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

Klaus Gessner*
Uwe Ring
Institut für Geowissenschaften, Johannes Gutenberg-Universität, 55099 Mainz, Germany
Christopher Johnson T.H. Huxley School of Environment, Earth Science and Engineering, Imperial College, London SW7 2BP, UK
Ralf Hetzel GeoForschungsZentrum, Telegrafenberg, 14473 Potsdam, Germany
Cees W. Passchier Institut für Geowissenschaften, Johannes Gutenberg-Universität, 55099 Mainz, Germany
Talip Güngör Jeologi Mühendisligi Bölümü, Dokuz Eylül Üniversitesi, 35100 Bornova, Turkey

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 a ductily 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. Lavier et 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.

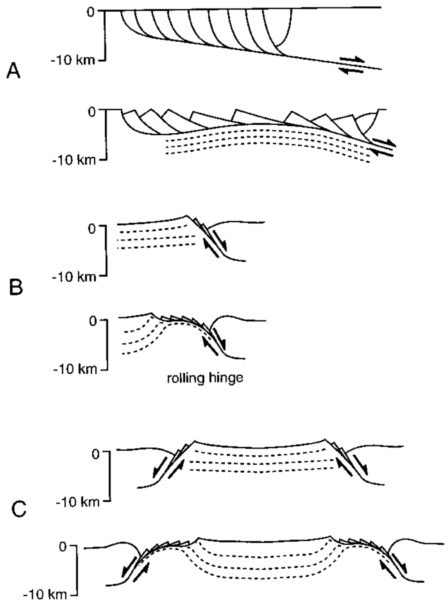

Figure 1. Schematic cross sections for development of detachment faults. A: Listric detachment system with steep normal faults merging in flat basal cutoff, which evolves into gently domed structure (from Wernicke, 1981; Spencer, 1984). B: Rolling-hinge model in which footwall of steep normal fault is deformed by flexural uplift. Because active fault plane becomes too flat to accommodate further brittle strain, new faults form in hanging wall. Note how planar fabrics in footwall become increasingly exhumed toward detachment (from Buck, 1988). C: Conceptual model for central Menderes metamorphic core complex, with symmetric array of two rolling-hinge detachment systems. Note how syncline structure is superimposed on initially horizontal planar fabric.

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 tectonometamorphic 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 Kuzey detachment in the north (Hetzel et al., 1995) and the south-down Güney detachment in the south (Emre and Sözbilir, 1997), both of which cut the upper levels of the Alpine nappe pile for a distance of ~80 km. The Kuzey 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 Güney 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.

---

*Present address: CSIRO Division of Exploration and Mining, P.O. Box 437, Nedlands, WA 6009, Australia. E-mail: klaus@ned.dem.csiro.au.

Geology; July 2001; v. 29; no. 7; p. 611–614; 4 figures; Data Repository item 2001067.

