic output centres are located, morphological irregularities developed and the topography is very disordered and irregular. In these regions, the lacustrine sediment environment disappeared. The lavas, lahar breccias, and pyroclastic fall-out deposits are arranged in decreasing order away from the volcanic axes.

Moving away from the volcanic centres, interrelated lake and stream environments maintained their existence and sediment development continued across these regions.
Çokköy Formation

The Çokköy Formation is widespread in the study area; the unit mainly comprises pebblestone, mudstone, marl, tuff, and limestone. It is the unit where boron sediments are observed in western Anatolia. The unit is dominantly characterized by grey, white, green, and brown colours and mostly includes pebblestone, sandstone, marl, and mudstone intercalations and tuff interbedded. Pebbles generally have a medium cemented, polygenic, and medium-well roundedness. At the base of the sequence, pebbles are angular. Gradation, tabular cross-bedding, and imbrication developed in the clastic levels. Limestone is located at the uppermost levels of the succession and sediments, starting in the form of clayey limestone, continue with limestone.

Presenting a 200 m-thick sedimentary succession, the unit rests nonconformably on the basement rocks and the Tunçbilek Formation at the base, and conformably with the Çayca Tuff and the Kızılçay volcano volcanics.

Based on gastropod and ostracoda fossils found in the unit, its age was determined to be of the lower-middle Pliocene ( Baş 1986). Kapan-Yeşilyurt (2000), in their study carried out around Hamitabad in Domanıç region, established the age of the unit to be of the Dacian (lower Pliocene), and Kaya (2009) established it to be of the late Miocene. Furthermore, the age of this unit is considered by us to be of the upper Miocene (?)-lower Pliocene, since tuffs under the succession radiometrically indicate the lower-middle Miocene.

Lithological, stratigraphical, and structural characteristics of the succession suggest that the grain size decreases up to the top, the lacustrine environment increasingly deepens, and it is passive in tectonic terms. The fact that tuffs in the area still maintain their existence demonstrates that volcanic activity occasionally continues to be occurring.

Emet Formation

The unit mainly consists of lacustrine limestone and marl. At the base, the unit starts with sandstone and mudstone and continues upwards with marl, cherty and siliciferous limestone, and limestone levels. The succession contains rarely mudstone and coal seams. The unit is characterized by typical white, yellowish, light grey, and beige colours. At the base of the unit, siliciferous and cherty limestone is common, and in the top sections, clayey limestone and marl levels are widespread.

The limestone is composed of clayey micrite, oosparite, and sandy limestone and is interbedded with siliciferous bands. They cover broad regions in the study area. Siliciferous layers are 1 cm to 0.5 m in thickness. The succession coincides with coal seams with a maximum thickness of 7 cm and without lateral continuity.

The unit shows a lateral and vertical transition at the base with the Çayca Tuff. At the top, it is unconformably covered by the Kirazpınar Formation, the Yakaca Formation, and the Kütahya Formation. Outside the study area, basalt, which covers the limestone layer as a plateau in some places, exists in the Kuşuköy site in the southwest of Kütahya (Akdeniz and Konak 1979). In the region between Örenköy and Gümüşköy, it is observed that the Emet Formation is cut by a basaltic dike.

The Emet Formation is a product of the last period in which sedimentation developed before the region rose altogether and where the lacustrine environment outcrops over vast areas of the region. Existence of silica in the environment demonstrates the effect of volcanism around the lake. Covering a broad area, lake waters extended their boundaries. In many locations, such as the Porsuk Valley, it is almost oriented in a horizontal position, with its layer thickness reaching up to 1.5 m and succession thickness reaching up to 150 m. However, open folds are sparsely observed across the unit. In the unit, desiccation cracks, load structures, and intraclastic carbonate levels can also be observed.

Nebert (1960), based on the fossils that he discovered in limestone layers in the west and north of Tavşanlı, assigned the age of the unit to the Levantine (upper Pliocene). Other researchers assigned the age of the Emet Formation to the lower Miocene (Yağıcın et al. 1985) based on substantial amounts of gastropoda and ostracoda fossils across the formation and the upper Miocene (Koçyiğit and Bozkurt 1997), the middle-upper Pliocene (Akdeniz and Konak 1979; Baş 1983, 1986), and the Romanian (upper Pliocene), based on the characteristic mollusca fauna across the Domanıç and Tunçbilek regions (Gün et al. 1979; Kapan-Yeşilyurt 2000; Kapan-Yeşilyurt and Taner 2001). Şengüler (1999) as well as Beseme (1969) assigned the age of the unit to the Pliocene. Ark and Temur (2003) assigned its age to the upper Pliocene on the basis of its being cut by the upper Pliocene-Quaternary aged volcanic rocks. Furthermore, Celik (1999) assigned the age of the unit in the Domanıç basin to the middle-early upper Pliocene based on the fossils discovered. In the light of these data, the age of the unit is considered by us to be of the lower Pliocene.

