ABSTRACT

STRUCTURE AND TECTONICS OF THE LATE CENOZOIC TRANSTENSIONAL AKSU SEDIMENTARY BASIN, SW ANATOLIA

by Ersin Kaya

This study documents the internal structure, stratigraphy and tectonic evolution of the middle Miocene–Quaternary Aksu sedimentary basin (AB) within the Tauride mountain belt in SW Anatolia. The NNW-trending, ~80-km-wide AB is separated in the east from a basement high composed of the Triassic-Cretaceous tectonostratigraphic units of the Tauride carbonate platform by a right-oblique normal fault system, not by a west-vergent thrust fault as previously suggested (“Aksu Thrust”). The sedimentary fill of AB consists of shallow marine to deltaic, lacustrine, fluvial-alluvial fan deposits, and becomes progressively younger toward the south (Antalya Bay). These rock units are crosscut by syn-depositional, NE-SW-oriented normal faults and NNW-SSE-oriented oblique-slip faults, collectively representing a dextral transtensional stress regime, which has controlled the accommodation space in the basin. AB and the adjacent Köprüçay and Manavgat sedimentary basins evolved in a regional dextral transcurrent fault system in the upper plate of the left-oblique convergent margin of the Cyprean (Cyprus) Arc to the SE.
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1. INTRODUCTION

The Neogene Aksu sedimentary basin is one of several, ~N-S-trending subparallel depocenters within the center of the Isparta oroclinal bend (known as the Isparta Angle – IA) in SW Turkey (Fig. 1). The Isparta Angle is a sharp cusp within the Tauride continental block and occurs at the intersection between the Hellenic – Aegean (west) and Cyprus (east) arcs. It is located at the boundary between the extending Aegean Extensional Province in the west and the uplifting and W-SW-moving Anatolian Plateau in the east (Robertson and Woodcock, 1982, 1984; Dilek and Rowland, 1993; Glover and Robertson 1998a, 1998b; Dilek and Sandvol 2009). The area occupying the center of the Isparta Angle extends into the Bay of Antalya to the south that is a tectonically active basin undergoing both extensional and strikeslip deformation (Schildgen et al., 2012). The left-lateral Kale (KF), Acigöl (AF) and Burdur (BFZ) Fault Zones on the western limb of the Isparta Angle are interpreted as the landward continuation of the Pliny-Strabo Trench, which is a major transform fault system spatially associated with the Hellenic Trench (Verhaert et al., 2006; Over et al., 2013). The right-lateral Kirkavak fault on the eastern limb of the Isparta Angle extends offshore connecting with a major transform fault system in northern Cyprus to the southeast (Fig. 1) (Glover and Robertson 1998a, 1998b; Monod 2002). Thus, the Isparta Angle and the Neogene sedimentary basins within its center are situated in a modern convergent zone between the Africa and Eurasia plates, and their geological history provides an important archive for the mode and nature of structural, sedimentological and tectonic processes that have been taking place here since the early Miocene.

Paleomagnetic studies in the western Tauride belt have shown that there has been very little to no rotation of the Isparta Angle during the last 10 Ma (Kissel and Laj 1988; Glover and Robertson 1998a; Tatar et al., 2002). This finding implies that any crustal deformation within and around the Isparta Angle is not related to possible rotational motions of the eastern and western limbs of this oroclinal bend. Offshore seismic data from the Bay of Antalya in the south indicate that high-angle normal faults crosscut and offset its Miocene and Pliocene sedimentary strata (Isler et al., 2005; Hall et al., 2014). There also exist numerous faults crosscutting the Miocene sedimentary units in the Manavgat Basin (Figs. 1 and 2) with normal offsets and dextral strike-slip components (Karabiyikoglu et al., 2000). Earthquake focal mechanisms obtained from the Aksu Basin and SW Turkey reveal transtensional and tensile stress solutions at shallow
hypocenters (<30 km depth; Schildgen et al., 2012). The only evidence for the existence of compressional stress in the area comes from the southeastern part of the Bay of Antalya where the hypocenters of thrust faulting-induced earthquakes appear to be located at depths more than 70 km. This inferred compressional stress is interpreted to have resulted from the northward subduction of the African lithosphere at the Cyprus Trench (Kalyancioglu et al., 2011; Schildgen et al., 2012).

Despite all these independent lines of geological and geophysical evidence indicating the predominance of extensional and transtensional stress regime and associated deformation within and around the Isparta Angle since the middle-late Miocene, some researchers have argued for the occurrence of late Miocene-Pliocene contractional deformation structures associated with west-directed thrust faulting in this region (Poisson et al. 2003, Ciner et al. 2008 and Poisson et al. 2011). Specifically, Poisson et al. (2003), Ciner et al. (2008), and Poisson et al. (2011) have argued that a west-vergent thrust fault (“Aksu Thrust”) on the eastern limb of the Isparta Angle emplaced the Triassic-Cretaceous assemblages of the Antalya Complex on top of the Neogene Aksu Basin strata. This interpretation has two major implications: (1) major contractional deformation, as young as 2 million years ago, affected the region in an otherwise broadly extensional stress regime. (2) The Miocene-Pleistocene Aksu sedimentary basin formed as a thrust-loaded foreland basin. The currently available tectonic models for the geological evolution of the western Tauride Belt and its potential for hydrocarbon plays have been strongly influenced by these “thrust fault” interpretations.