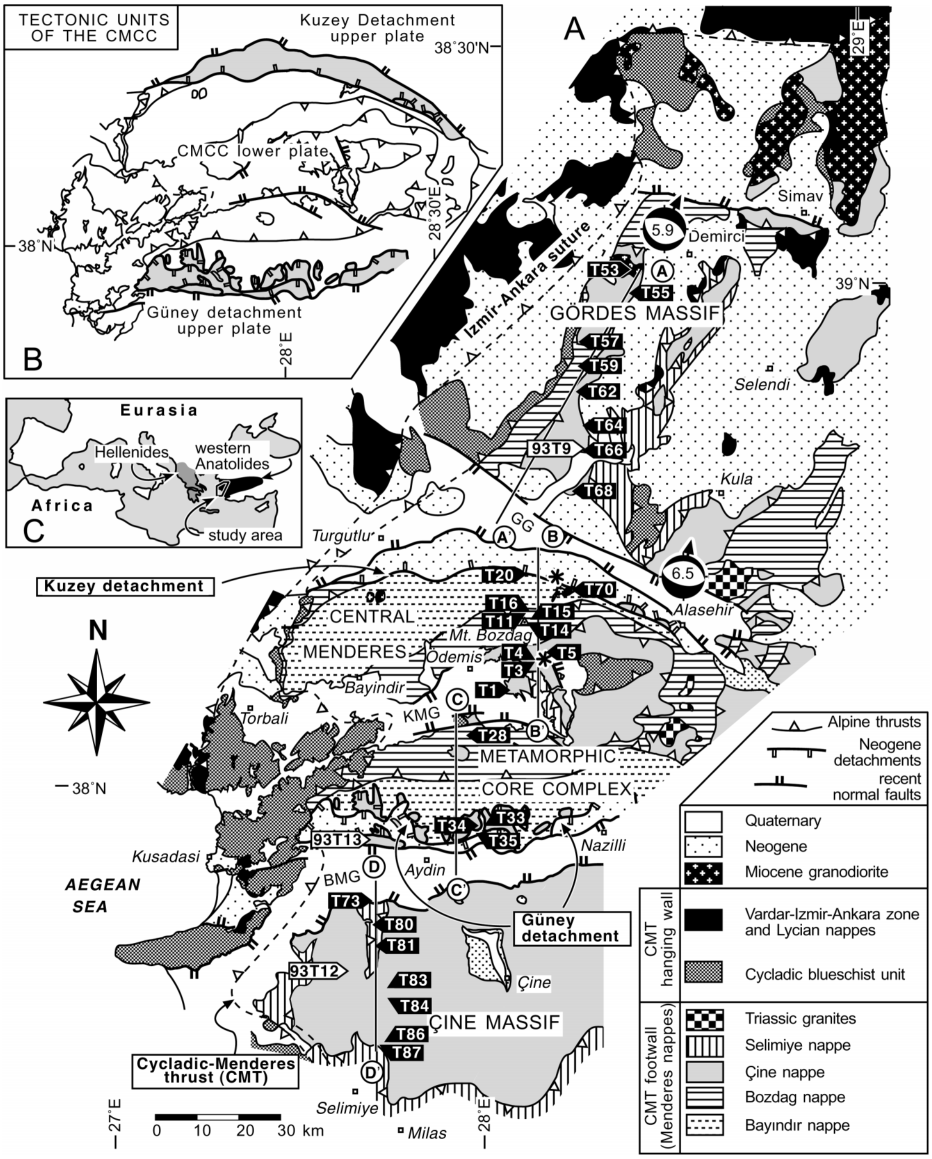

Figure 2. A: Tectonic map of Anatolide belt in western Turkey. Cyclades-Menderes thrust (CMT) separates Alpine high-pressure units in its hanging wall from Menderes nappes in its footwall. Circled letters refer to cross sections A-A′ to D-D′ in Figure 3A; black flags with numbers refer to fission-track sample localities; white flags with numbers refer to $^{40}Ar/^{39}Ar$ data in GSA Data Repository (see footnote 1); asterisks refer to high-grade orthogneiss used as marker to estimate down-dip displacement at Kuzey detachment; location, fault-plane solutions (lower-hemisphere focal projections; black indicates shortening quadrants), surface magnitude, and slip vectors of March 1969 Demirci and Alasehir earthquakes (Eyidogan and Jackson, 1985). GG—Gediz graben, KMG—Küçük Menderes graben, BMG—Büyük Menderes graben, CMCC—central Menderes metamorphic core complex. B: Area of upper plate of Kuzey and Güney detachments. C: Location of study area in Mediterranean.

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 ~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 activity north of the Gediz graben is related to ongoing lithospheric extension (Seyitoglu et al., 1997).

The Gediz graben and the Büyük Menderes graben separate the central Menderes metamorphic core complex from adjacent plateau-like areas: the Gördes massif to the north and the Çine massif to the south. In both the Gördes and Çine massifs, flat-lying Miocene sediments overlie the subhorizontally foliated basement. Eocene foliation, bedding of the Miocene sediments, and remnants of a late Miocene erosion surface (Yilmaz et al., 2000) 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 ~45 km and an amplitude of ~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 μm, 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

---

[1] GSA Data Repository item 2001067, Table of fission-track data and sample localities, Table of white mica $^{40}Ar/^{39}Ar$ data, Release spectra and isotope correlation diagrams of white mica $^{40}Ar/^{39}Ar$ measurements, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