Considering fossils contained in it, the Emet Formation suggests a broad and shallow lacustrine environment. Desiccation cracks and caliche layers, which are sporadically observed in the unit, reveal that the lacustrine sediments are occasionally on the surface.

Kocayataktepe Formation

Showing exposures in the northwest sections of the study area, the unit mostly comprises slightly consolidated, poorly sorted, and, particularly of ophiolitic origin, pebbles and blocks, mostly in the base, and infrequently pebbles from the Emet Formation. Pebbles and blocks demonstrate variations between angular and well-rounded shapes depending on the lithology. In general, it is observed in dark brown, dark grey, bluish, and dark greenish colours. In the
unit, Lebküchner (1959) determined siliciferous tree trunks that can reach several metres in length.

Mainly being a product of a high-energy environment, the unit is characterized by its chaotic structure of fast sedimentation. In the succession, cross strata are infrequently observed. In this respect, it can be concluded that sedimentation took place in a high-energy alluvial fan. Exposing over a narrow section in the northwest of the study area, the formation unconformably covers all the units. Maximum observable thickness of the unit is 50–60 m around the Kocayataktepe site.

No fossils could be discovered in the Kocayataktepe Formation. However, the stratigraphic location of the unit suggests that it is of the upper Pliocene age (Baş 1983).

The unit demonstrates sedimentation in an alluvial fan environment where coarse conglomerates and large blocks were irregularly deposited. A morphology of a low-relief and stagnant lacustrine environment, which had dominated the region from the late Miocene, changed its location during the late Pliocene. Topography, probably destroyed by new tectonic activity in the region, gained roughness and fault-controlled fan environments occurred.

**Kirazpınar Formation**

The unit mainly consists of indistinctly stratified pebblestone, sandstone, siltstone, and mudstone dominated by yellowish, beige, and reddish colours. Blocks and pebbles are poorly sorted, 1–30 cm in diameter, angular to semi-angular in shape, and slightly to moderately consolidated. Pebbles mostly belong to the ophiolitic rocks from the Tavşanlı Zone.

Showing typical exposures around Kirazpınar Village, the unit starts here at the base with grey- and pink-coloured mudstone levels. In that exposure, carbonate-filled fissures, which developed perpendicular to the strata and are in parallel with each other, are observed. The width of these fissures varies from a few centimetres to 20 cm. To the top, the succession continues with pebblestone and sandstone intercalations and involves cross-bedding.

The formation outcrops in the study area, across the middle sections, and mostly around the Karaöz Horst. The Kirazpınar Formation unconformably overlies those units in its base. The thickness of the unit is about 40 m.

The unit contains substantial amounts of *Unio* sp. fossils in the west of Kirazpınar (Özburan 2009). In addition, the fact that the unit spreads over the lower Pliocene-aged Emet Formation with an angular unconformity suggests that the unit is of the Pleistocene age.

The unit outcrops in the north of the Yellice Horst. The Kirazpınar Formation is mainly associated with the activity of the Kütahya Fault Zone (KFZ), meaning that it is a fault-controlled sedimentary unit. Irregular deposition across the succession, grain size distribution, open and closed fissures developed in the unit, and normal fault planes indicate apparent tectonic activity.

While structural elements reflecting the compression/transpression regime are observed in older units, development of open and closed tension fissures in the Kirazpınar Formation suggests that the unit developed under the extensional tectonics. This regime change must have been in the period when the Kütahya Graben started to develop. Lithologic, stratigraphic, and structural characteristics of the unit reflect sedimentation in the stream, alluvial fan, flood plain, debris flow, and lacustrine environments. The unit mainly comprises materials carried from the Yellice and Karaöz horsts.

**Yakaca Formation**

The unit consists of very slightly consolidated pebble, sand, silt, and clay, and outcrops over widespread areas below the alluvial at the base of the recent Kütahya Graben valley. The unit primarily is reddish, pinkish, brown shaded, and grey coloured. Pebbles are angular to semi-angular in shape.

