Tectonic evolution of the Menderes massif core complex and Alasehir graben, southwestern Turkey: counter evidence to a rolling-hinge mechanism

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ABSTRACT

New structural evidence suggests that the evolution of the Alasehir graben and exhumation of the Menderes massif core complex in southwestern Turkey cannot be explained by the commonly applied rolling-hinge model. I examine micro- and mesoscale deformation across the Alasehir detachment fault. Petrographic analysis of Sahlili granitoid footwall rocks demonstrates depth-varying ductile deformation, and kinematic and petrofabric co-ordination with host Menderes massif metamorphic rocks. Using existing geochronological data, I constrain the Sahlili granitoid as an early Miocene synextensional pluton exhumed from mid-to-upper crustal levels. I also conduct theoretical fault displacement analysis on late-stage brittle normal faults in the Neogene strata of the detachment’s hanging wall, which yields a post-Miocene extension of >7%.

Integrated observations including late-stage slip, lack of microstructural foliation-parallel contraction and non-systematic cross-cutting mesoscale fault relations across the detachment suggest that the rolling-hinge mechanism does not govern core complex exhumation. Close temporal and spatial relations of synextensional plutons with initiation of regional extension predict that magmatism plays an important role in geodynamic evolution. I recommend a thermotectonic model that incorporates effects of crustal heating to better explain the character of core-complex development for a highly extended terrane with a strong magmatic history.

Keywords: Menderes metamorphic core complex, detachment, rolling-hinge, western Anatolia, Turkey
INTRODUCTION

The Alasehir graben is located in the eastern part of the Aegean extensional province (Fig.1). The province, which encompasses western Turkey, the Aegean Sea and the Balkan region, has been a site of widespread continental extension since the Oligocene (Ciftci and Bozkurt, 2007).

Numerous studies have focused on the structural and regional geology of the Alasehir graben (e.g. Hetzel et al., 1995a,b; Purvis and Robertson, 1997,2001; Sozbilir, 2001) and graben evolution (e.g. Cohen et al., 1995; Kocyigit, 1999; Yilmaz et al., 2000; Seyitoglu et al., 2002; Purvis and Robertson, 2005a). Yet, inferences regarding basin development and detachment faulting remain controversial. Some authors suggest that the tectono-evolution of the Alasehir graben is governed by a rolling-hinge mechanism. The presently inactive Alasehir detachment fault on the southern margin of the graben is a previously high-angle detachment fault that progressively rotated to its current low-angle dip (Gessner et al., 2001; Seyitoglu et al., 2002; Isik et al., 2003; Cemen et al., 2005; Seyitoglu and Isik, 2009). Others interpret the fault as an initially low to moderate-angle listric structure (Hetzel et al., 1995b; Kocyigit, 1999; Sozbilir, 2001). Most deductions are based on simplistic deductions obtained from preliminary stratigraphic interpretations.

Accordingly, I present structural evidence that shall better explain the evolution of the graben system in relation to ductile and brittle deformation across the Alasehir detachment fault. Based on recent field work conducted in the Degirmendere valley near Sahlili, I provide (1) a microstructural account of the ductile-brittle transition along the Alasehir detachment fault based on petrographic analysis of the Sahlili granitoid footwall.
Figure 1. Simplified tectonic map of the Aegean and Mediterranean region with main plate boundaries, major suture zones and fault systems. White arrows indicate direction of plate convergence; black arrows show direction of Miocene-Recent extension. Square outline depicts location of study. EAFZ - East Anatolian fault zone, IAESZ - Izmir-Ankara suture zone, ITS - Inner-Tauride suture, MM - Menderes massif, NAFZ - North Anatolian fault zone (modified from Dilek, 2006).
rocks, (2) fault displacement analysis of late-stage brittle structures and a quantitative
estimate of extension in Neogene synextensional sediments of the hanging wall and (3) a
reconstruction of the deformation history of the region based on integrated micro- and
meso-scale observations in the footwall and hanging wall of the Alasehir detachment
fault. By doing so, I suggest that the commonly applied rolling-hinge model (cf. Buck,
1988) is not sufficient in explaining the exhumation record of the central Menderes
Massif core complex and related graben system; the present low-angle orientation of the
Alasehir detachment most likely reflects the fault’s original dip.