This study is aimed at documenting the internal structure and stratigraphy of the Aksu Basin, specifically the geometries, patterns and kinematics of different fault systems in and around it, in order to better constrain the Miocene to Plio-Pleistocene sedimentary basin evolution and the related geological processes in this convergence zone. Thematic structural mapping at macroscopic, mesoscopic and outcrop scales were used to document the nature and geometry of formation boundaries, fault planes and other lineaments in the Aksu Basin. Several structural traverses were also made across the inferred “Aksu Thrust” in order to understand the geometry and kinematics of faulting associated with this tectonic discontinuity. The results of my thesis work are inconsistent with a thrust fault mechanism for the origin of this tectonic discontinuity and for the evolution of the Aksu sedimentary basin. Instead, this study shows that
the Aksu basin evolution and its structure and stratigraphy have been strongly controlled by a broad, dextral transtensional fault system, which has affected the regional tectonics of the eastern limb of the Isparta Angle since the middle Miocene. The ramifications of this interpretation and the new model presented in this thesis for the regional tectonic models are thus far-reaching.

2. REGIONAL GEOLOGY AND TECTONIC HISTORY OF THE WESTERN TAURIDES

The Tauride belt in southern Turkey represents a Gondwana-derived ribbon continent, composed of Paleozoic–Mesozoic meta-sedimentary and meta-volcanic rock assemblages underlain by a Precambrian basement. These units underwent progressive episodes of contractional deformation associated with the southward emplacement of the Neotethyan ophiolites in the late Cretaceous, followed by the further southward displacement and thrust-imbrication of the ophiolite and mélangé nappes (i.e. Lycian Nappes) in the Eocene-early Miocene as a result of continental collisions in northern Anatolia (Dilek and Rowland, 1993; Dilek and Sandvol, 2009). The Bey Daglari carbonate platform in the western limb of the Isparta Angle includes shallow-water limestones, dolomites and neritic limestones ranging in age from the Upper Triassic to the Eocene (Fig. 2; Robertson and Woodcock, 1982, 1984). The Anamas-Akseki platform in the eastern limb of Isparta Angle is composed of Triassic-Jurassic and lower Cretaceous, plant-bearing clastic rocks, reefal limestones and dolomites (Robertson and Woodcock, 1982, 1984; Poisson et al., 1984; Dilek and Rowland, 1993). Both the Bey Daglari and the Anamas-Akseki platform carbonates are tectonically overlain by the Antalya Complex (Antalya Nappes), which consists of Triassic-lower Cretaceous rift-drift volcano-sedimentary units and Cretaceous ophiolites and mélanges, along west- and east-directed thrust sheets, respectively (Fig. 2) (Robertson and Woodcock, 1982, 1984; Poisson et al., 1984; Dilek and Rowland, 1993).

Following the complete ocean closure and continent-continent collisions in the Neotethyan realm in northern and Central Anatolia in the early Eocene (Harris et al., 1994; Okay et al., 1998; Dilek, 2006; Dilek and Altunkaynak, 2007; Sarifakioglu et al., 2013), two major nappe systems were developed and displaced southward to their current positions in the Tauride belt. The Beysehir-Hoyran Nappes were thrust south-southwestward from the Inner-Tauride
suture zone onto the Anamas-Akseki platform in the eastern limb of the Isparta Angle in the late Lutetian – early Miocene (Poisson et al., 1984; Dilek and Rowland, 1993; Kocyigit and Deveci, 2007). The Lycian Nappes were displaced south-southeastward onto the Bey Daglari platform in the western limb of the Isparta Angle during the late Oligocene-early Miocene (Poisson et al., 1984; Dilek and Rowland, 1993; Kocyigit and Deveci, 2007). After the southward emplacement of these nappes systems and the tectonic burial of the Tauride Platform beneath the allochthonous thrust sheets, the area south of the Isparta Angle experienced subsidence and shallow marine deposition in the early to middle Miocene (Robertson et al., 2003).

The central and southern parts of the Isparta Angle area are occupied by the middle Miocene and younger shallow marine and fluvial-lacustrine sedimentary rocks (Figs. 2 and 3). These Neogene sedimentary units occur in a series of ~N-S-trending sub-basins (Manavgat, Köprüçay and Aksu), which are separated from each other by the Kirkkavak (Monod et al., 2002) and Aksu Faults (Akay et al., 1985; Ciner et al., 2008). These NNW-SSE-running faults are part of larger-scale, regional fault systems within the Anamas-Akseki platform and within the South-Central Tauride belt. Some of these regional faults are seismically active and appear to have affected the dynamic landscape and drainage network development in the entire Isparta Angle area (Schildgen et al., 2012).

Recent biostratigraphic data from the Upper Miocene marine sedimentary rock units, which are currently exposed at ~1.5 km (absl) elevation in the SW Tauride belt show that these rocks were uplifted to their current positions after 7 Ma (Schildgen et al., 2012). This regional uplift coincided with the timing of the Messinian crisis in the eastern Mediterranean and of the alkaline volcanism within the Isparta Angle (Dilek and Altunkaynak, 2009; Dilek and Sandvol, 2009; Cosentino et al., 2012). P-wave tomography data from this region show highly attenuated velocities, compatible with high heat flows and the occurrence of young volcanic rocks, collectively interpreted as a manifestation of upwelling asthenosphere along a slab tear within the downgoing African lithosphere (Francalanci et al., 2000; Dilek and Altunkaynak, 2009; Dilek and Sandvol, 2009; Biryol et al., 2011). The inferred asthenospheric upwelling explains the observed regional uplift since the late Miocene and the crustal weakening that resulted in the formation of major fault systems showing tensional and transtensional earthquake focal mechanisms (Schildgen et al., 2012). Thus, the combined geological and geophysical evidence
point to widespread extensional deformation in and around the Isparta Angle since the late Miocene.

