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Yo-yo Tectonics of the Niğde Massif During Wrenching in Central Anatolia

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Abstract: Yo-yo tectonics occurs in wrench zones in response to switches between transpression and transtension or to changes in the geometries of faults during these modes of deformation, and involves multiple cycles of burial and exhumation. The Niğde Massif, Turkey, is a spectacular example of a tectonic yo-yo: it experienced two complete cycles of burial and exhumation in a zone of oblique displacement. The two cycles, one regional and one more local in scale, together occurred over > 80 m.y., from Cretaceous burial to Miocene cooling and exhumation. Temperature-time paths calculated using apatite fission track age and length data, combined with published U/Pb, $^{40}Ar/^{39}Ar$, and biostratigraphic ages and a new $^{40}Ar/^{39}Ar$ biotite age for ignimbrite overlying the massif, are the basis for inferring the duration, rates, and driving forces of yo-yo cycles. Exhumation may be more rapid than burial because burial occurs at tectonic rates, whereas the combined effects of buoyancy and coupling of surface processes (especially erosion) and tectonic denudation accelerate exhumation of buried continental material.

Key Words: apatite fission track, exhumation, Niğde Massif, wrench zones, yo-yo tectonics

Orta Anadolu'da Niğde Masifi'nin Doğrultu Atımlı Faylanması Sırasındaki Yo-yo Tektoniği

Özet: Yo-yo tektoniği yüksek eğimli verev atımlı fayların etkin olduğu alanlarda fay geometrisinin değişmesi yada bölgesel sıkışma (transpression) ve gerilme (transtension) alanlarının yer değiştirmesi sonucu gelişir. Bu sayede tüm bölge birden fazla gömülme ve yüzeylenme döngüleri ve bunlara bağlı olarak gelişen çok fazlı metamorfizmaya maruz kalır. Niğde Masifi yo-yo tektoniğinin en güzel örneklerinden birini sergiler. Massif verev atımlı bir deformasyon zonu içerisinde iki tam gömülme/yüzeylenme döngüsü geçirmiştir. Biri bölgesel, diğeri daha çok yersel ölçekte gözlenen bu döngüler Kretase'den (gömülme) Miyosen'e (soğuma ve yüzeylenme) kadar süren ~80 My'dan daha uzun bir süre zarfında tamamlanmıştır. Bu çalışmada apatit fizyon iz yaşlarından elde edilen sıcaklık-zaman eğrileri önceden yayınlamış U/Pb, Ar/Ar, biyostratigrafik yaşları ve ignimbritlerde elde edilen yeni $^{40}Ar/^{39}Ar$ biyotit yaşı ile birlikte yorumlanarak yo-yo tektoniğinin oluşum zamanı, hızı ve buna neden olan kuvvetler ortaya konmuştur. Yüzeylenme gömülmeye oranla daha hızlı gelişebilmektedir, çünkü gömülme sadece tektonik hızlara bağlı olarak gelişirken, yeryüzeyindeki süreçler, özellikle erozyon, yüzücülük (izostatik yükselme) ve tektonik aşındırma (denüdasyon) derine gömülmüş kıtasal malzemenin yüzeylenmesini hızlandırmaktadır.

Anahtar Sözcükler: apatit fizyon izi, yüzeylenme, Niğde Masifi, doğrultu atımlı fay zonları, yo-yo tektoniği

Yo-yo Tectonics

Cycles of burial and unroofing (yo-yo tectonics) may occur in continental crust during orogeny, e.g., during repeated episodes of thrusting (burial) and erosion. Burial and unroofing cycles may also occur in strike-slip (wrench) zones as steps and bends in strike-slip and associated oblique-slip faults evolve through time. This behaviour is predicted for wrench systems (Wilcox *et al.* 1973; Crowell 1974; Sylvester 1988), but evidence in the geologic record is sparse. Although the magnitude of burial in yo-yo cycles may be large in convergent-dominated systems, owing to the scarcity of well-documented examples in strike-slip fault zones, there are unresolved questions about yo-yo tectonics processes in wrench zones, including: (1) What are the rates of burial and exhumation?; and (2) Does the magnitude of vertical motion change, either systematically or randomly, through time? These questions can be addressed using an example of yo-yo tectonics that occurred during oblique displacement and that is recorded in metamorphic and sedimentary rocks of the Niğde Massif and adjacent Ulukışla Basin in and near the Central Anatolian fault zone (CAFZ), Turkey (Umhoefer *et al.* in press) (Figure 1).

