An active bivergent rolling-hinge detachment system: Central Menderes metamorphic core complex in western Turkey

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ABSTRACT

Two symmetrically arranged detachment systems delimit the central Menderes metamorphic core complex and define a bivergent continental breakaway zone in the Anatolide belt of western Turkey. Structural analysis and apatite fission-track thermochronology show that a large east-trending syncline within the Alpine nappe stack in the central part of the orogen is related to late Miocene–early Pliocene to recent core-complex formation. The syncline formed as a result of two opposite-facing rolling hinges in the footwalls of each of the two detachments. Back-rotation of the syncline limbs suggests that the detachments rotated from an initial dip of 40°–60° to a currently shallow orientation of 0°–20°.

Keywords: detachment faults, core complexes, fission-track dating, extension tectonics, Turkey.

INTRODUCTION

Metamorphic core complexes form when continental lithosphere extends at high rates and strain within the upper crust becomes localized in detachment faults. Detachment faults are commonly exposed as low-angle to horizontal shear zones, along which sedimentary or low-grade metamorphic rocks of a brittlely deforming upper plate are placed against medium- to high-grade rocks of aductly deforming lower plate. Controversy exists about the initial angle and incremental development of the detachment faults during core-complex formation. While some authors infer low-angle normal-fault geometries for the basal cutoff throughout the development of core complexes (Wernicke, 1981; Spencer, 1984) (Fig. 1A), others claim that the low dip angles are not original (Buck, 1988) (Fig. 1B). The latter author inferred that flat-lying detachments were rotated from an initial high angle into a low-angle orientation by upward flexing of the footwall as an isostatic response to unloading. Footwall uplift below detachment faults may occur in the form of a rolling-hinge mechanism, by which the footwall of a large-scale normal fault is progressively exhumed by a transient fault-bend fold migrating toward the hanging-wall plate (Axen et al., 1995). Axen and Bartley (1997) argued that rolling hinges are not restricted to steep initial fault dips, and that compelling geologic evidence for rolling-hinge tectonics is difficult to obtain. Laviet al. (1999) showed in a numerical model that an initially steep fault evolves into a rolling hinge in a self-consistent manner as a brittle-elastic response to lithospheric stretching of the upper crust.

We report on the structure and cooling history of the central Menderes metamorphic core complex in western Turkey, which is an example of an initially steeply dipping, bivergent rolling-hinge detachment system that has been active since late Miocene–early Pliocene time.

CENTRAL MENDERES METAMORPHIC CORE COMPLEX

The Anatolide belt of western Turkey formed during Eocene emplacement of Cycladic high-pressure units onto the Anatolian microcontinent, producing a regionally consistent greenschist facies foliation in all tectono-metamorphic units and in the shear zones defining their boundaries (Ring et al., 1999; Gessner et al., 2001). Since the early Miocene, the Anatolide belt has undergone distinct periods of extensional deformation (Şengör, 1987; Hetzel et al., 1995; Yilmaz et al., 2000). Defined by structural architecture and cooling history, the central Menderes metamorphic core complex extends ~100 km east-west and 50 km north-south in the central part of the Anatolide belt. It is bounded by two east-striking, symmetrically arranged detachment systems (Fig. 2), the north-down GuÈney detachment in the north (Hetzel et al., 1995) and the south-down GuÈney detachment in the south (Emre and Stözübirli, 1997), both of which cut the upper levels of the Alpine nappe pile for a distance of ~80 km. The GuÈney detachment dips 15°–20°N, and its hanging wall consists of south-dipping Miocene alluvial sediments, locally underlain by small volumes of amphibolite-grade orthogneiss. The footwall exposes a greenschist facies mylonitic shear zone of early Miocene age (Hetzel et al., 1995).

The GuÈney detachment is exposed along the northern shoulder of the Büyük Menderes graben as a 0°–15°S-dipping cataclastic shear zone that constitutes the basal cutoff to Neogene supra-detachment basins.
Down-dip displacement along the detachments is largest in the central part of the core complex; laterally the faults either die out or terminate against small-offset high-angle normal faults. A distinct garnet-bearing orthogneiss present in the internal part of the central Menderes metamorphic core complex as well as in the hanging wall of the Kuzey detachment suggests a minimum down-dip displacement of \( \sim 12 \) km (Fig. 3). Displacement-to-length relationships (Cowie and Scholz, 1992) of the fault roughly suggest a similar displacement at the Güney detachment.