Mostly spreading over the west-central sections of the study area, the unit must comprise sediments placed on flood plains by the Kocasu Creek, which is the main tributary of the Felent Stream today. No fossils were discovered in the unit. However, it is considered to reflect an alluvial environment in the Pleistocene appropriate to its position in the succession.

**Taşlıtepe volcanics**

In the study area, basalt, andesitic basalt, and olivine basalt containing volcanic rocks were examined under the name of Taşlıtepe volcano. Lava is generally black, blackish brown, and reddish black in colour, amygdaloidal in texture, porphyritic textured in thin sections, and contains plagioclase, pyroxene, and olivine phenocryst.

In the south of the Örenköy, these volcanic rocks are represented by black, dark grey-coloured vesicular basalts and dark pink-coloured andesites. Arık and Temur (2003) defined samples taken from the south of the Solçalı Hill as olivine basalt and samples taken from the Balıklı site, Taşlıtepe, and Çaltepe as basalt. They reported that the volcanic cut with the Emet Formation exists in sill form between the Quaternary-aged units (the Yakaca Formation) and runs parallel to the NE–SW- and NW–SE-oriented faults.

It seems that the volcanic rocks crosscut with and cover the Yakaca Formation across their outcrops in the east of the Solçalı Hill. In the geophysical resistivity study report for the Kütahya-Porsuk basin, prepared by the General Directorate of State Hydraulic Works (1985; DSİ in the Turkish acronym), it is stated that basalts in the region exist as a cover above the uppermost Neogene formations (the Çayca Tuff, the Çokköy and the Emet Formations); this lava cover becomes thinner towards the east, then comes to an end, and its thickness can reach up to 50 m.
Basalt, andesitic basalt compositions, and lava, which have been defined to be of the Pliocene in previous studies, are observed to sporadically bake limestone from the lower Pliocene Emet Formation (in the northwest of Ilıca). Radiometric dating was not carried out for the volcanic rocks. Therefore, the age of the volcanic rock, comparing its stratigraphic level to ages given by previous studies, is considered to be of the Plio-Quaternary.

Kütahya Formation

The unit mainly consists of alluvial fans that developed in various fault segments of the KFZ. The widest one spreads over the area where the town of Kütahya is located and mostly developed across the southern edge of the graben. This suggests that the southern edge of the graben is more active than the northern edge. These fans are mostly controlled by faults, and some are associated with the stream drainage system. In particular, the widest fan on which the town of Kütahya is located is a sedimentary rock brought here by the Keçegreği Creek drainage system through flooding. This creek initially flows from the approximately 1900 m high Yellice Mountain to the north, reaches the KFZ, and then turns to the northeast, reaching the Kütahya Graben. This drainage system substantially lost its energy when it reached the Kütahya Plain and formed a broad alluvial fan by depositing its sediment. In addition, other creeks, such as the Büngüldek Creek, the Boyalı Creek, and the Selbaskın Creek, similarly carry materials collected from the hills across the horst to the graben.

Sediments are in the form of fault apron deposits and show an irregular succession. Grains are angular to semi-angular and mostly originated from the Emet Formation. The maximum thickness of the unit is measured at the intersecting regions of the fans and sections which are closest to the fault zone. Koçyiğit and Bozkurt (1997) measured the thickness of the unit to be approximately 150 m in the north of Ortaca Village.

Due to movement of the KFZ, tilt and back-tilt developed in the strata, reaching up to 40°. The number of fans along the southern edge is more than that along the northern edge. Furthermore, the fans developed along the southern edge cover broader areas. Therefore, the southern edge rose more quickly and showed more activity. These fans were also supported by materials, such as slope debris, which rose over a short period of time with the effects of the KFZ and came down from the steep slopes.

Not being as active as the southern edge and undergoing evolution in stages, the northern fan has an alluvial fan developed by the Taşpınar Creek in the west of Parmakören. In addition, flowing further towards the west, around the Taşlı Hill, the Tarla Creek deposited the materials carried before the Parmakören Fault. The sediment distribution of both fans is not as wide as that of the southern edge; therefore, the thickness of the sediments is less.

The Kütahya Formation may spread over the Kirazpınar Formation at the base and it is essentially above all the units since it is the youngest sediment in the region after the alluvium. Although it cannot be directly observed in the study area, the unit can only be transgressed by alluvium with unconformity. The age of the unit is given to be the Holocene according to its stratigraphic position.