Central Anatolia and the Ecemiş Fault

Central Anatolia is located between zones of active collision in SE Turkey and extension in western Turkey. Main geologic elements are the Central Anatolian Crystalline Complex (CACC; Akıman *et al.* 1993); the Central Anatolian fault zone (CAFZ; including its southern segment, the Ecemiş fault; Koçyiğit & Beyhan 1998); the Ulukışla, Tuz Gölü, and Sivas basins; and the Pliocene to recent Cappadocian volcanic province (Figure 1).

The Ecemiş fault experienced 60 km (Jaffey & Robertson 2001) to 80 km (Koçyiğit & Beyhan 1998) of sinistral offset, and is an active structure (Koçyiğit & Beyhan 1998; Jaffey *et al.* 2005). The fault may have formed at the southeastern edge of the CACC microcontinent during oblique convergence. It was dominated by left-lateral slip in the Late Eocene to Middle Miocene, but became more transtensional/extensional in the Late Miocene–Early Pliocene (Jaffey & Robertson 2001).

The Niğde Massif (Figure 1) is a migmatite-cored structural dome at the southern margin of the CACC (Göncüoğlu 1981, 1982, 1986; Whitney & Dilek 1997, 1998, 2001; Whitney *et al.* 2001, 2003). The massif is overlain by Paleocene to middle Eocene basin deposits (Gautier *et al.* 2002 and references therein) that have been locally metamorphosed to greenschist facies and intensely deformed (Umhoefer *et al.* in press).

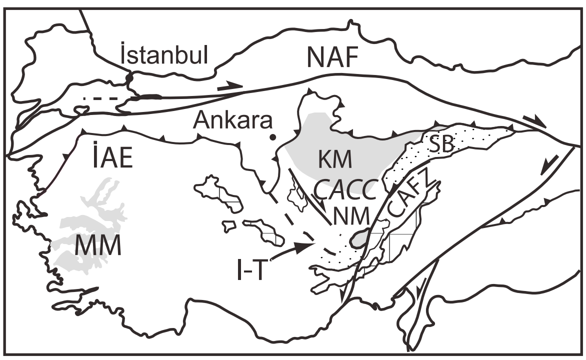

Figure 1. Map of Turkey showing locations of selected major metamorphic and tectonic elements. Abbreviations: CACC– Central Anatolian Crystalline Complex (Kırşehir Massif + Niğde Massif + associated massifs); CAFZ– Central Anatolian fault zone; EF– Ecemiş fault segment of the CAFZ; İAE– İzmir-Ankara-Erzincan suture zone; I-T– Inner-Tauride suture zone; KM– Kırşehir Massif; MM– Menderes Massif; NAF– North Anatolian Fault; NM– Niğde Massif; SB– Sivas Basin.

Yo-Yo Cycles

Burial #1 – Exhumation #1

Late Cretaceous regional metamorphism and deformation of the Niğde Massif occurred in the first burial cycle during regional-scale collision, a protracted event involving crustal thickening via collision and ophiolite emplacement (Tekeli *et al.* 1984; Andrew & Robertson 2002; Parlak & Robertson 2004). Two models for the regional metamorphism of the Niğde rocks have different implications for the duration and rate of burial. If ophiolite emplacement (from the north: Göncüoğlu 1986; or south: Andrew & Robertson 2002; Clark & Robertson 2005) drove burial, then burial was very rapid. Ophiolitic rocks in the region were emplaced in the Late Cretaceous (~91 Ma; Lytwyn & Casey 1995; Dilek *et al.* 1999), coeval with zircon crystallization in Niğde migmatite and granite (Whitney *et al.* 2003). It is therefore difficult to account for the timing and magnitude of burial (15–21 km) during metamorphism with this model.

If crustal thickening (± ophiolite obduction) during oblique collision buried Niğde protoliths (Whitney *et al.* 2001, 2003), the duration of burial #1 is not well defined, but was likely dominantly Cretaceous given the timing of initial collision (Clark & Robertson 2002). The time from initiation of burial to the peak of metamorphism may therefore have been > 40 m.y., corresponding to a burial rate of < 0.5 mm/year (Figure 2).