**GEOLOGIC SETTING**

**Extensional tectonics in western Turkey**

Southwest Turkey is dominated by E-W trending graben basins (Fig. 2). These
basins developed as a response to pervasive crustal extension in late Oligocene-early
Miocene time (Dilek, 2006). However, interpretations regarding causes, stages and
timing of extension in western Turkey are controversial. Three main tectonic models
have been proposed to explain the cause of N-S extension in western Turkey. These
include (1) Late Oligocene-Early Miocene orogenic collapse of thickened crust following
closure of the Neotethyan ocean along the Izmir-Ankara suture (Seyitoglu and Scott,
1991) (2) back arc spreading with slab rollback resulting in southward migration of the
Aegean trench (McKinzie, 1978; Le Pichon and Angellier, 1979; Jackson and McKinzie,
1988; Jolivet et al., 1998; Okay and Satir, 2000) and (3) tectonic westward escape of the
Anatolian Plate along the plate’s boundaries, East Anatolian and North Anatolian fault
systems (Dewey and Sengor, 1979; Sengor, 1985). Although proposed onset of extension
Table 2. Simplified regional geologic map showing distribution of main graben basins and salient fault systems in southwestern Turkey. 

Alasehir graben (AGr) study in square outline. AG - Acipayam graben, AGr - Alasehir graben, BaG - Baklan graben, BG - Burdur graben, BMG - Buyuk Menderes graben, DB - Demirci basin, GB - Gordes basin, KB - Kavacik Basin, KG - Kutahya graben, KMG - Kucuk Menderes graben, SB - Selendi basin, SG - Simav graben, UGB - Usak-Gure basin (modified from Ciftci and Bozkurt, 2008).
varies between 5 to 60 Ma, many commonly agree that extension initiated by latest Oligocene-early Miocene time.

**Menderes Massif**

The Menderes metamorphic complex is a NE-SW oriented sub-elliptical metamorphic dome that is cross-cut by three main graben systems: the Alasehir graben to the north, Kucuk Menderes graben in the central portion and Buyuk Menderes graben in the south (Fig. 2). These grabens subdivide the Menderes massif into northern, central and southern submassifs respectively. The submassifs are characterized by a Precambrian core sequence that consists of augen gneisses, metagranites and high-grade schists with a Palaeozoic-Cenozoic cover sequence that includes schists and marbles of varying metamorphic grade (Bozkurt and Oberhansli, 2001).

The basal and cover sequences of the Menderes massif collectively consist of several nappe systems formed during the late Mesozoic-early Cenozoic shortening events in western Anatolia (Ring et al., 2001). Metamorphism is said to have resulted from burial associated with the emplacement of the Lycian nappes and ophiolitic thrust sheets (Yilmaz, 2002). Subsequent exhumation of the Menderes massif is suggested to have initiated at 36±2 Ma (Lips et al., 2001).

**The Alasehir graben and detachment**

The Alasehir graben (Seyitoglu and Scott, 1996), also referred to as the Gediz graben (Bozkurt and Sozbilir, 2004; Ciftci and Bozkurt, 2007, 2008, 2009; Lips et al., 2001), is an east-west trending structure that is approximately 150 km along strike. Graben fill varies in age from Miocene to Recent time and forms the cover units to the pre-Neogene metamorphic basement of the Menderes massif (Yilmaz et al., 2000;
Seyitoglu et al., 2002). Prominent lithologies comprise laterally gradational fluvial and alluvial conglomerate, sandstone and mudstone. Rocks are poorly lithified and clast population indicates the Menderes massif as the main sediment source.

The Alasehir detachment fault (Fig. 3), also referred to as the Karadut detachment (Emre and Sozbilir, 1997), Kuzey detachment (Gessner et al., 2001) and Camkoy detachment (Kocyigit et al., 1999), is located on the southern margin of the Alasehir graben. The low-angle (~20°) north-dipping normal fault marks the abrupt contact between the metamorphic Menderes massif core complex basement in the hanging wall and the Neogene basin sediments in the hanging wall. Three major intrusive granitoid bodies, including the Sahlili granodiorite (Fig. 4), occur along the footwall of the fault in the central submassif of the Menderes core complex.