3. STRATIGRAPHY AND SEDIMENTOLOGY OF THE AKSU BASIN

The stratigraphy and sedimentology of the Aksu Basin is well documented in the literature, although the formation names, boundaries and ages are varied (Akay and Uysal, unpublished report, 1985; Akay et al., 1985; Glover and Robertson, 1998; Poisson et al., 2003, 2011; Ciner et al., 2008). Ages of the formations are largely based on macro- and microfossils obtained from the sedimentary rocks in the basinal strata (Akay et al., 1985; Glover and Robertson, 1998a). There are no absolute radiometric or isotopic age data available from the basinal units. K-Ar and U-Th dating methods on various basinal units have been tried, with no success. K-Ar age dating of biotite grains separated from a tuffaceous sandstone layer within the Yenimahalle Formation was inconclusive because of potential atmospheric contamination. U-Th dating of the Antalya tufa and travertine deposits was also unsuccessful because the age of these deposits exceeded the age range for this method (>600000 years) (Glover and Robertson, 1998).

In this study we followed the stratigraphic terms and nomenclature used by Akay et al. (1985) and Glover and Robertson (1998a) in delineating the formation names, although we have augmented and/or modified some of these terms and names based on our own field observations, as necessary. In the following sections, the salient characteristic features of the basinal units are described briefly, from the eldest to the youngest, providing their areal contact relationships, thicknesses, lithological make-ups, microfossil contents and ages on the basis of our findings and the extant literature.

3.1. Aksu Formation

The Aksu Formation is the oldest sedimentary unit in the Aksu basinal strata (Fig. 3). Near the eastern margin of the basin it locally overlies the Triassic basement rocks along an angular unconformity (Fig. 4); it is laterally and vertically transitional into the Karpuzcay Formation (Akay et al., 1985; this study). The maximum thickness of the Aksu Formation is ~1200 meters (Akay et al., 1985). Ciner et al. (2008) divided this unit into three members: Kapikaya conglomerate, Karadag conglomerate, and Kargi conglomerate. Islamoglu (2002) used
the Aksu Formation name just for the Serravallian-Tortonian deposits that are exposed in the western portion of the basin.

The type localities of the Aksu Formation are in the northeastern and northwestern parts of the basin (Fig. 5A). The detrital material in the formation shows spatial variations. Poorly sorted conglomerate and conglomeratic sandstone in the western part of the basin are composed of rounded clasts of fine-grained, beige micritic Jurassic limestone and Triassic light gray limestone and yellow sandstone (Fig. 5B), whereas in the eastern part of the basin it contains abundant clasts of red and green radiolarites, Triassic hallobia-bearing limestone, and ophiolitic rocks (serpentinite, dolerite, basaltic volcanic rocks) (Fig. 5D) (Akay et al., 1985; this study). Intercalations of thin layers of siltstone-sandstone and laminated tuffaceous sandstone are common in the conglomeratic units (Fig. 5C). The Aksu Formation rarely includes blocks of reefal limestone, which contains *Stylophora, Heliastrea, Plesiastrae, Favia, Tarbellastrae and Porites corals*, indicating Burdigalian-Langhian ages (Ciner et al., 2008). Based on this information and the occurrence of nannoplanktons, planktonic microfauna and benthonic microfaunas, Akay et al. (1985) and Ciner et al. (2008) assigned a Langhian-Tortonian age to the Aksu Formation.

3.2. Karpuzcay Formation

The Karpuzcay Formation is coeval with and slightly younger than the Aksu Formation (Fig. 3), and is unconformably overlain by the Plio-Pleistocene formations. Locally, it is faulted against these formations (Fig. 2). It is the most extensive unit in the basin with a thickness locally reaching up to 1500 meters (Akay et al., 1985).

The Karpuzcay Formation consists mainly of conglomerate, sandstone and mudstone alternations (Fig. 6). Conglomeratic layers contain clasts of chert, various limestone types and serpentinite. Sandstones are gray, green, to dirty yellow in color, and display cross-bedding, cross-lamination, and well-developed graded bedding (Fig. 6). The majority of clasts are made of ophiolitic rock types (serpentinite, chert, and dolerite); tuffaceous sandstone layers are common within the conglomerate and conglomeratic sandstone units. The matrix of the conglomerate and sandstone rocks is predominantly calcareous. Mudstone rocks are generally laminated and include 15-20-cm-long concretions (Fig. 6). Based on the occurrence of *planktonic foraminifera*
and *nannoplakton* its age is estimated as Langhian-Tortonian age by Akay et al. (1985) and Ciner et al. (2008).

### 3.3. Gebiz Limestone

The Upper Miocene Gebiz Limestone unconformably overlies the Karpuzcay Formation in its type locality near the Town of Gebiz in the southeastern part of the basin (*Figs. 2 and 7*). It is vertically and laterally transitional into the Messinian Eskikoy Formation (*Fig. 3*). It is locally faulted against the Triassic-Jurassic rocks of the Antalya Complex along the eastern margin of the Aksu Basin, and against the younger basinal strata within the basin (*Fig. 3*). The maximum thickness of the Gebiz Limestone is ~40 meters in its type locality near the Town of Gebiz (Akay et al., 1985; this study).