The metamorphic history of the Niğde Massif is distinct from that recorded by other metamorphic massifs in the CACC. For example, the Niğde Massif alone records a high-temperature crustal melting event that involved widespread migmatization and generation of a peraluminous intrusion (the Üçkapılı granite), and a *P*-*T*-t path involving rapid cooling following protracted high-temperature (upper amphibolite facies) metamorphism (Whitney *et al.* 2001, 2003). In contrast, the northern parts of the CACC (Kırşehir and Akdağ massifs) record a simple clockwise *P*-*T* path of burial and heating followed by decompression and cooling, and the structural fabrics are consistent with orthogonal convergence.

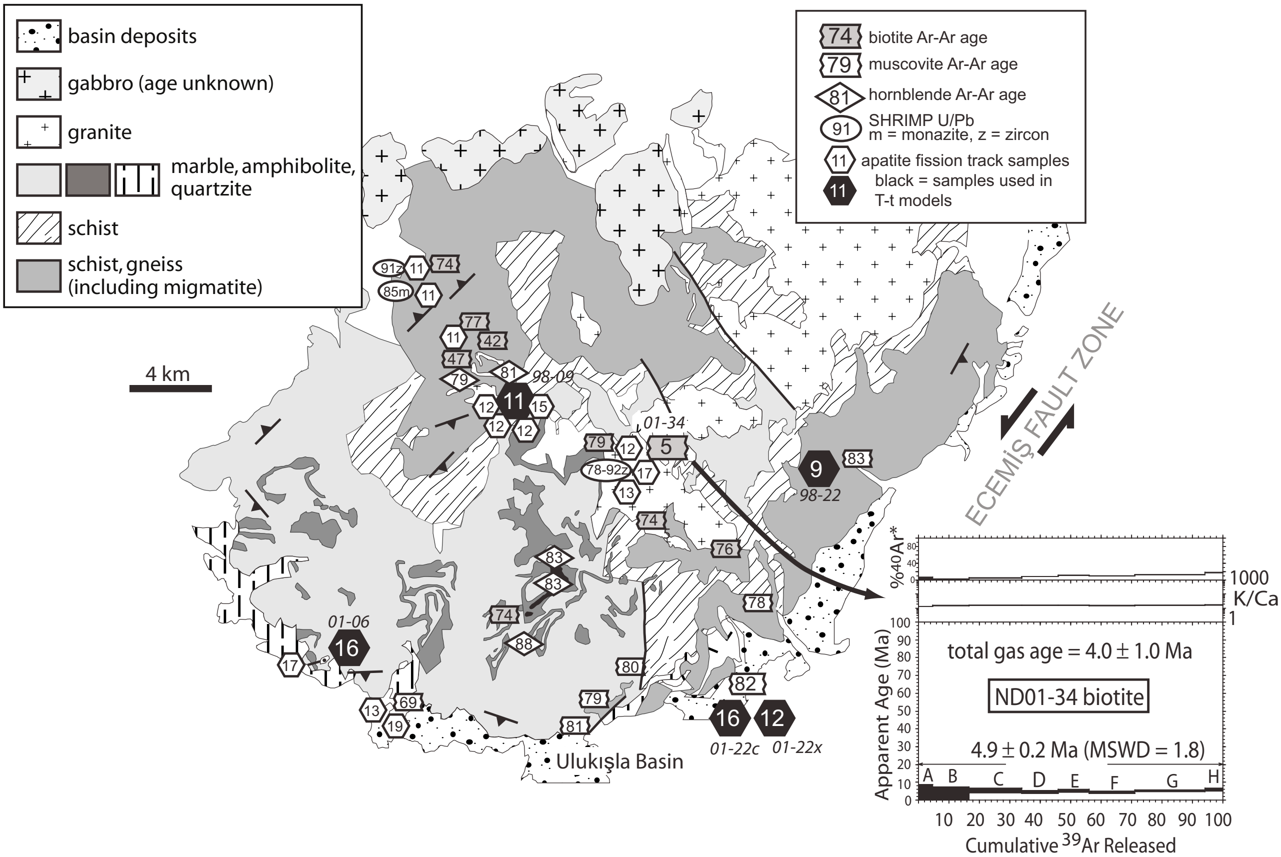

Figure 2. Geologic map of the Niğde Massif showing published geochronology data (from Fayon *et al.* 2001; Whitney *et al.* 2003; Umhoefer *et al.* in press; and Whitney *et al.* 2007), as well as a biotite $^{40}Ar/^{39}Ar$ spectrum for ignimbrite that overlies the metamorphic and plutonic basement (this study). Niğde geology modified from maps by Atabey (1989a, b) and Atabey *et al.* (1990).