**THE ROLLING-HINGE MODEL**

Low-angle (dip<30°) detachment faults are controversial because (1) slip on low-angle normal faults does not conform to the current theory of fault mechanics and (2) major earthquakes (M>6) on such faults are rare (Axen, 2007). Several models have been formulated which explain detachments as initially steep normal faults that rotate to gentle dips; some rotate while slipping, accompanied by intervening blocks (Proffett, 1977) while others rotate passively to lower dips.

Isostatic rebound is the suggested mechanism responsible for tilting such large-scale detachment faults (Spencer, 1984). As the upper plate is displaced laterally, the footwall progressively rebounds and arches into a dome, rotating the high-angle fault to gentler dips. This “rolling-hinge” mechanism thus can be applied to initially steep faults that tilted to gentler dips.
Figure 3. Field photomosaics depicting (a) exposed footwall surface (F) of the Alasehir detachment and overlying hanging wall (H) basin sediments. E-W trending Alasehir graben with northern shoulder visible in the far distance. (b) North-dipping (~20°) detachment surface with highest present elevation of ~1250m.
Figure 4. Local geologic map of the study region showing occurrence of the Sahlili intrusive, pre-Neogene Menderes massif metamorphics and Miocene basin sediments. Thin-section samples collected from exposures in the Degirmendere valley. A-A’ cross-section profile of supradetachment basin and Neogene strata on Alasehir detachment (modified from Oner et al., 2009).
The rolling hinge model (Buck, 1988; Wernicke and Axen, 1988) proposes that a normal fault surface consists of a more steeply dipping active ramp that is progressively unroofed and rotated to a lower dip by an antiformal hinge that migrates through the footwall (Fig. 5). The footwall rises as it becomes tectonically denuded by hanging-wall slip with the result that the active ramp is eventually abandoned and left behind as an inactive low-angle fault surface. Subsequently, a new fault system develops in the hanging wall of the initial fault with the original throw of the initial fault remaining constant after rotation.

Thus, predictions of the rolling-hinge model include (Beratan and Neilson, 1996):

1. Active faulting that migrates through space and time; depositional basins will form sequentially in the down-dip direction.

2. Range sized blocks will be stranded on top of flattened up-dip sections of the detachment fault. Slip will continue on the steeply dipping, active, down-dip section.

3. Blocks near the hinge will not be subject to large rotation. Detached upper-plate blocks will rotate significantly away from the hinge, as the hinge migrates further in the down-dip direction.

4. Isostatic rebound will occur immediately after tectonic unloading. Location of uplift caused by isostatic rebound will also follow direction of fault migration.

Field tests for rolling-hinge models, ones that provide consistent structural evidence for temporal fault migration and associated sedimentological deposition, include examining strain patterns in the rocks of the footwall of a normal fault. According to
Figure 5. Schematic model of rolling-hinge mechanism. Normal fault surface, in dark outline, consists of a steeply dipping active ramp. As the hanging wall (HW) is displaced laterally, the footwall (FW) isostatically rebounds and arches into a dome. This results in rotation of the fault block that occurs by antiformal hinges. The hinges are fault bend folds that migrate through the footwall in the down dip direction. Note the structurally higher relative position of the footwall, as indicated by the red dots, with progressive rotation.

The widening fault segment with sequentially tilted fault blocks reach an orientation where slip can no longer be accommodated. These are abandoned and left behind as inactive low angle fault surfaces. A newer fault is formed in the hanging wall to accommodate strain (modified from Axen and Bartley, 1997).
Axen and Bartley (1997), mylonitic foliation that develops in the early stages of detachment slip is useful in constraining strain histories as predicted by the rolling-hinge model. The foliation will commonly form in an orientation that is subparallel to the ductile shear zone. The foliation will also show evidence of hinge-related strain shortening as it enters the lower hinge and lengthening as it exits the hinge. Subsequently, foliation will display signs of lengthening as it enters the upper hinge and shortening on its exit from the upper hinge in the footwall. This implies that fabrics formed at the lower hinge may be overprinted by fabrics formed at the upper hinge.