Alluvium

Alluvium comprises pebble-sand-silt-clay grained valley sediments, which are deposited by current creeks and drainage systems. Alluvium is mainly deposited in the Felent Stream valley, which flows through the Kütahya Plain from the northwest to the southeast. The Porsuk Stream, located in the east of the study area, is another important drainage system. According to DSİ (1965, 1985) data, the thickness of the alluvium varies from 5 to 20 m in the Porsuk Stream basin. Spreading unconformably over all the units in the region, the alluvium is generated by these two large streams and their tributaries.

Morphology

In the north of the study area, approximately N50°E, the Kızıltepe, Karaöz, and Anbartepe horsts are oriented parallel to each other, and, among these horsts, the Seyitömer and Sabuncupınar grabens spread. In these horsts is the Tavşanlı Zone, which consists of the Upper Cretaceous ophiolitic rocks and melange outcrops. Both grabens are filled with a succession consisting of two bundles of the lower-middle Miocene and Pliocene. However, fills of these grabens produced from the first package are different from each other. In addition, in the south of the study area at approximately N65°W is oriented the Kütahya Graben, at a location inconsistent with these structural elements. In the Yellice Horst, located south of the graben, are the Afyon Zone rocks, which primarily comprise metamorphic rocks. The morphological characteristics of grabens in the region, the N–S-oriented Seyitömer and Sabuncupınar grabens and the inconsistent Kütahya Graben, are presented below.

Seyitömer and Sabuncupınar Grabens

The Seyitömer Graben is about 25 km long and approximately 14 km wide. The Seyitömer Graben has taken its current morphology from the NE–SW faults limiting the graben. The graben stretches in the north outside the study area and ends in the south with the faults from the Kütahya Graben. The Gümüşgölçük Fault (GgF), which limits the western edge of the graben, is about 6 km long and has normal fault characteristics. The N60°W oriented fault has an apparent morphology and reveals itself by lithologic differences. Here rocks from the base and
the Neogene sediments adjoin. Along the eastern edge of the graben, it is not possible to follow an apparent fault plane showing continuity. The fault must probably have been covered by younger sediments. The Beke Formation, comprising pebblestone, sandstone, and siltsone, and the Tunbilek Formation, comprising pebblestone, sandstone, siltsone, marl, claystone, tuff, limestone intercalation, and coal seams, are the main fill of the Seyitömer Graben.

At an orientation of approximately N30°–35° E, the Sabuncupınar Graben spreads in the north beyond the study area and ends in the south with the faults limiting the Kütahya Graben. The Çayca Tuff from the first package and the Kızılkaya volcanics above it consist of the graben fill. These two units are extensively observed in the Sabuncupınar Graben. This suggests that the Karaöz Horst, which is located between the two grabens, was an important structural threshold during the lower-middle Miocene (Özburan 2009).

A common cover of these two grabens and all the horsts in the region is the Pliocene second package. This package starts at the Seyitömer Graben with angular unconformity above the first package and conformably in the Sabuncupınar Graben. The first unit of this package is the Çokköy Formation, which starts with pebblestone and then turns into sandstone, siltstone, and claystone intercalation. Being located above, the Emet Formation starts at the base with sandstone and claystone intercalation and continues with mudstone, limestone, and marl.

### Kütahya Graben

The most prominent morphological element in the region is the approximately N65° W orientated Kütahya Graben. The Kütahya Graben is one of the largest grabens in central western Anatolia. It is about 50 km in length and 2–8 km in width. The northern edge of this asymmetric graben is multi-part and irregular. The southern edge is more apparent, linear, and steep. The Yellice Horst, located in the south of the graben, is 1901 m in height. Higher and steeper slopes exist across the middle section of the southern edge. Creeks along this edge underwent strike–slip faulting with left-lateral oblique normal faults. In the west and east of the Yellice Horst, the topography is subdued. Large and steep slopes are rare. In these sections, the faults meet the horst obliquely. Small- to medium-scaled alluvial fans developed across the intersections between the horst and the Kütahya Graben. The most typical is observed around Kütahya. On the northern edge of the horst, shutter ridge and back tilting formed. Due to rapid vertical movement, alluvial terraces with a height of about 1150–1400 m exist across the Yellice Horst, Çifteyataktepe site, and south of the Dabulga Hill.