In the Niğde Massif, high-temperature mineral lineation subparallel to the Ecemiş fault and *P-T-*t evidence for a long duration of high-temperature regional metamorphism are consistent with oblique collision (Whitney *et al.* 2001, 2003). The high-grade (including migmatitic) foliation and lineation observed in the core of the Niğde Massif are consistent with crustal flow during transpression. Crustal flow, perhaps involving partially molten crust, in an oblique regime transposed initially steep planar fabrics to shallow orientations that are subparallel to the length of the orogen (Whitney *et al.* 2007).

Lower-grade, localized top-to-S shear zones overprinted a top-to-N high-grade fabric. Following metamorphism and intrusion of a granite (92–85 Ma, with youngest U/Pb zircon rim age of 78 Ma), the rocks cooled rapidly through the closure temperatures of Ar in hornblende, muscovite, and biotite (Whitney *et al.* 2003, 2007; Figure 2). These data correspond to a cooling rate of ≥43 °C/m.y. between 81–74 Ma for the high-grade core and lower rates (16–21 °C/m.y.) for structurally higher basement units. We have proposed that rapid cooling and exhumation correspond to extension related to a switch from transpression to transtension along the wrench zone (Umhoefer *et al.* in press). According to this model, the Ecemiş fault and an ancestral mid-crustal fault system (wrench zone) have been active for >90 million years, and likely first developed during highly oblique collision along the southeastern margin of the Central Anatolian microcontinent (Umhoefer *et al.* in press).

Rocks at the massif's eastern margin were at the surface by the latest Cretaceous or Paleocene (Gautier *et al.* 2002). Exhumation duration, from youngest crystallization of migmatites to exposure of basement, was therefore ~15 m.y. at a rate of ~ 0.8–1 mm/yr (Figure 2).

Burial #2 – Exhumation #2

The massif shed material into a marine basin through the middle Eocene, followed by Eocene folding and reverse faulting of basin deposits (Clark & Robertson 2002, 2005; Umhoefer *et al.* in press). The Eocene event may have been related to collision of the Anatolide-Tauride belt with Eurasia, likely involving transpression along the CAFZ.

Regional resetting of apatite fission track (AFT) ages suggests that the entire massif was at depths greater than those of the partial annealing zone (PAZ, 120–60°C) for fission tracks in apatite (Fayon & Whitney 2007). Burial of basin sediments and reburial of basement started in the middle Eocene (~50 Ma) following deposition of nummulitic limestone involved in burial-related deformation (Umhoefer *et al.* in press). Burial duration is bracketed by stratigraphic and AFT ages and was likely ~20–25 m.y. Depth of burial (6–10 km) is estimated from temperature-sensitive index minerals (e.g., chlorite) and reasonable geothermal gradients, indicating a burial rate of ~0.2–0.5 mm/yr.

Final cooling is recorded by Miocene AFT ages of 17–9 Ma (Fayon *et al.* 2001; Umhoefer *et al.* in press) (Table 1). Ignimbrite with a 5 Ma biotite $^{40}Ar/^{39}Ar$ age directly overlies basement with AFT ages of 12–17 Ma (Figure 2). The exhumation mechanism was likely a combination of erosion and faulting related to motion on the Ecemiş fault, as suggested by the large number of brittle faults, particularly along the eastern margin of the massif.

Modeling of apatite fission track ages and track length distribution using the AFTSolve modeling program (Ketcham *et al.* 2000) provides limits on likely timing and rates of final cooling and unroofing. Such modeling can test whether reburial involved temperatures below, within, or above the partial annealing zone for fission tracks in apatite. In addition, the time at which model paths enter the partial annealing zone can be varied to test how well different *T-t* histories reproduce the AFT data (as indicated by a goodness-of-fit [GOF] parameter [Table 2] related to the probability of fit between the calculated paths and input parameters). For example, no range of model conditions produced a good fit for Niğde ages or track lengths. Reburial must have involved *T* >120 °C for a duration sufficient to anneal fission tracks in apatite (Fayon & Whitney 2007).