Other structural methods for inferring the presence of a rolling-hinge mechanism in detachment faults comprise surveying depositional and tilting patterns in the hanging wall. The rolling-hinge model predicts that blocks of the hanging wall will be sequentially tilted and consequently abandoned with the migration of the passing hinge (Buck, 1988; Wernicke and Axen, 1988; Axen and Bartley 1997). In turn, faults and related synextensional sediments will typically form in a pattern that follows the direction of fault migration (Axen and Bartley, 1997), implying that these structures will progressively become younger in age towards the graben.

But, field tests are by no means conclusive, and compelling field observations that prove the existence of a rolling-hinge mechanism are lacking, especially in the case of the Alasehir graben. A micro- and mesoscopic examination of deformation structures and their implications, however, can lead to better informed conclusions about graben evolution.
Ductile deformation: Microstructural study of the Sahlili pluton in the footwall

The Alasehir detachment surface separates high grade metamorphic and igneous rocks of the Menderes core complex and Sahlili pluton in the footwall from the brittlely deformed Neogene basin sediments in the hanging wall. The NE-SW elongated Sahlili granodiorite pluton, which intruded the central Menderes submassif, is exposed within and below the Alasehir shear zone for over an area of more than 25 km$^2$.

This study examines a complete sequence of strained granodiorite samples, ranging from a relatively undeformed coarse-grained protolith outside the shear zone to highly strained, fine-grained mylonites proximal to the centre of the shear zone. Using optical microscopy, four microstructural types are recognized in the rocks of the Sahlili granodiorite: protolith, protomyolinite, myolinite and ultramylonite. These types represent an increase in intensity of mylonitization from relatively undeformed (protolith) to most highly deformed (ultramylonite). The boundary division between these types is arbitrary because a gradation between each exists. However, each type is readily recognizable by ductile fabric development, grain size and microstructural characteristics.

All thin sections of oriented samples are cut perpendicular to foliation and parallel to lineation.

Protolith
The light grey-coloured, holocrystalline, phaneritic, equigranular granodiorite is mainly composed of quartz, plagioclase, K-feldspar and biotite. Accessory minerals include apatite, allanite, titanite, zircon and opaque minerals. In thin-section, the protolith is characterized by coarse, relatively strain-free grains. Sericitization and argillitization alteration is common in plagioclase grains. Albite and Carlsbad twinning are also typical features.
**Protomylonite**

Slightly elongate feldspar grains and significant grain size reduction characterize the transition of the protolith to the protomylonite. Grain size reduction is evident along grain boundaries creating conjugate bands with small grains of quartz, referred to as recrystallization bands. The S-C fabric of the protomylonite is defined by fine-grained recrystallized quartz and mica that mark the C-planes, and feldspar porphyroclasts and minor aligned biotites that distinguish the S-planes. Kinematic indicators including ‘core and mantle structures’ and $\sigma$- porphyroclasts (Passchier and Trouw, 1996) formed by large feldspar porphyroclasts that are surrounded by recrystallized quartz ribbons (Fig. 6a).

**Mylonite**

Mylonites are characterized by further grain size reduction, with twinned feldspars that fracture commonly along cleavage planes. Shear-sense indicators include lozenge-shaped biotite fish and feldspar grains that define S-planes. The C-surfaces of the S-C fabric are marked by recrystallized euhedral biotite which extend as tails from the biotite fish and elongate recrystallized quartz ribbons (Fig. 6b). Some samples display $\sigma$- and $\delta$- asymmetric feldspar porphyroclasts with weak stair-stepping.