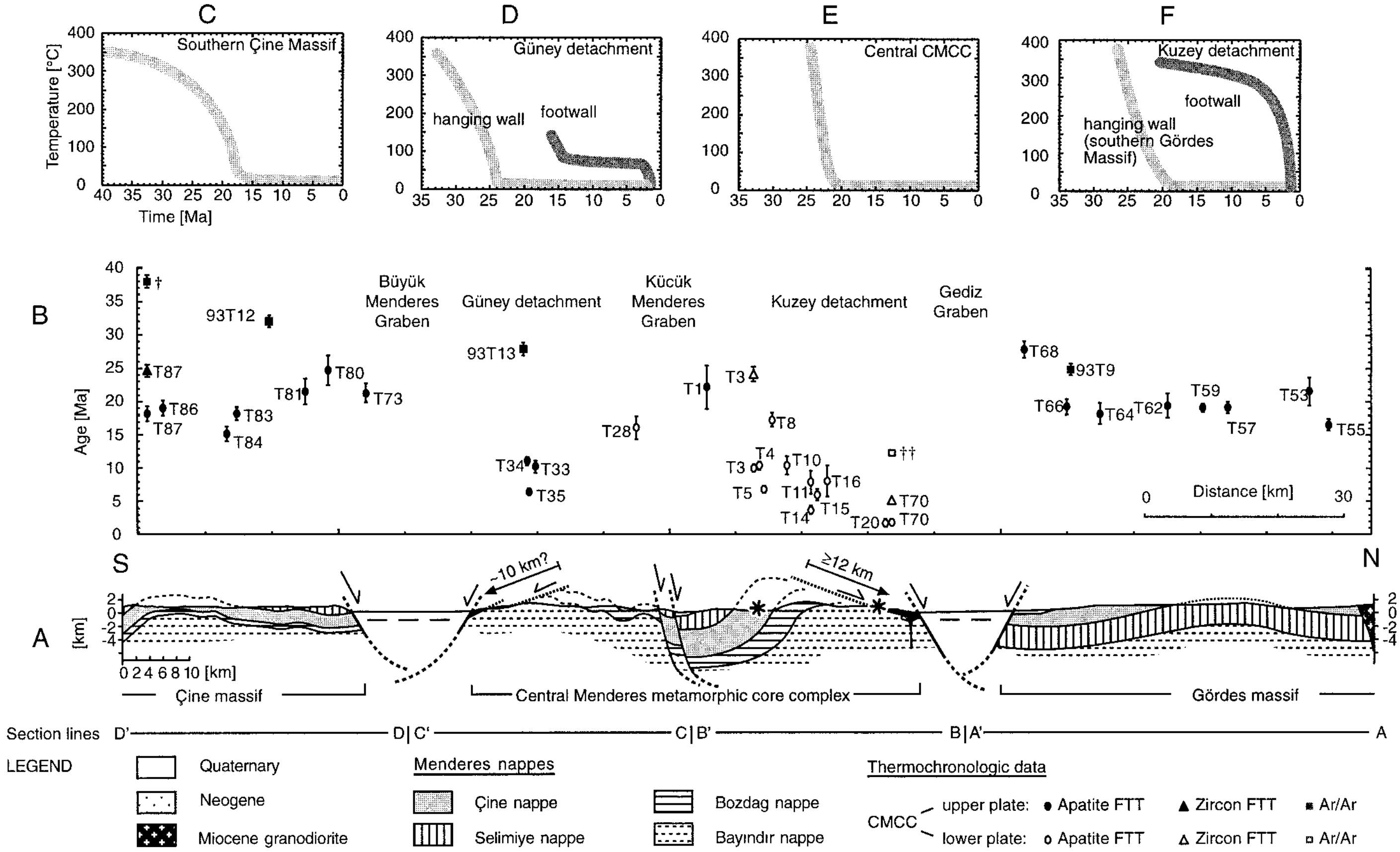

Figure 3. A and B: Structural cross sections (for position and legend, refer to Fig. 2) and cooling ages in relation to position along this section of central Menderes metamorphic core complex (CMCC); FTT—fission-track thermochronology; sample numbers correspond to Figure 2 except those indicated by dagger (Hetzel and Reischmann, 1996) and double daggers (Hetzel et al., 1995). Cooling in footwall of Kuzey detachment is well defined and shows pronounced increase in cooling rate at ~5 m.y. Dashed lines indicate inferred maximum depth of basement in grabens (Cohen et al., 1995).

Miocene. It affected the Gördes and Çine massifs (Fig. 3C) and the higher levels of the nappe pile in the Küçük Menderes graben (Fig. 3E). During this period, temperatures within much of the central Menderes metamorphic core complex remained above ~110 °C, the closure temperature for apatite fission tracks (Hurford and Green, 1982). (2) The second phase of cooling is restricted to the central Menderes metamorphic core complex and is marked by cooling in the footwall of the two detachments to temperatures below ~60 °C (Fig. 3, D and F). Initial cooling is delimited by the ^{40}Ar/^{39}Ar and zircon fission-track analyses from the footwall to the Kuzey detachment. These data indicate accelerated cooling (~50 °C/m.y.) since ~5 Ma. Final cooling to below ~60 °C, defined by the apatite fission-track data from the footwall of the Kuzey detachment, occurred during the Pliocene-Pleistocene. Due to unsuitable sample lithology, cooling in the footwall of the Güney detachment is only poorly defined. However, because structure across the two detachments is similar, a similar cooling history is inferred for both footwall areas.