Topography is asymmetric across different slopes of the Yellice Horst. The northern edge of the horst is steeper than the southern edge. On the northern slope of the mountain, intermittently developed, N50°–75° W orientated, northwesterly inclined (>60°) normal oblique faults exist. On the southern slope, erosion by streams is not yet fully developed. Particularly on the northern side of the horst, upstream erosion has already begun. The plateau in the Yellice Horst is about 1300 m in height and tilted to the north. This plateau does not have a large and deeply excavated valley and erosion is reflected in several phases. On the northern slope, a cuesta is observed depending on the south-oriented tilting of the erosional surface on the northern slope near the hill.

Quaternary sediments are mainly limited by the Kütahya Graben. Quaternary sediments are mainly limited by the NW–SE-oriented faults. The succession starts at the base with red- and brown-coloured coarse pebblestones. Their internal structure is chaotic and in the form of debris flow and fan pebblestones. Moving away from the fault zone, grain size becomes finer, turning into white, medium-thick stratified clayey sandstone. The facts that fan sediments developed in front of the KFZ are unconsolidated, the size of fans is not so large, and stream beds are deep and narrow indicate that the rise occurred very recently. This also demonstrates that the horst, early in the Quaternary period, had not already risen to its current position.

### Structural geology

Faults and folds are common in the region. However, faults are more the dominant structure. Folds primarily developed in the lower-middle Miocene successions. The fold axial is mostly NE–SW and NW–SE oriented. Folds are generally observed to be open and symmetric and, locally, to be tight and overturned. Traces of this N–S-oriented compression, affecting the lower-middle Miocene successions, are observed in the Seyitömer open-pit lignite mine located in the Seyitömer Graben (Figure 4A and 4B). The late Miocene and younger sediments are not folded. However, they may be folded near the faults as a result of the shear displacement along the faults. Therefore, folding must have developed as a result of the approximately N–S-oriented compression before the late Miocene.

Faults in the region may be divided into two groups based on their types:

1. Reverse faults (Figure 5)
2. Normal and oblique faults (Figures 6 and 7)

### Reverse faults

In the study area, reverse faults are mostly observed in the middle-upper Miocene Çokköy Formation and the lower Pliocene Emet Formation. Most of the reverse faults developed in the succession and show a 15–80 cm displacement (Figure 5). Reverse faults are concentrated
Figure 4. (A) Overturned anticline and reverse fault in the Tunçbilek Formation in the Seyitömer coal mine. (B) Field photograph showing open-folding structure in the Tunçbilek Formation.

Figure 5. Some of the widely observed reverse faults. (A) Thrust sheet of the Tavşanlı Zone ophiolitic rocks (PzMzt) thrusted over the Emet Formation (Te). (B) Thrust fault in the Emet Formation with a ramp-flat geometry and associated fault-bend folding. (C)–(F) Thrust faults in the Çökköy Formation.
Figure 6. Fault planes of the main faults in the region. (A) Fault plane of the last phase of Kütahya Fault. (B) Oblique sinistral strike-slip Yakaca Fault. (C) Fault plane of the first phase of Gevrekseydi Fault. (D) Kocayataktepe Formation observed in the oblique sinistral strike-slip fault plane.

Figure 7. (A)–(D) Field photographs representing high-angle normal faults along the sediments of the Çökköy Formation.
in the Sabuncupınar Graben. Although they are small and medium sized, these faults are important in understanding the structural history of the region. The largest reverse fault in the region is of a thrust nature (Figure 5A). Observed at the edge of the Kütahya–Eskişehir roadway, this reverse fault and the ophiolitic melange from the Tavşanlı Zone were thrust onto the lower Pliocene Emet Formation. The fact that many reverse faults and thrusts, which developed across various locations and in different-aged units, exist demonstrates that the compression factor is not a very short-term or local factor. Considering folds and reverse faults in the region together, it can be mentioned that the compression phase, in and around the Kütahya region, was effective during the early-middle Miocene and the late Pliocene.

**Normal and oblique faults**

In the study area, many normal and oblique slip faults developed (Figures 6 and 7). They can be classified into two groups according to their limiting structural elements and their ages.

1. NE–SW-oriented faults limiting the NE–SW horsts and grabens


Fault kinematic analysis, using data from striated fault planes of oblique and normal faults, was performed in order to determine the kinematic framework of faulting during each of the inferred extensional phases. Slickenfibres, where possible, were used to determine the sense of motion. The minimum number of slickenline data required to construct a stress tensor is 4 in the direct inversion method (Angelier 1979); the data of pre-Plio-Quaternary faults containing less than this number were not used. The fault-slip data were collected mainly from major fault contacts between the pre-Plio-Quaternary and the Plio-Quaternary sedimentary cover from the Kütahya Graben. The data were processed using the direct inversion method (INVD) of Angelier (1990). Using the fault-slip data, 12 stress configurations were constructed. The resulting fault plane analysis suggests a NW–SE- and NE–SW-directed extension (Figure 8, Table 1).