**Ultramylonite**

The microstructure of the ultramylonites is dominated by planar bands of very fine grained quartz, feldspar and biotite. Foliation is defined by slight grain elongation of feldspar, however, rounded, equant sized feldspar porphyroclasts are equally common. Fig. 7(a) shows a representative example (03DEG07) of this mylonite type. The regular S-C fabric that characterizes previous mylonite stages is no longer present.
Figure 6. Microstructural kinematic indicators observed in ductilely deformed granodiorite. (a) photomicrograph of protomylonite sample 32DEG07 showing S-C fabric. C-planes are defined by fine-grained recrystallized quartz (Qtz) and biotite (Bt). S-planes are marked by feldspar porphyroclasts (Plag), ribbon Qtz and minor Bt. (b) photomicrograph of mylonite sample 21DEG07. Lozenge shaped biotite fish and asymmetric feldspar porphyroclasts characterize S-planes. Biotite fish tails and elongate quartz ribbons define C-planes. All thin sections cut parallel to lineation and normal to foliation plane. XPL.
Figure 7(a). Photomicrograph of ultramylonite sample 03DEG07 with foliation defined by rounded and slightly elongate feldspar porphyroclasts set in a fine-grained matrix of quartz (Qtz), feldspar (Plag) and biotite (Bt). (b) Photomicrograph of ultramylonite sample 31DEG07 shows brittle microfaulting overprint ductile mylonitic fabric. All thin sections cut parallel to lineation and normal to foliation plane. XPL.
Cataclastic deformation is also observed in the footwall of the Sahlili granodiorite rocks. Cataclasis progressively increases proximal to the Alasehir detachment surface and a gently north-dipping cataclastic foliation is observed sub-parallel to the main detachment fault. In thin section, cataclasites, breccia and microbreccia display angular to sub-rounded quartz, feldspar and biotite that exhibit kinking, twinning and undulose extinction. Mineral assemblages of chlorite, sericite, epidote and calcite are common alteration products. Brittle structures include fractures, veining and microfaults (Fig. 7b) which overprint mylonitic fabric formed at depth.

**Brittle deformation: outcrop mapping and extension estimate in the hanging wall**

The Sahlili pluton mylonitic rocks and high-grade Menderes massif rocks are cross-cut by approximately E-W trending normal faults of variable dip. These faults correspond to late-stage deformation structures that are commonly observed in the hanging wall of the Alasehir detachment system. A wide range in scale exists: displacements range from kilometers to millimeters. Majority of these faults are north-dipping synthetic faults. However, antithetic S-dipping faults are not uncommon. Fault dip angles vary from low-angle (~25°) to almost subvertical (85°). In some sets, high-angle N-dipping faults cross-cut S-dipping faults, while in others S-dipping faults displace older N-dipping faults. Additionally, steeply dipping faults commonly appear to cross-cut gently dipping faults, though instances where the reverse is true are also observed (Fig. 8). Displacement by secondary faults is more pronounced in the hanging wall than in the footwall.

Extensional strain accommodated by late-stage brittle structures is measured along six cross-sectional exposures of the Miocene Gobekli unit in the hanging wall of
Figure 8. No regional systematic age difference can be interpreted from the cross-cutting relationships of multiple fault generations in the Gobekli unit. S-dipping antithetic fault F1 is cross-cut by N-dipping synthetic fault F2, both of which are older than the low-angle F3 fault that is subparallel to the main detachment. In another set, N-dipping synthetic fault F’1 is cross-cut by S-dipping antithetic fault F’2.
the Alasehir shear zone. Figures 9-11 show the existing variety of macroscopic fault
types, including high-angle synthetic and antithetic normal faults, low-angle normal and
listric faults. The ‘initial length’ technique (Gross and Engelder, 1995) determines
extensional strain in the scanline direction by dividing change in length of beds by the
original length (ΔL/L₀). The technique returns an average minimum extensional strain of
7.0±0.22%.

However, calculating extension by summing observed fault lengths commonly
underestimates the contribution of small, unobserved faults to total strain. Previous
studies have estimated extension from “small”, unsampled faults to determine total
elongation (Marrett and Allmendinger, 1991; Walsh et al., 1991; Gross and Engelder,
1995) by employing theoretical fault displacement population analysis. Total elongation
can be established from the heave (h) for each fault and the cumulative number of faults
sampled (N). The total number of faults with displacements greater than or equal to d is
written as

\[ N \approx d^C \]  \hspace{1cm} (I)

where the exponent C characterizes the relative abundance of large faults to small faults.
C is the negative slope of the central, linear portion of a log N vs. log h plot. Total
elongation is estimated using N when C<1.