The largest, continuous exposure of the Gebiz Limestone along the southeastern margin of the Aksu Basin runs NW-SE, parallel to the general trend of the basin. It consists mainly of bioclastic limestone, marl, claystone and mudstone, with local occurrences of reefal limestone. The limestone units contain abundant *gastropod*, and *pelecypod* fossils (*Fig. 7*). The age of the Gebiz Limestone is a subject of debate. Akay et al. (1985) assigned a Messinian age to it based on their biostratigraphic data, whereas Glover and Robertson (1998) estimated a Tortonian age for it. More recently, Poisson et al. (2011) assigned a Messinian age to the Gebiz Limestone based on *planktic foraminifera* assemblages in it (*Fig. 3*).

### 3.4. Eskikoy Formation

The Eskikoy Formation mainly crops out in the middle part of the Aksu basin where it unconformably overlies the Aksu and Karpuzcay Formations. Locally, it rests unconformably on or is faulted against the Triassic-Jurassic recrystallized limestones of the Antalya Complex (*Fig. 2*). It is laterally and vertically transitional into the Yenimahalle Formation. The maximum thickness of the Eskikoy Formation is estimated to be around 300 meters (Akay et al., 1985; this study).

The Eskikoy Formation consists of sandy conglomerate and sandstone with mudstone interlayers. The conglomerate is poorly sorted with mostly rounded pebbles and clasts of Jurassic micritic limestone, and Triassic chert and basaltic rocks (*Figs. 3*) (Akay et al., 1985; this study).
Akay et al. (1985) have interpreted this formation as a lateral equivalent (chronologically correlative) of the Gebiz Limestone and have considered its age as the Messinian. Based on their finding of planktonic foraminifera in its marl units, such as *Orbulina*, *Biorbulina*, *Globigerinoides trilobus*, *G. obliquus extremus*, *G. obliquus s.s.*, *G. bollii*, *G. emeisi*, *G. aperture*, *Globigerinita seminulina*, *S. sphaeroides*, *Globigerena nepenthes*, *G. conglomerate*, *G. bulloides*, *G. aperture* and *Globigerinita incrusta*, Poisson et al. (2003) assigned an Upper Miocene age for the Eskikoy Formation (Fig. 3). This finding is consistent with the stratigraphic and chronological interpretations of Akay et al. (1985).

3.5. Yenimahalle Formation

The Yenimahalle Formation is best exposed in the Yenimahalle area on the west side of the Aksu River valley in the south and in the Gebiz area in the eastern part of the basin. It conformably overlies the Gebiz and Eskikoy Formations and is vertically transitional into the overlying Calkaya Formation. Locally, it is also unconformably overlain by the Belkis conglomerate near Dorumlar Village. The total thickness of the Yenimahalle Formation is about 250 meters.

The Yenimahalle Formation is composed of blue-grey siltstone with interbedded sandstone and graded gravelstone, and includes conglomerate in its upper part (Fig. 8A) (Glover and Robertson, 1998). Low angle cross-bedding and lamination, trough cross-bedding, ripple lamination, fining upwards sand channels and gravel/conglomerate lenses are some of the characteristic features of this formation (Glover and Robertson 1998; this study). Sandstone concretions are locally common (Fig. 8D). The following salt-water bivalve and gastropod mollusk shells have been found in this formation: *Acanthocardia sp.*, *Ostrea sp.*, *Cerastoderma edule*, *Paphia sp.*, *Dentalis sp.*, *Gibbula sp.*, *Fusinus sp.*, and *pectens* (Fig. 8B, 8C; Glover and Robertson 1998; this study). Glover and Robertson (1998) interpreted the Yenimahalle Formation as a product of shallow-marine environment. The lower member of the Yenimahalle Formation in the Gebiz area contains Margaritae and Puncticulate zones, indicating a Lower Pliocene age (Fig. 3) (Poission et al., 2003).
3.6. Calkaya Formation

The Calkaya Formation is gradational downward into the Yenimahalle Formation and is overlain conformably by the Antalya tufa-travertine deposits (Figs. 2 and 9). Glover and Robertson (1998) defined the Çalkaya Formation as a combination of the Pliocene Alakilise and Eskikoy Formations. However, in this study we have separated these two units from each other since there is no observable direct contact between them. Additionally, the Eskikoy Formation is older than the Yenimahalle Formation based on the occurrence of Messinian *planktonic foraminifera* and *corals* (Poisson et al., 2003).

The Calkaya Formation consists of marly siltstone, sandstone and conglomerate. Its lower part is lithologically similar to the upper part of the Yenimahalle Formation. Coal seams, 25-30 cm in thickness, are locally interbedded with siltstones (Fig. 10C). Low-angle cross bedding, through cross-bedding, ripple-lamination and hummocky cross-stratification are common features in the Calkaya units (Fig. 9). Locally, grain size coarsening upward (into conglomerates) in the sequence is well developed (Fig. 11). Abundant bivalve and gastropod molluscs, ostracods and foraminifera are found in the Çalkaya Formation (Figs. 10A, 10B; Glover and Robertson 1998; this study). Glover and Robertson (1998) interpreted the Calkaya conglomerate as marine in origin based on the occurrence of pebbles bored by sponges and marine bivalves. Pliocene – Upper Pliocene ages have been suggested for the Çalkaya Formation by Akay et al. (1985), and Glover and Robertson (1998) since it contains similar fossil assemblages as in the underlying Yenimahalle Formation (Fig. 3).