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

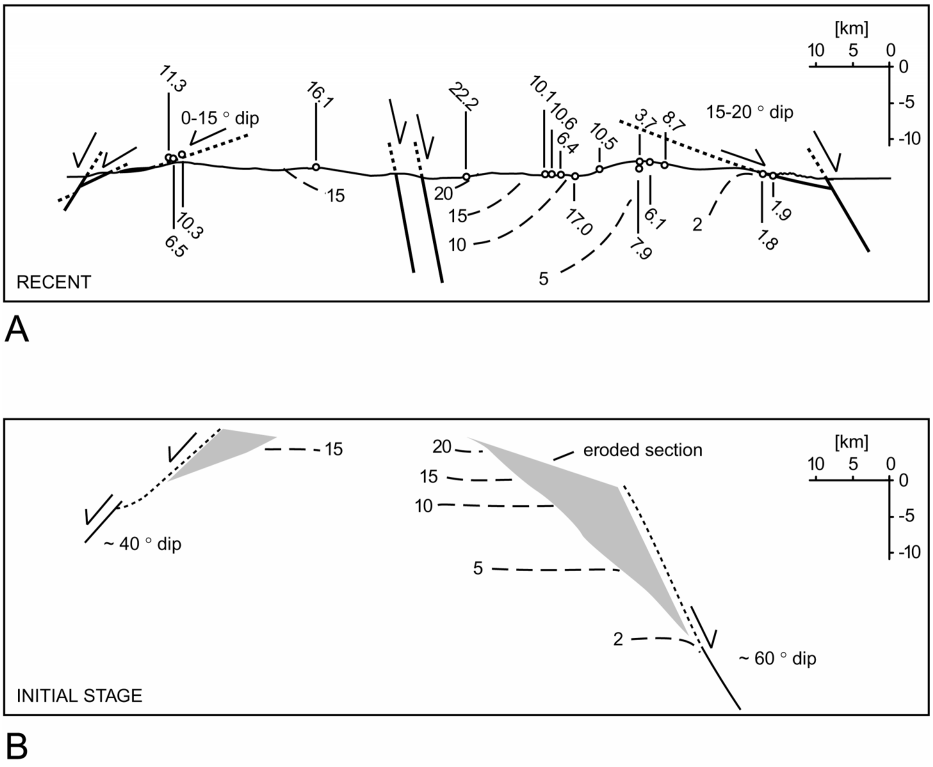

Figure 4. Graphic reconstruction of relation between cooling ages and initial orientation of detachment faults. A: Projection of apatite fission-track data from Figure 3 onto cross-section plane. Dashed lines refer to extrapolated time lines subparallel to regional foliation. Note that regional foliation formed during Eocene crustal shortening. B: Retrodeformed cross section, where intersection points between foliation and detachment faults have been rotated to flat, preflexure orientation of regional fabric, resulting in steep initial dip of fault. Shaded areas represent eroded section from footwall of detachments, removal of which has contributed to flexing and folding of central Menderes metamorphic core complex into its current synclinal form.

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 preflexure 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 Büyük 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.

ACKNOWLEDGMENTS

Funded by the Deutsche Forschungsgemeinschaft (grants Ri 538/4-1, 538/4-2, and 538/4-3 and Graduiertenkolleg 392, Stoffbestand und Entwicklung von Kruste und Mantel). We thank Roger Buck, Donna Whitney, and Gary Axen for constructive reviews; Paul Bons for thoughtful discussions; and Osman Candan and Özcan Dora for providing maps.

REFERENCES CITED

Axen, G.J., and Bartley, J.M., 1997, Field tests of rolling hinges: Existence, mechanical types, and implications for extensional tectonics: Journal of Geophysical Research, v. 102, p. 20 515–20 537.

Axen, G.J., Bartley, J.M., and Selverstone, J., 1995, Structural expression of a rolling hinge in the footwall of the Brenner Line normal fault, eastern Alps: Tectonics, v. 14, p. 1380–1392.