A displacement population plot representing measured offsets in 106 faults
encountered in the Gobekli unit is shown in Fig. 12. The value of C≈1.17 indicates that
small faults accommodate a significant portion of the total strain; elongation along these
faults is more than or equal to elongation due to large faults (Fig. 12). Therefore, the
estimated 7%
Figure 9. (a) Field photo and (b) sketch of an outcrop surface in the upper Miocene Gobekli unit. The faulted sedimentary section is composed of distinct red coloured fluvial clastic rocks. Major north-dipping synthetic faults with minor antithetic faults form conjugate sets.
Figure 10(a). Field photograph and (b) sketch of Miocene Gobekli unit composed of lacustrine sediments. Note antithetic faults cross cut north-dipping synthetic faults.
Figure 11. Field photograph and sketch of micro-mesoscale faults in the Gobekli unit. Multiple fault generations with synthetic N-dipping faults are cross-cut by younger faults.
Figure 12. Fault displacement population of all faults identified through outcrop images. C=1.17, indicating that the 7% elongation underestimates the true elongation value for the survey area. N=number of faults sampled; h=fault heave.
tectonic elongation is less than the true value, which cannot be accurately estimated from the sampled population of faults.

**DISCUSSION**

*Synextensional granitoid pluton*

Microstructural features of feldspar, quartz and biotite demonstrate that mylonitization in the Alasehir shear zone took place in low to medium-grade conditions within a temperature range of ~250-400 °C (cf. Passchier and Trouw, 1996). The occurrence of ‘core and mantle structures’ constituting slightly deformed host grains and recrystallized grains near the edges in the protomylonites suggest that dislocation creep (Barber, 1985) was the dominant deformation process. Large grains with mildly deformed centers to subgrains with bent twins imply that recrystallization occurred by subgrain rotation (van der Pluijm, 1991, Passchier and Trouw, 1996). The mylonitic foliation, defined by elongate feldspar grains, thus was possibly formed by dynamic recrystallization. Rotation recrystallization continued to transform large, protomylonitic grains into smaller recrystallized grains. This grain size reduction in the mylonites was further characterized by grain elongation (S-C structures, Fig. 6b) which involved grain boundary migration. The development of biotite fish suggests that basal plane slip also occurred simultaneously (Lister and Snoke, 1984). Finally, grain boundary sliding in superplastic deformation (Rutter et al., 1994) most likely formed the extremely fine-grained aggregates seen in the ultramylonites.

Kinematic indicators in the oriented samples include S-C fabrics, biotite fish, and σ- and δ- porphyroclasts that consistently show a top to N-NE normal sense of shear. These interpretations are in agreement with meso-scale shear indicators in the host metamorphic and granitoid rocks exposed in the Alasehir shear zone. The rocks display a
penetrative extensional fabric that is defined by a NE-SW trending, NNE-plunging mineral lineation and a gentle north-dipping (~25°) WNW-NNW striking mylonitic foliation (Isik et al., 2003).

The presence of ductile mylonitic rocks at the surface with relatively strain-free protolith at depth (Hetzel et al., 1995) suggests that the Sahlili granitoid is a mid-crustal synextensional intrusion (Fig. 13). An analogous retrograde greenschist facies overprint (Isik et al., 2003) as well as geometric and kinematic co-ordination of the Sahlili granitoid’s deformational fabric with that of the host metamorphic rocks further implies that both shared concurrent extensional deformation (cf. Davis and Reynolds, 1996).

Pluton emplacement and movement along major extensional detachments share close relations which help constrain the age of detachment faulting (Coney, 1980). Published geochronology data of the Sahlili granitoid and host metamorphic rocks present an approximate constraint on magmatism and timing of exhumation in the footwall of the Alasehir shear zone. Catlos et al. (2008) obtained a Th-Pb ion microprobe monazite age of 21.7±4.5 Ma for the Sahlili granitoid. This advocates that exhumation of the Menderes massif and crustal extension had already begun.