3.7. Tufa Deposits

The Antalya tufa and travertine deposits occur in an area of 30 km x 40 km on the west side of the Aksu Basin and continue southward under water into the Bay of Antalya. Much of the City of Antalya is founded on these deposits, which get thinner from the west (250 m) to the east (30 m). They conformably overlie the Pliocene Calkaya Formation (Fig. 9). The oldest tufa deposits at the bottom are made of clay-rich microcrystalline carbonates, containing gastropods and algal fossils. The entire tufa-travertine sequence is crosscut by two sets of NW-SE and NE-SW running, conjugate oblique-slip faults, which locally define the geometry of its margins and exposure. There is no absolute age for these tufa deposits.
3.8. Belkis Conglomerate

The Belkis Conglomerate is the youngest unit in the Aksu Basin, and rests unconformably over the Pliocene Yenimahalle and the Miocene Karpuzcay Formations (Fig. 12). It crops out only in the southern part of the basin, in the Yenimahalle-Çalkaya sub-basin (Fig. 2). It is lithologically similar to the underlying Pliocene conglomerate of the Yenimahalle Formation. It is highly heterogeneous and composed mainly of rounded clasts of Cretaceous limestone, serpentinite and chert in a poorly sorted sandstone-siltstone matric (Fig. 12). The ancient city of Aspendos was built of and on this conglomerate.

Based on our stratigraphic, sedimentological and fossil observations and the results of the previous studies in the Aksu Basin, we interpret its sedimentological record as a manifestation of deposition in a fluvial, fluvial-delta, beach setting in the middle Miocene, progressing in time to a lacustrine and lagoon environment in the latest Miocene, and then to a brief period of tidal flat and very shallow marine (marine incursion?) conditions in the early Pliocene. Return to entirely terrestrial conditions and deposition in fluvial floodplains and channels along the ancestral Aksu River, together with the regional uplift, produced the Pleistocene fluvial terraces of the Belkis Conglomerate.

4. STRUCTURAL GEOLOGY AND ARCHITECTURE OF THE AKSU BASIN

The Aksu Basin is a NNW-SSE-oriented, rectilinear depocenter, which is about 15 to 30 km wide and 80-90 km long, and it is bounded on its three sides by the Mesozoic sequences of the Tauride belt (Fig. 2). The Antalya tufa and travertine deposits delimit the SW edge of the basin, and the Quaternary coastal sediments of the Bay of Antalya cover its units in the south. The Aksu Basin is bounded on the east by the Paleozoic–Mesozoic platform carbonates, Triassic-Jurassic rift-drift assemblages and ophiolitic rocks of the Antalya complex (Figs. 2 and 13) (Poisson et al., 1984; Poisson et al., 2003). To the west, the Aksu basin is juxtaposed against the Beydaglari carbonates of the Tauride Platform along oblique-slip faults and/or unconformities (Figs. 2 and 13). In the north, the middle Miocene Aksu Formation locally overlies the Lycian Nappes and Bey Daglari carbonates unconformably; however, locally the Aksu Formation rocks tectonically rest on these two tectonostratigraphic units along a low-angle, NW-vergent thrust fault (Fig. 2).
4.1. Intra-basinal regional fault patterns and kinematics

We have divided the entire Neogene Aksu depocenter into two sub-basins based on the areal distribution of the sedimentary strata, fault patterns and kinematics, and fault-controlled deformation along and across the basin axis (Figs. 13 and 14). The Aksu-Karpuzcay sub-basin in the north is predominantly filled with the middle to upper Miocene (Langhian-Tortonian) sequences of the oldest Aksu and Karpuzcay Formations (Fig. 13). The original stratigraphic contacts between these two formations are superimposed by normal and transtensional oblique-slip faults, along which the Aksu Formation units are invariably exposed in the footwalls (Fig. 15). The Yenimahalle-Çalkaya sub-basin in the south consists mainly of the younger Plio-Pleistocene sequences and of the Uppermost Miocene Gebiz Limestone and the Eskikoy Formation in part (Fig. 14). The modern Aksu River valley and its Quaternary deposits also occupy the center of this sub-basin. Stratigraphic contacts between the various formations remain intact and the basinal strata generally show gentle to sub-horizontal dip angles, collectively indicating that this sub-basin has experienced less deformation effects in comparison to the Aksu-Karpuzcay sub-basin to the north.

The basinal strata in the both sub-basins are crosscut and displaced by two systems of NW-SE – and NE-SW – striking, conjugate oblique-slip faults, which locally truncate and offset the modern Aksu River and its tributaries (Figs. 13 and 14). These faults are almost all transtensional in nature with significant normal-slip components, and they cause local uplifts and knick-points along streams and stream channels (Fig. 16). Pull-apart sub-basins and small Quaternary depocenters are locally well developed along these transtensional faults (Fig. 14). The rectilinear margins of the Pleistocene Antalya tufa and travertine deposits are also defined by these faults systems (Fig. 3). These observations collectively indicate that some of these NW-SE – and NE-SW – striking, conjugate faults are active.

Directions of tectonic offset along the stratigraphic contacts, formation boundaries and bedding layers show that the majority of the NW-SE – and NE-SW – striking, conjugate faults are right-lateral in their slip sense, and that the amount of displacement vary between tens of meters to several km (Figs. 13 and 14). Figures 17 and 18 show a series of interpretive structural cross-sections, taken across and parallel to the axes of the two sub-basins, that depict the geometry and spatial distributions of these transtensional fault systems. The fault geometries on
these cross-sections are based on our measurements of the surface expressions of the observed fault planes, and the stratigraphic thicknesses of the formations are constrained based on the extant borehole data from the Aksu and Manavgat Basins that extend down to the basinal strata for several km.