![Figure 8](image-url)

Figure 8. Lower hemisphere, equal area projection of principal stress axes constructed from fault-slip and slickenline data the using New direct inversion method (Angelier 1994). The data used to construct the projection are from Table 1.
Table 1. Results of stress tensor determinations obtained with the slickenlines (using the new direct inversion method, Angelier 1994).

<table>
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<tr>
<th>Site</th>
<th>( \sigma_1 ) (degree)</th>
<th>( \sigma_2 ) (degree)</th>
<th>( \sigma_3 ) (degree)</th>
<th>Host unit</th>
<th>Number of cross-cutting</th>
<th>Number of phases</th>
<th>Type of faults</th>
<th>Trend</th>
<th>Plunge</th>
<th>( \phi ) (degree)</th>
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Directions cut each other. The first set played an important role in the development of the early-middle Miocene basins. NE–SW-oriented major faults and NW–SE-directed secondary faults meet each other at obtuse angles and show a small strike–slip displacement. This conjugate fault set is compatible with the N–S compressional stress. Slip planes of such faults are generally eroded or covered by younger units.

**NW–SE- and E–W-oriented fault zones limiting the Kütahya Graben**

The youngest fault system in the region is the NW–SE and E–W oriented one. In the study area, the approximately NW–SE-oriented Kütahya Graben is limited by normal, strike–slip oblique faults. Faults comprising the southern and northern sections of the graben will be described separately.

**South of the Kütahya Graben**

The southern edge of the asymmetric Kütahya Graben is limited by intermittently en echelon fault segments in various sizes which are oriented parallel with each other. Therefore, the fault set which is observed in the form of the southern edge faults is called the KFZ.

**Kütahya Fault Zone**

The KFZ is roughly NW–SE oriented and a maximum of 4.5 km wide and 50 km long. Formed by segments in various lengths parallel with each other across the southern edge of the Kütahya Graben, this zone controls the topography and asymmetry of the graben. Along these segments, the northern block is down-dropped compared to the southern block. Steps and triangular facets formed by the segments in morphology are particularly apparent around Sofuköy. In the Yellice Horst, elevation is about 1900 m and in the middle of the Kütahya Graben, elevation is about 950 m. Along the zone, the Quaternary sediments and the Palaeozoic–Mesozoic Afyon Zone rocks meet each other. In this region, some of the slopes in the valleys were laterally displaced and hanging valleys developed due to the left-oblique slip of the KFZ. Linear springs and alluvial fans are the most prominent evidence of the morphology of the KFZ.

In many locations around the fault zone, dolomitic marbles from the base were sheared and developed as fault gauge. Fault gauge contains sporadic fault breccias up to 5 cm in thickness. White-coloured and unconsolidated materials reach up to 35 m in thickness.

Being the major fault of the KFZ, the Kütahya Fault (KF) is approximately N50°–70°W and, on average, 55°NE oriented. Grooves, fault scratches, and parabolic marks indicate that the fault initially acted as right-lateral oblique
and then as left-lateral oblique slip. Data showing the right-lateral component were obtained from a fault plane around Okçu Village. Probably the first movement of the KFZ was right oblique, then left oblique. While the slope of the fault line on the fault plane is $23^\circ\text{–}36^\circ\text{NE}$, the slope of the youngest fault lines is $65^\circ\text{–}70^\circ\text{NW}$ on average (Figures 6A and 8). There is no direct data with regard to the age of the KFZ. However, its age is likely to be of the Pleistocene since it cuts the Kirazpinar Formation. This age is consistent with the Pleistocene age which was determined based on the location of the Yakaca Formation, a fill of the Kütahya Graben, in the stratigraphic succession.

**North of the Kütahya Graben**

The northern edge of the graben has a low inclined slope and is not controlled by any distinct fault system. Across this edge, some faults that can be called edge faults are E–W oriented (Yakaca, Doغا, Gevrekseydi, Karaöz, Parmakören, and İnköy faults) and some faults are NW–SE oriented (Alayunt Fault). The number of fans developed across the northern edge and the distribution areas of the fans are lower compared to the southern edge. Furthermore, the Felent Stream flows near the northern edge of the graben. Such characteristics of the graben indicate that the southern edge rose before the northern edge and was more active.