For this study, we evaluated a migmatitic metapelite (AFT age = 10.8 ± 1.8 Ma), a garnet-sillimanite schist from the eastern basement (9.4 ± 2.2 Ma), and a quartzite from the southern (structurally highest) basement (15.7 ± 3.1 Ma) (Figure 1). We also modeled paths for a deformed basin conglomerate from the early Cenozoic strata along the eastern margin of the massif: a foliated granitic clast (15.8 ± 3.6 Ma), and a composite sample of matrix + clasts of basement lithologies (12.2 ± 2.2 Ma). Metamorphic temperature for the metaconglomerate did not exceed ~350 °C, as a white mica $^{40}Ar/^{39}Ar$ age for this sample is Late Cretaceous (82 Ma; Umhoefer *et al.* in press).

We modeled cooling starting from 2 different time intervals: (a) 65–55 Ma, and (b) 20–10 Ma (Figure 3). The older range is slightly younger than $^{40}Ar/^{39}Ar$ mica ages and slightly older than ages inferred from fossils in the adjacent basin that also contains clastic material from the basement. The younger range is 5–15 m.y. older than the overlying ignimbrite.

For all samples, best-fit paths are consistent with cooling from T > 120°C at 20–10 Ma. However, no models fit the track length characteristics of the migmatite sample well, and only models with cooling at <20 Ma have a good fit for the AFT age data for this sample, with 'good' defined as a GOF value >0.5. In contrast, models for the southern quartzite and the basin samples have high GOF values for age and track length. These results may indicate that the core of the massif was not exhumed as rapidly as the margin, and spent more time in the partial annealing zone during exhumation. If so, the part of the massif closest to the Ecemiş fault experienced the most rapid exhumation, consistent with general models for wrench-related exhumation.

If the reburied rocks were exhumed from 6–10 km between 10–5 Ma, unroofing rates were 1.2–2 mm/year. If the rocks reached the surface prior to 5 Ma, as seems likely, exhumation rates were >1.5–2.5 mm/year.

Discussion

Yo-yo Tectonic Regimes

It has long been recognized that strike-slip faults are important for understanding the dynamic evolution of

Table 1. Summary of apatite fission-track data.

Sample #	E Latitude/ N Longitude	Elevation (meters)	# of grains (for age calc.)	ρ_{std} x 10^6 cm^{-2} (track cnt)	ρ_s x 10^6 cm^{-2} (track cnt)	ρ_i x 10^6 cm^{-2} (track cnt)	U (ppm)	Fission-Track Age (Ma) $\pm 2\sigma$	X^2 Probability %	Mean Track Length (µm)	Standard Deviation (µm)
*ND01-6A	3749323	1600	5	1.551	0.556	8.08	51.6	15.7 ± 3.1	96.3	14.3	1.2
	3443282			-4855	-106	-1540				(n = 32)	
*ND01-22X	3749202	2628	21	1.538	0.318	5.894	37.9	12.2 ± 1.6	7.9	13.5	1.58
	3457284			-4855	-271	-5018				(n = 35)	
*ND01-22C	3749202	2630	5	1.499	0.819	11.38	75.2	15.8 ± 3.6	47.3	14.1	1.25
	3457284			-4855	-117	-1627				(n = 28)	
**ND98-09	3756910	1590	20	1.298	0.406	7.124	54.3	10.8 ± 1.8	92.1	13.7	1.39
	3448790			-8263	-161	-2824				(n = 46)	
**ND98-22	3754540	1645	20	1.326	0.157	3.255	24.3	9.4 ± 2.2	91.1	13	2
	3500150			-8714	-82	-1700				(n = 15)	

* Age data from Umhoefer *et al.* (2007), updated with additional grains; track length data: this study; n = number of confined tracks counted.