The E-W-trending profiles (AA’ through DD” in Figure 17) show that the transtensional fault systems affect the nearly 3-km-thick basinal strata, and that they extend down into the basement units beneath the sedimentary basin sequences. The fault recurrence interval is about 3 to 4 km on average in both sub-basins. Fault planes are mostly planar (no listric geometry) and dip moderately to steeply. Sedimentary layers in the hanging walls of some of the faults exhibit 15° to 60° horizontal-axis rotations and tilting, associated with syn-depositional faulting (Figs. 13, 14, 17 and 18). The characteristic horst and graben structure produced by these transtensional faults systems in both sub-basins indicate that fault-controlled subsidence was important in additional accommodation space development within the entire Aksu Basin. The entire Aksu Basin sedimentary package is underlain by the rift-drift and ophiolitic assemblages of the Antalya Complex (Dilek and Rowland, 1993), which in turn rests tectonically on the Cretaceous carbonates of the Bey Daglari Platform along a west-vergent thrust fault (Fig. 17).

The NW-SE-trending profiles (EE’ through GG” in Figure 18) display similar structural features as those observed along Profiles AA’ through DD”. In addition, we observe on these three profiles that fault-controlled tilting of the sedimentary strata is minimal (<10°) to none, and that the Plio-Pleistocene stratigraphic units in the Yenimahalle-Çalkaya sub-basin maintain their sub-horizontal to horizontal, initial depositional geometries. Deposition of the Karpuzcay Formation appears to be controlled by transtensional fault-controlled increase in its accommodation space during the middle Miocene (Profiles EE’ and FF’ in Fig. 18).

4.2. Intra-formational fault patterns and kinematics

Faults, fault patterns, their crosscutting relationships, and fault kinematics were also mapped on outcrop-scales along roadcuts in both sub-basins in the field. The outcrop-scale faults mimic the geometry and kinematics of the intra-basinal regional faults in general, and show the similar patterns in NW-SE – and NE-SW- striking fault orientations. Figures 19, 20 and 11 show the outcrop maps of the sedimentary strata and the measured faults in the Aksu, Yenimahalle and
Calkaya Formations, respectively. In all three formations, the moderately to steeply dipping faults have average spacing of 5-10 cm to several meters and form extensional mini horst-graben structures. Similar to their regional counterparts, these smaller-scale faults also show pure normal to oblique-slip sense of displacements, indicating their transtensional nature. Most of them are planar with mm-scale damage zones along them. Some faults are buried by the overlying, younger sedimentary layers, indicating their syn-depositional origin (i.e., Fig. 11). Where slickenside lineations and shear sense indicators are observed (i.e., Fig 16), the kinematics of transtensional faulting is well documented.

4.3. Structural analysis

Representative bedding plane and fault plane orientations are plotted in lower-hemisphere, equal-area projections to analyze their density distribution in 2-dimensions (Figs. 21 and 22). Figure 21 displays the bedding plane orientations measured in the Aksu, Karpuzcay, Eskikoy and Yenimahalle/Çalkaya Formations in both great-circle (upper panels) and contour diagram plots (lower panels). We observe two important phenomena in these plots: (1) Bedding planes measures in the oldest two formations (Aksu and Karpuzcay) dip moderately to steeply to the NE and SW. A clear majority of the outcrop maps in the Aksu Formation dip to the E-NE, toward the eastern margin of the basin, whereas the faults in the slightly younger Karpuzcay Formation show a more bimodal distribution. (2) Bedding planes in the younger (uppermost Miocene and Plio-Pleistocene), Eskikoy, Yenimahalle and Çalkaya Formations are subhorizontal to very gently-dipping, indicating that they have not been affected much by fault-induced tilting.

Figure 22 displays the fault plane orientations measured in the Aksu and Yenimahalle/Çalkaya Formations in great-circle plots. Based on unequivocal shear sense indicators observed in the field, we have classified the outcrop-scale faults as normal (left panels) and oblique-slip (right panels) faults. The normal faults in all three formations are oriented NE-SW with moderate to steep dips to the NW and SE. We see a slight deviation of the fault plane azimuths in the younger Yenimahalle/Çalkaya Formations to a more northerly orientations, suggesting a ~20°-30° counterclockwise rotation of the minimum principle stress (Sigma-3) orientation across the basin during the Plio-Pleistocene. The oblique-slip transtensional faults (upper-right panel) in the oldest Aksu Formation exhibit nearly N-S-oriented azimuths with steep dips to the east, whereas those in the younger Yenimahalle/Çalkaya Formations (lower-right
panel) have NW-SE-azimuths with very steep dips both to the north and the south. This observation is also consistent with a slight counterclockwise rotation of the minimum principle stress (Sigma-3) orientation across the basin during the Plio-Pleistocene.

4.4. **Eastern margin of the Aksu Basin: Its nature and kinematics**

Our systematic study of the intra-basinal and intra-formational faults, their patterns and kinematics, and our structural analysis indicate that the NE-SW – and the NW-SE – oriented conjugate fault systems are the components of a region-wide transtensional deformation and stress regime that have affected the middle Miocene and younger Aksu basinal strata. There is no structural evidence for thrust faulting and related contractional deformation in the eastern Aksu Basin strata. Then, the major question that needs to be addressed is the nature of the fault contact between the basinal strata and the older Antalya Complex along the eastern margin of the Aksu basin (Figs. 2, 13 and 14). A west-directed thrust fault origin of this contact, as proposed in some of the previous studies (Poisson et al., 2003; Ciner et al., 2008; Poisson et al., 2011), is not compatible with the fault patterns and kinematics we have observed in and across the basin. Therefore, we made several traverses along and across this major tectonic discontinuity along the eastern margin of the Aksu Basin during the course of this study.