Evidence against rolling-hinge evolution

Previous studies suggest that the rolling-hinge model is a good model for the tectonic evolution of the Alasehir graben (Seyitoglu and Sen, 1998; Gessner et al., 2001; Seyitoglu et al., 2002; Isik et al., 2003; Cemen et al., 2005; Seyitoglu and Isik, 2009). According to the studies, the present geometry of the Alasehir graben is in accordance with the rolling-hinge model’s sequential development of fault systems and associated sedimentary units. The first initially high-angle fault, active in the Early Miocene, controlled the synextensional deposition of the Alasehir and Agidere units. The second
Figure 13. Sahlili granitoid showing progressive unroofing with continued extension through time. Accompanied formation of supradetachment basin and Neogene strata on the Alasehir detachment. Sediment flux from the footwall of the host Menderes massif and Sahlili granitoid is evident in the clast population observed in the Miocene units.
high-angle normal fault (Fig. 4), formed in the hanging wall of the initial Alasehir detachment fault, directed sedimentation of the Gozbekli unit. The most recent, currently active third separates the older graben fill from Quaternary alluvium. Each newly-formed fault system propagated rotation of the previous fault, resulting in the present day low-angle dip of the Alasehir detachment (Seyitoglu et al., 2002).

The temporal migration of graben development and sedimentological data from the hanging wall may allow interpretation in the context of a rolling-hinge model. However, data are insufficient to eliminate other modes of detachment evolution. In fact, our field evidence suggests that the rolling-model cannot be applied to explain the evolution of the Menderes massif and Alasehir shear zone. No foliation-parallel shortening is observed, as is predicted by the model. Results from the microstructural study show ductile structures that are uniformly developed with a top-to-NNE shear sense subparallel to the gently dipping detachment fault. This would not necessarily occur if the fault was initially high-angle and subsequently rotated to gentler dips as an inactive fault block at structurally upper levels of the crust.

Late-stage low-angle slip on the Alasehir detachment also rules out the occurrence of rolling-hinge tectonics. The low-angle detachment zone has recorded activity as recently as 7±1 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ laser-probe age dating performed by Gessner et al. (2001). The 7±1 Ma age reflects movement and further exhumation of the detachment fault during most of the Miocene. In addition, recent geochronological data (Lips et al., 2001) imply that extensional fabric in the Sahlili granitoid rocks continued to form during this time, and that the final cooling of the granitoid occurred in 1.9±0.4 Ma.
(Gessner et al., 2001b). These findings disagree with the rolling-hinge model that suggests an abandoned, inactive rotated low-angle fault.

Cross-cutting fault relationships in the brittle deformation of the hanging wall also show no systematic age difference between sets. As shown in Fig. 8, N-dipping high-angle faults offsets S-dipping and vice versa. Sub-horizontal faults cross-cuts and is cross-cut by both these sets. This confirms simultaneous fault activity.

The rolling-hinge model predicts that blocks near the high-angle hinge will not be highly rotated, while detached pieces of the upper plate will quickly rotate as they migrate away from the hinge. However, Figure 9 is a field photomosaic of the Gobekli formation, the older overlying basin strata, that shows sub-horizontal bedding. Yet, variable bed tilting relations characterize the Miocene units. This variability is attributed to active back-rotation and scissor faulting. Therefore, one cannot infer current subhorizontal bedding orientations of sedimentary strata to solely be a product of rolling-hinge rotation.

*Magmatism, metamorphic core complexes and highly extended terranes*

The above observations not only question the wide-spread applicability of the rolling hinge model on core complex formation, but also emphasize the simplistic model’s misleading attempt to characterize tectonically complex regions. Studies attributing the rolling-hinge model to the tectonic evolution of the Menderes massif and Alasehir shear zone have not considered potential effects of along-strike variations and magmatism in pre-extensional and synextensional settings. Buoyancy responses due to magma bodies or solidified plutons, stresses of injection and cooling as well as
consequent adjustment of the geothermal gradient (Axen and Bartley, 1997) can possibly modify local and regional stress fields.

This lack of attention to the magmatic history is especially significant as low-angle, core-complex style faulting “almost never occurs without accompanying magmatism” (Parsons and Thompson, 1993). Previous studies conducted in the Basin and Range Province of the North American Cordillera (Davis, 1980; Reynolds and Rehrig, 1980; Gans et al., 1989; Lucchitta and Suneson, 1996) and southern Aegean islands (Avigad and Garfunkel 1991) exemplify the critically important role of magmatism in development of highly extended terrains and metamorphic core complexes.