Buck, W.R., 1988, Flexural rotation of normal faults: Tectonics, v. 7, p. 959–973.

Cohen, H.A., Dart, C.J., Akyüz, H.S., and Barka, A., 1995, Syn-rift sedimentation and structural development of the Gediz and Büyük Menderes graben, western Turkey: Geological Society of London Journal, v. 152, p. 629–638.

Cowie, P.A., and Scholz, C.H., 1992, Displacement-length scaling relationships for faults: Data synthesis and discussion: Journal of Structural Geology, v. 14, p. 1149–1156.

Emre, T., and Sözbilir, H., 1997, Field evidence for metamorphic core complex, detachment faulting and accommodation faults in the Gediz and Büyük Menderes grabens, Western Anatolia: International Earth Science Colloquium on the Aegean and Surrounding Regions 1995, Proceedings, v. 1, p. 73–94.

Eyidogan, H., and Jackson, J., 1985, A seismological study of normal faulting in the Demirci, Alasehir and Gediz earthquakes of 1969–70 in western Turkey: Implications for the nature and geometry of deformation in the continental crust: Royal Astronomical Society Geophysical Journal, v. 81, p. 569–607.

Galbraith, R.F., 1992, Statistical models for mixed ages: International Workshop on Fission Track Thermochronology, 7th Philadelphia, Abstracts with Programs, p. 7.

Gallagher, K., 1995, Evolving temperature histories from apatite fission-track data: Earth and Planetary Science Letters, v. 136, p. 421–435.

Gessner, K., Ring, U., Passchier, C.W., and Güngör, T., 2001, How to resist subduction: Evidence for large-scale out-of-sequence thrusting during Eocene collision in western Turkey: Geological Society of London Journal (in press).

Hetzel, R., and Reischmann, T., 1996, Intrusion age of Pan-African augen gneisses in the southern Menderes massif and the age of cooling after Alpine ductile extensional deformation: Geological Magazine, v. 133, p. 565–572.

Hetzel, R., Ring, U., Akal, C., and Troesch, M., 1995, Miocene NNE-directed extensional unroofing in the Menderes massif, southwestern Turkey: Geological Society of London Journal, v. 152, p. 639–654.

Hurford, A.J., and Green, P.F., 1982, A users guide to fission track dating: Earth and Planetary Science Letters, v. 59, p. 343–354.

Lavier, L.L., Buck, W.R., and Poliakov, A.N.B., 1999, Self-consistent rolling-hinge model for the evolution of large-offset low-angle normal faults: Geology, v. 27, p. 1127–1130.

Ring, U., Gessner, K., Güngör, T., and Passchier, C.W., 1999, The Menderes massif of western Turkey and the Cycladic massif in the Aegean—Do they really correlate?: Geological Society of London Journal, v. 155, p. 3–6.

Schaffer, F., 1900, Das Maeanderthalbeben vom 20. September 1899: Mitteilungen der kaiserlichen und königlichen geographischen Gesellschaft Wien, v. 43, p. 221–230.

Şengör, A.M.C., 1987, Cross faults and differential stretching of hanging walls in regions of low-angle normal faulting: Examples from western Turkey, *in* Coward, M.P., et al., eds., Continental extensional tectonics: Geological Society [London] Special Publication 28, p. 575–589.

Seyitoglu, G., Anderson, D., Nowell, G., and Scott, B., 1997, The evolution from Miocene potassic to Quaternary sodic magmatism in western Turkey: Implications for enrichment processes in the lithospheric mantle: Journal of Volcanology and Geothermal Research, v. 96, p. 127–147.

Spencer, J., 1984, Role of tectonic denudation in warping and uplift of low-angle normal faults: Geology, v. 12, p. 95–98.

Wernicke, B., 1981, Low-angle normal faulting in the Basin and Range province: Nappe tectonics in an extending orogen: Nature, v. 291, p. 645–648.

Yilmaz, Y., Genç, S.C., Gürer, F., Bozcu, M., Yilmaz, K., Karacık, Z., Altunkayak, S., and Elmas, A., 2000, When did the western Anatolian grabens begin to develop?, *in* Bozkurt, E., et al., eds., Tectonics and magmatism in Turkey and the surrounding area: Geological Society [London] Special Publication 173, p. 353–384.

Manuscript received November 13, 2000
Revised manuscript received March 5, 2001
Manuscript accepted March 19, 2001

Printed in USA