The Neogene sedimentary rocks of the Aksu Basin are juxtaposed against the Triassic-Jurassic and Cretaceous rift-drift and ophiolitic assemblages of the Antalya Complex along a major, NW-SE – running oblique-slip normal fault, along which the basinal strata are situated in the hanging wall. The topographic gradient across this oblique-slip fault is 500 m and more, with the Antalya Complex making up the rugged, uplifted footwall units (Figs. 2, 13 and 14). Field images in Figures 23, 24 and 25 display the regional extent of this fault system and its effects on the landscape along and across the eastern margin of the Aksu Basin. The generally NW-SE-running, dextral oblique-slip fault system displays short NE-SW bends and jogs, along which the mode of displacement is normal with the down-dropped hanging walls commonly facing to the NW. The sedimentary layers in the Aksu Formation in the hanging walls dip moderately to steeply to the east, into the W-SW-dipping fault planes of the NW-SE-oriented transtensional fault system along the eastern margin of the basin (Figs. 17 and 18). These features are analogous to those structures documented from extensional fault systems in rifted passive margins and metamorphic core complexes.
Figure 26 exhibit a series of field photos from the faulted contact between the Aksu Formation and the Triassic rift-drift sequence across from the Karacaoren Dam and near the Village of Haciismailler (Fig. 2). A heterogeneous conglomerate of the Aksu Formation rests on the hanging wall of a steeply west-dipping oblique-normal fault (Fig. 26A) and shows moderate dips (~40°) to the east, into the fault plane. The slickenside lineations on the fault plane (Triassic rock units) here have shallow rakes and low-angle plunges to the SW (Fig. 26B), suggesting oblique-normal fault kinematics. Farther to the east into the Triassic sequence in the footwall, we see tight, upright to west-overturned folds in hemi-pelagic sandstone, siltstone and shale rocks (Fig. 26C). These ductile structures in the Triassic-Jurassic and Cretaceous units are the manifestations of the westward tectonic emplacement of the Antalya Complex from a Neotethyan oceanic basin onto the passive margin of the Tauride carbonate platform in the late Cretaceous. They do not represent Miocene and younger contractional structures.

5. TECTONIC EVOLUTION OF THE AKSU BASIN

5.1. Boundary conditions

The structural data and analysis presented in this study indicate the effects of transtensional deformation associated with a major right-lateral, oblique strike-slip fault system along the eastern margin of the Aksu Basin. The minimum age of the development of this right-lateral oblique-slip fault system appears to be middle Miocene, based on the oldest sedimentary units in the Aksu Basin. Transtensional deformation in the broader Isparta Angle area has been proposed by other researchers (Glover and Robertson, 1998a, 1998b; Aksu et al., 2014; Deveci and Kocyigit, 2007; Verhaert et al., 2006; Temiz et al., 1997, 2000; Over et al., 2013).

Using the offshore seismic reflection data from the Bay of Antalya farther south, Hall et al. (2014) proposed that the bay and the eastern limb of the Isparta Angle have undergone extensive extensional deformation since the late Miocene. Their seismic profiles (NE of Lines F, L and K) do not show any structural evidence for Tortonian and younger contractional deformation in and across the bay.
5.2. Tectonic model

Using our structural data and interpretations, the existing information in the literature, and the regional boundary conditions discussed above, we put forward a tectonic model to explain the geological evolution of the Neogene Aksu Basin in a broadly transtensional stress regime, associated with a dextral oblique-slip fault zone in the eastern limb of the Isparta Angle (Fig. 27). In this model, the inferred transtensional fault system is a splay of a broader dextral shear zone, which is part of a right-lateral transform fault domain that connects the Cyprus Trench to the east with the Pliny – Hellenic Trench to the west (Fig. 27A). The nearly N-S-trending, Neogene Aksu, Manavgat and Köprücay Basins and the Aksu and Kirkkavak Faults separating these basins within the Isparta Angle are all situated along this broad transform fault domain.

We posit that following the last episode of contractional deformation that emplaced the Lycian and Hoyran-Beysehir Nappes from the north onto the Tauride Platform in the south during the early Miocene, the right-lateral transform fault plate boundary was established between the Cyprus Trench and the Isparta Angle. Initial phases of transtensional deformation along this boundary created a hybrid, terrestrial-shallow marine accommodation space on the eastern limb of the Isparta Angle for the deposition of sediments derived mainly from the Antalya Complex (to the east) (Fig. 27B). The middle to Upper Miocene Aksu and Karpuzcay Formations were deposited in fluvial, deltaic to beach environments situated in the hanging walls of WNW-dipping regional normal faults and adjacent to the NW-SE-running dextral transtensional depocenters. Rapid uplift of the Antalya Complex in the footwalls of these transtensional fault systems provided the topographic gradient and gravitational potential energy for the necessary fluvial erosion and transport for sediment supply.