**Karaöz Fault**

The Karaöz Fault (KaF), 9 km in length, approximately E–W oriented and a $70^\circ\text{S}$ inclined right-lateral oblique normal fault, is located in the middle of the study area. The fault starts from the Kınalı Ridge and continues to the east through the north of Karaöz Village. Located at the base of the graben fill, the Kirazpinar Formation is limited by the KaF in the north. The fact that some dry valleys show right-lateral displacement indicates that this fault also involves an oblique component. Koçyiğit and Bozkurt (1997) reported that, nearby, north of Gevrekseydi-Doغا and Yakaca villages, strata of the Miocene units and folds developed inside the units have axial orientations with right-lateral displacement.

**The Parmakören Fault Zone**

The Parmakören Fault Zone (PKZ) limits the Kütahya Graben and the Karaöz Horst. The fault zone is approximately E–W, located at $60^\circ\text{–}70^\circ\text{S}$. The PFZ mainly consists of the Parmakören and İnköy faults. Being the major fault of the PFZ, the Parmakören Fault starts in the north from around the Enne Dam Pond and stretches towards Parmakören Village in the east. The Parmakören Fault is about 6 km in length and is a normal fault inclined to the south. The southern block is down-dropped compared to the northern block. Triangle-shaped faces formed by the fault and topography stepped towards the south are evident in morphology. In the south of İnköy, the approximately E–W-oriented fault and the mélange and alluvium from the base meet each other. The fault is about 4 km in length.

**Alayunt Fault Zone**

The Alayunt Fault Zone is a 17 km-long zone formed in the north of the Kütahya Graben, around Perli, Alayunt, and Büyükşaka villages. Along the zone, the Miocene sediments and the Quaternary alluvial sediments meet each other.

Some of the faults controlling the northern edge of the Kütahya Graben are E–W-oriented faults. These faults, from west to east, are the Yakaca Fault (YF), the Doغا Fault (DF), and the Gevrekseydiköy Fault (GF).

**Yakaca Fault**

The YF is just north of Yakaca Village, about 4.5 km in length, located at $N83^\circ\text{W}$, with $82^\circ\text{SW}$ and a left-lateral oblique normal fault (Figures 6B and 8).

**Doğa Fault**

The DF continues from Doğa Village, after which it is named, for approximately 2.2 km to the west; it is an E–W-oriented and south-dipping normal fault. The southern block is down-dropped compared to the northern block. Its presence was identified by a step formed in the morphology.

**Gevrekseydiköy Fault**

the Gevrekseydiköy Fault starts from about 500 m north of Doğa Village and continues 4.6 km to the east. The fault trend is approximately E–W, $60^\circ\text{–}80^\circ\text{S}$. In the fault plane, observed just north of the Doğa Village, two different fault lines ($10^\circ\text{E}\text{–}52^\circ\text{W}$) are observed, showing lateral-slip and dip-slip. The fault includes fault planes dipping at an average of $60^\circ\text{SE}$ with rakes of $10^\circ\text{E}$. This plane clearly demonstrates that the lateral element is left-lateral (Figures 6C and 8).

**Geological evolution**

In the study area, four different tectonic phases developed during the Neogene–Quaternary period. These are as follows:

1. the approximately N–S compressional regime, early-middle Miocene;
2. tectonic quiescent, erosion, and sedimentation period, late Miocene-early Pliocene;
3. final phase of the N–S compressional period, middle-late Pliocene; and

Phases of tectonic evolution are shown in Figure 9. The region was characterized by an approximately N–S compression during the early-middle Miocene. Approximately NE–SW and NW–SE axial oriented folds and identically oriented oblique conjugate faults developed along this phase. Such structures, developed under the N–S compressional regime, also exist today in the Tibetan Plateau. Among the conjugate faults, dominant NE–SW-oriented faults led to the development of the NE–SW-oriented horsts and grabens. Such faults also enabled the volcanic activity in the region. The Seyitömer Graben was filled with fluvial and lacustrine sediments containing coal intercalations while the Sabuncupınar Graben was filled with volcanic rocks and lacustrine sediments. Volcanics are similar in petrographic and stratigraphic terms to calc-alkaline volcanic rocks in the Biga Peninsula and western Anatolia.