The Kuzey and Güney detachments root in the Pliocene-Pleistocene to recent Gediz graben and the Büyük Menderes graben, both of which were seismically active in historic time (Schaffer, 1990; Eyidogan and Jackson, 1985) (Fig. 2A). The Gediz and Büyük Menderes grabens are associated with several geothermal fields, and Miocene to recent volcanic activities are parallel to each other and also parallel the fission-track cooling-age pattern. Across the central Menderes metamorphic core complex, however, Eocene foliation and the boundaries of the tectonometamorphic units define an east-trending syncline with a wavelength of \( \sim 45 \) km and an amplitude of \( \sim 10 \) km (Fig. 3). Across this syncline, fission-track cooling ages show a significantly different pattern and Miocene sediments occur only in fault-bounded blocks in the hanging wall of the detachment faults. Because the earlier contractional history of the central Menderes metamorphic core complex is similar to that of the Gördes and Çine massifs (Ring et al., 1999; Gessner et al., 2001), syncline formation is likely to postdate earlier crustal shortening.

**COOLING HISTORY**

Samples for fission-track thermochronology were collected along a north-south transect across the Anatolide belt (Figs. 2 and 3B) parallel to the regional displacement direction during exhumation. The samples were analyzed with the external-detector and zeta-calibration approach (Hurford and Green, 1982), and the ages were calculated by the central-age method of Galbraith (1992). The 31 apatite fission-track analyses yielded apparent ages ranging between 27.9 ± 1.2 m.y. and 1.8 ± 0.6 m.y.1 Apatite track-length data are unimodal and >14 \( \mu \)m, indicating a simple cooling history in which most samples cooled rapidly relative to the period over which tracks accumulated (their apparent age) to temperatures below which little or no track annealing occurred (<60 °C). The apatite fission-track analyses have been used to produce cooling curves by the quantitative modeling approach of Gallagher (1995). Where possible, these cooling curves have been further defined with zircon fission-track data and white mica and biotite \(^{40}\)Ar/\(^{39}\)Ar ages (Fig. 3, C–F; see footnote 1).

The cooling curves reveal a two-stage cooling history for the Anatolide belt. (1) An early phase of cooling commenced during the late Oligocene and ended in the early to middle
DISCUSSION AND CONCLUSIONS

The outcrops of the Çine and Gördes massifs and the structurally higher levels of the Alpine nappe stack exposed in the central part of the central Menderes metamorphic core complex were at, or close to, Earth's surface by early Miocene time. These areas, along with their flat-lying Eocene foliation, can be viewed as being pinned to Earth's surface, providing a fixed framework in time and space to consider the subsequent emergence of the central Menderes metamorphic core complex.

Since the middle Miocene, the structure and cooling history of the Anatolide belt were modified by a second stage of exhumation. Related cooling ages become progressively younger toward the detachment faults and jump to older ages in their hanging walls. This is because breakaway along both detachment faults brought successively deeper and hotter parts of the nappe pile of the central Menderes metamorphic core complex from beneath the Çine and Gördes massifs, as illustrated by the converging cooling curves in Figure 3 (Earth's surface acts as a near-isothermal boundary to the system). We argue that the syncline structure and the brittle detachment systems are related. Unloading along the detachments induced upward flexing of the upper crust and rotated the currently exposed detachment surfaces to lower angles during progressive exhumation. One consequence of the rolling-hinge model of Lavier et al. (1999) is the creation of ~3 km of relief across the modeled fault. The creation of relief promotes erosion; thus, denudational unloading acts together with tectonic unloading to produce the syncline defined by the Eocene foliation (Fig. 4A). Viewed in cross section, the fission-track ages intersect with the trace of this foliation along the current topography. To illustrate the relation between syncline formation, cooling ages, and initial dip of the detachment faults, traces of the foliation have been labeled with the approximate cooling age. These traces may be viewed as approximating the successive positions of the ~110 °C crustal isotherm for rapidly cooled rocks. Assuming continuous regional Alpine foliation and common pre–late Miocene cooling history across the Anatolide belt, the syncline can be retrodeformed to an inferred flat initial orientation. The intersection points of foliation with the detachments then define an initially steep fault.
dip (Fig. 4B). This results in angles of ~60° for the Kuzey and ~40° for the Güney detachment during active faulting. The space between the restored dip of the faults and the trace of current topography represents the missing section of the footwall that has been removed by erosion.

Even though this graphic restoration of the prefxure geometry is a simplified approach, it shows that a low-angle origin of the detachments bounding the central Menderes metamorphic core complex is unlikely. Furthermore, the amount of displacement and the overall footwall geometry of the Kuzey and Güney detachments agree well with the numerical rolling-hinge model of Lavier et al. (1999).

Our model implies that the faults that bound the Gediz and Büyükl Menderes grabens formed as the two detachments were rotated into shallower orientations; i.e., detachment and graben faults are related and manifest different stages of faulting and exhumation. Thermal modeling suggests that cooling related to core-complex formation started at ~5 Ma, and seismic activity suggests that this process is still active. The estimated displacement of ~10–12 km implies that the detachments operated at average slip rates of ~2 km/m.y.

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