Recent works (Dilek and Whitney, 2000; Dilek and Altunkaynak, 2009; Dilek et al., 2009) have documented the geodynamics of late Cenozoic magmatism in the Aegean region. These studies link collision of the Sakarya and Anatolide-Tauride continental blocks in the late Paleocene-early Eocene with emplacement of plutons along the Izmir-Ankara Suture Zone and Sakarya block. Eocene volcanism is a result of slab break-off related asthenospheric upwelling and associated partial melting of the subducted-mesasomatized continental lithospheric mantle (Dilek and Altunkaynak, 2007). This causes thermal weakening of the crust, which when coupled with resumed Tethyan subduction and slab-rollback extension, coincides with tectonic collapse and initiation of extension in late Oligocene-early Miocene time. This is further intensified by rapid slab retreat of the Hellenic subduction zone and widespread pluton intrusions in the broader Aegean region.

As previously discussed, the early Miocene synextensional Sahlili pluton’s petrofabric and cooling ages correspond to the regional onset of extension and
accompanying magmatism. This demonstrates close temporal and spatial relations of
tectonic extension and magmatism, which have several different implications from
models on detachment evolution in which crustal heating is not a factor. The observations
indicate that upper and lower plate extension occurs in areas of thermally weakened crust.
Extension in deeper crustal levels is accompanied by intrusion of plutons, which are
mostly silicic in composition (Luchhitta and Suneson, 1996). The upper-crust is
sufficiently hot to allow ductile deformation at temperatures as low as 250-300° and the
formation of a low-angle fault (Parsons and Thompson, 1993).

Thus, this model allows us to predict that the timing and character of
metamorphic core complex deformation and detachment faulting cannot be isolated from
important effects of magmatism (Fig. 14). The rolling-hinge model may provide a
stratigraphic framework that allows explanation of low-angle faulting in the upper levels
of the crust, however, tectonic history of detachments show that core complex associated
deformation evolves in space and time with the onset, arrest and migration of crustal
heating.

CONCLUSIONS

The Sahlili granitoid is an early Miocene pluton that was exhumed from mid- to
upper levels in the footwall of the Alasehir detachment fault. The kinematic, geometric
and petrofabric co-ordination of the Sahlili pluton with that of its host Menderes massif
metamorphic rocks indicates that the Sahlili pluton is a synextensional intrusion.
Differentially strained rocks demonstrate the existence of depth-varying ductile
deformation.
Late-stage brittle structures with no systematic age differences characterize deformation of synextensional strata in the hanging wall of the Alasehir detachment fault. Insignificant translation of >7% of post-Miocene extension is accommodated by mesoscale synthetic and antithetic E-W high angle faults.

Combined observations of deformation in the hanging wall and footwall suggest that the rolling-hinge model cannot explain the evolution of the Alasehir graben. Despite appropriate sedimentological patterns, absence of microstructural foliation-parallel shortening and evidence of late-stage slip rule out the application of the rolling-hinge mechanism. Instead, I suggest that the low-angle orientation of the detachment fault reflects its relict dip.

Evidence against the rolling-hinge mechanism serves as a reminder that the evolution of core-complexes, detachment faulting and associated graben formation cannot be explained by stratigraphic inferences alone. Extension and magmatism are closely related, as exemplified by the age and deformation of the synextensional Sahlili pluton. In turn, timing and character of deformation in a core-complex are spatially and temporally determined by crustal heating. I recommend an integrated thermotectonic model to evaluate the timing and cause of initiation of core-complex exhumation, especially in a region with strong magmatic history like that of the Menderes massif and Alasehir detachment fault.
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REFERENCES CITED
Barber, D. J., Reeder, R. J., and Smith, D. J., 1985, A tem microstructural study of dolomite with curved faces (saddle dolomite): Contributions to Mineralogy and Petrology, v. 91, no. 1, p. 82-92.


-, 2005, Sedimentation of the Neogene-Recent Alasehir (Gediz) continental graben system used to test alternative tectonic models for western (Aegean) Turkey: Sedimentary Geology, v. 173, no. 1-4, p. 373-408.


Spencer, J. E., 1984, Role of tectonic denudation in warping and uplift of low-angle normal faults: Geology, v. 12, no. 2, p. 95-98.


Yilmaz, Y., 2002, Tectonic evolution of western Anatolian extensional province during the neogene and quaternary: Geological Society of America Abstracts with Programs, v. 34, no. 6, 179 p.