The N–S compression appeared to be discontinuous. The graben fill was folded locally with the reactivation of the compression developed at the end of the middle Miocene. Since the late Miocene, the compression has ceased and the region has been tectonically quiescent. A brief phase of cessation is marked by the development of a regional, flat-lying erosional surface, developed above all of the units including the upper Miocene–lower Pliocene. Before the first phase of the uplift of the Yellice Horst, the NE–SW-oriented horsts and grabens appeared to considerably lose their topographic characteristics as a result of this erosional phase. The remnants of the present, slightly south-oriented erosional surface may stretch along the smooth southern slope of the Yellice Horst up to the plateau, at the top. The erosional surface may be used as a time marker to distinguish between the earlier and the later events.

On the other hand, in the region, the Çokköy Formation, starting with coarse clastics and then turning into sandstone and mudstone intercalation, and the Emet Formation dominated by marl, were deposited. These units overlap the horst nearby, covering the entire region. Immediately after the deposition of the Emet Formation, the N–S-oriented compression, probably activated again in the region during the middle Pliocene, and the ophiolitic slab from the Tavşanlı Zone were thrusted over the Emet Formation. Following this second compression phase, the tectonic activity probably became quiescent again in the region and the Kocayataktepe Formation was unconformably deposited.

During the late Pliocene-Quaternary, the N–S-oriented extensional regime activated in the region and the Kütahya Graben started to develop. Present topography of the region is mainly formed by the NW–SE- and E–W-oriented faults. These faults caused the opening of the Kütahya Graben and the uplifting of the Yellice Horst (Figure 9E). The NW–SE-oriented Kütahya Graben cut and displaced the Seyitömer and Sabuncupınar grabens.

In conclusion, when stratigraphic and structural data are evaluated together, it is demonstrated that no uniform
Conclusions

The Kütahya region underwent several phases of Neogene to Quaternary faulting, resulting in a dense network of faults of variable orientation. Our geological mapping of the area has revealed the presence of two groups of structural basins with different ages and orientations.

The Neogene–Quaternary successions and the major structures recorded in the western part of Anatolia around the Kütahya region reveal the following geological history. Over a slightly inclined topography, continental basins formed during the early Miocene. This was followed by the development of a phase of approximately N–S compression which began generating two sets of faults, which formed a conjugate pair. They are oblique-slip faults having a major dip-slip and a subordinate strike-slip component. The faults are NE–SW and NNW–SSE oriented. The former set, which is by far the most dominant set, controlled the development of the Kızıltıpe, Karaoz, and Anbar-tepe horsts and the Seyitömer and Sabuncupınar grabens. The NE–SW-oriented tensional fissures and faults, formed under an approximately N–S compressional regime, were accompanied by intense igneous activity. Volcanoes formed above the faults, which restricted the extension of the lake basin(s). The volcanoes produced mostly andesitic and latitic lavas and pyroclastic rocks. In the Sabuncupınar Graben, lacustrine detrital rocks were abundantly deposited, alternating with minor development of volcanoclastics. The lower to middle Miocene successions underwent a shortening deformation, which produced NE–SW- and NW–SE-oriented folds and approximately NW–SE-oriented reverse faults. The Kütahya and surrounding area may have been similar to the Tibetan-type tectonic setting during the early-middle Miocene period.

After the middle Miocene, no important tectonic event was recorded in the region until the middle Pliocene, suggesting a tectonic quiescence period. Subsequently, N–S compression ceased, and a severe phase of erosion began (late Miocene–middle Pliocene). It produced a regional flat-lying erosional topography. Lake basins developed over the topography of low relief in this period; the lacustrine flat-lying erosional topography. Lake basins developed over an approximately N–S extensional regime. It is characterized in the study area by the activity of oblique normal faults cutting through all the previous units; it is also marked by the coeval deposition of coarse sediments. The recent morphological configuration was produced by the onset of a high-angle oblique normal fault onto an undulating palaeo-tectonic structure during the Plio-Quaternary. During this phase, the Yellice Horst rose to its present position as a NW–SE- and E–W-oriented structure. The Kütahya Graben clearly postdates upper Miocene–middle Pliocene structural features and is possibly of the late Pliocene-Quaternary. We conclude that in western Anatolia, starting from the Neogene, two basins associated with the N–S compressional/transpressional system and one basin associated with the N–S extensional/transtensional system were generated subsequently with an intervening period of intermontain basin formation. The transition from the compressional to the extensional system occurred in the middle-late Pliocene. In contrast to the proposed single extensional history, our data indicates a complex history with successive compressional and extensional episodes.

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