The continued dextral slip along the Aksu Fault on the eastern margin of the basin and the establishment of a sinistral fault system to the west, separating the Aksu Basin from the Baydağları Platform of the Tauride belt, produced N-NW-directed contraction along the northern margin of the basin. This process triggered intra-basinal uplift and southward tilting in the northern part of the basin, and shifted the main accommodation space within the basin farther south. The Yenimahalle-Çalkaya sub-basin developed within this new depocenter, receiving more sediments (Jurassic-Cretaceous micritic limestones) from the recently uplifted Beydağları platform in the west during the latest Miocene-early Pliocene. The ancestral Aksu River fluvial
system developed within this new sub-basin, forming the Messinian-lower Pliocene river terraces. A NW-SE-oriented lake formed in the eastern margin of the new sub-basin and produced the Gebiz Limestone (Figs. 14 and 27B). Following the end of the Messinian Crisis in the Mediterranean and as a result of rising sea-level, a marine incursion into the Yenimahalle-Çalkaya sub-basin generated a hybrid environment of salt and fresh water setting in tidal flats and delta fronts, where the Pliocene Yenimahalle-Çalkaya Formations were deposited.

The sinistral transtensional fault system (Antalya Fault) along the western margin of the Aksu Basin triggered the development of cold springs, which in turn produced the Antalya tufa and travertine deposits in the early Pleistocene. The youngest fluvial terraces along the ancestral Aksu River formed the middle Pleistocene Belkis Conglomerate within the sub-basin.
6. CONCLUSIONS

This study of the structural and tectonic evolution of the Aksu Basin allows us to draw the following conclusions.

- There are two major sub-basins in the Neogene Aksu Basin with different stratigraphy and structural patterns: Aksu-Karpuzcay in the north and the Yenimahalle-Calkaya in the south. The southern subbasin includes the younger, Plio-Pleistocene sedimentary sequences, whereas the northern sub-basin contains the older, Miocene sequences that display stratigraphic and structural evidence for the initial development of the Aksu Basin.

- The stratigraphy and the structural architecture of the NNW-SSE – trending Aksu Basin were controlled by right-lateral, transtensional deformation that affected the entire eastern limb of the Isparta Angle. This transtensional deformation was associated with a right-lateral transform fault domain that connects the Cyprus Trench to the east with the Pliny – Hellenic Trench to the west.

- NW-SE – and NE-SW – oriented, two major conjugate fault systems that operated synchronously with deposition affected the local accommodation space development and horst-graben formation within the basin.

- The purported “Aksu Thrust” along the eastern margin of the Aksu Basin does not exist. This fault is a dextral, transtensional fault, along which the Triassic-Jurassic rocks of the Antalya Complex are uplifted in its footwall.
7. REFERENCES


Islamoglu Yesim, 2002, the molluscan fauna and stratigraphy of Antalya Miocene basin West-Central Taurids, SW Turkey. Bulletin of the Mineral Research and Exploration Institute of Turkey 123-124, p. 27-58


Figure 2

Geological Map of the Aksu Basin

ANTALYA COMPLEX
- Kecili Formation (U. Cretaceous)
- Kikdir Formation (Upper Cretaceous)
- Carbonate Units (Triassic-Jurassic)
- Beydağları Platform
- Beydağları Carbonates (Jurassic-Cretaceous)
- Kuyubasi Dolomite (Middle-Upper Triassic)
- Kumluca Formation (M. Triassic-Maastrichtian)

Strike-slip fault
Thrust fault
Normal fault
Up/Down

Antalya Tufa and Travertine

Bay of Antalya

MEDITERRANEAN SEA
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<th>EPOCH</th>
<th>AGE</th>
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<th>THICKNESS (m)</th>
<th>FORMATION</th>
<th>LITHOLOGY</th>
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<td>Tortonian</td>
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<td>1200 - 2000</td>
<td>Karpuzcay Formation</td>
<td>Conglomerate, red colored sandstone, siltstone, mudstone intercalations with cross-beds and laminations. Locally tuffaceous sandstone. Mostly calcareous cement. Mudstone as 15-20 cm long concretions. Clasts in the conglomerate include: chert, serpentine, dolerite, Jurassic limestone, Triassic sandstone.</td>
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<td>Serravalian</td>
<td>Aksu Formation (KF)</td>
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<td>Aksu Formation</td>
<td>Several meters thick conglomerate intercalated with thin layers of siltstone, sandstone and laminated tuffaceous sandstone. Poorly sorted conglomerate with rounded clasts of mainly Jurassic limestone. Triassic sandstone, serpentine, chert, dolerite and basalt.</td>
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<td>Early Late</td>
<td>Calkaya Formation</td>
<td>270</td>
<td>Yenimahalle Formation</td>
<td>Siltstone, sandstone and mudstone interlayers; clayey limestone, conglomerates on top with local paleosol deposits. Extensive bioturbation. Cross-bedding, channel deposits.</td>
<td>Tidal flat and shallow marine</td>
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<td>Piacenzian</td>
<td>Antalya Travertine</td>
<td>250</td>
<td>Antalya Travertine</td>
<td>Coarse-grained sandstone-siltstone with cross-beds and lenticular conglomerate layers with clasts of Triassic-Jurassic limestone.</td>
<td>Fluvial-delta tidal flat</td>
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Figure 7
Figure 9
Figure 13
Figure 19
### Aksu Formation

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### Yenimahalle-Calkaya Formations

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Figure 23

NW  SE

Ophiolitic Melange  Gebiz Limestone

Yenimahalle Formation  Gebiz Town

NNW  SSE

Gebiz Limestone  Unconformity  Ophiolitic Melange

Alluvium  Triassic-Jurassic carbonates  Karpuzcay Formation
Figure 24
Figure 26