** Age data from Fayon *et al.* (2001); track length data: this study.

We employed the external detector method for fission-track dating as described by Naeser (1979). Apatite grains were mounted, polished, and etched in 5 N HNO_3 for 20 to 25 seconds. Mounts were covered with a low-U muscovite external detector. Induced tracks in the mica were revealed by etching in 48% HF for 10 minutes at room temperature. Track densities were used to calculate fission-track ages. The fluence gradient was calculated using track densities in a standard glass monitor (SRM612) at the top and bottom of the irradiation package. ρ_{std}, density of induced tracks in the standard glass micas; ρ_s, density of spontaneous tracks; ρ_i, density of induced tracks. The chi-squared (χ^2) statistic provides a useful measure for determining if dated grains from a sample belong to a single-age population (Galbraith 1981; Green 1981). When $\chi^2 < 5\%$ (the sample fails χ^2) the sample is has a heterogeneity of grain ages the reflect either compositional differences, a mixed population of grains ages, or both. Apatite FT ages calculated using a zeta of 293.5 for SRM 612 standard glass; apatite zeta determined using a weighted mean of 4 Fish Canyon tuff and 6 Durango age standards (Hurford & Green 1983). Apatite samples were irradiated at the Texas A&M Nuclear Science Center with a neutron dose of $1x10^{16}$ neutrons/cm^2.

Table 2. Goodness-of-fit (GOF) parameters resulting from AFTSolve fission track modeling.

Model	98-09		98-22		01-6A		01-22c		01-22x	
	age	t.l.	age	t.l.	age	t.l.	age	t.l.	age	t.l.
a	0.39	0.27	0.60	0.71	0.95	0.92	0.83	0.86	0.85	0.41
b	0.77	0.46	0.96	0.95	0.86	0.88	0.96	0.98	0.93	0.93

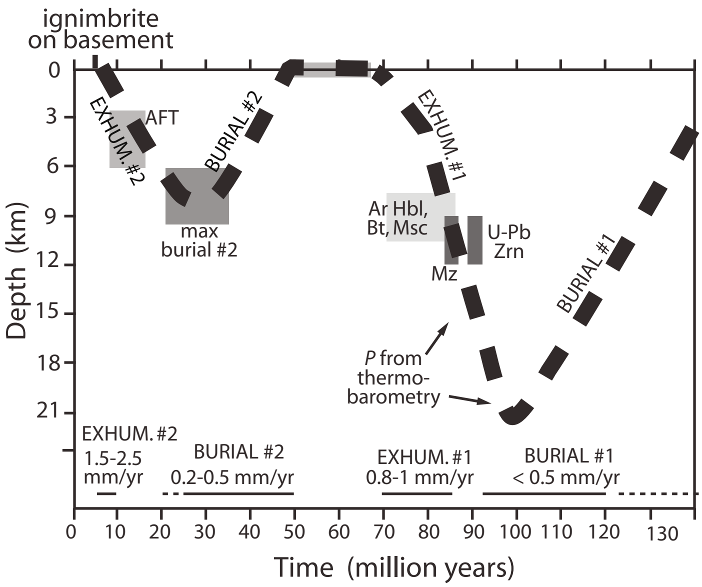

Figure 3. Depth-time path and rates for the Niğde Massif, from data in Whitney & Dilek (1998), Fayon *et al.* (2001), Whitney *et al.* (2001, 2003), Gautier *et al.* (2002), and Umhoefer *et al.* (in press). Dashed black line indicates path for rock exposed in exhumation #1.

orogens, and much attention has been given to understanding the role of lateral displacement in orogeny (e.g., Fitch 1972; Selverstone 1988; Tapponnier *et al.* 1990; Solar & Brown 2001). Yo-yo tectonics, which involves a major component of vertical motion is an expected phenomenon in orogeny and illustrates that strike-slip fault zones are important for deep crustal deformation and exhumation.

Multiple cycles of burial and exhumation are rarely observed in the geologic record because evidence is removed by erosion or because basement-basin pairs have not been examined in an integrated way to reveal records of burial-exhumation cycles. The example of yo-yo tectonics displayed by the Niğde Massif may be generalized to other strike-slip fault zones, such as in the North American Cordillera (Umhoefer & Schiarizza 1996) and SE Asia (Morley 2002). Without exposure and study of the critical narrow belt of deformed basinal rocks that locally lie unconformably on the basement on the eastern side of the massif (Gautier *et al.* 2002), and the discovery of perturbed $^{40}Ar/^{39}Ar$ spectrum of muscovite in the basement near the basement-cover contact along the eastern margin of the massif (Umhoefer *et al.* in press), the case for two cycles of burial and exhumation of the Niğde Massif would be ambiguous. It seems likely that other orogens have metamorphic domes for which that kind of evidence is missing or the basement-cover relations have not been studied in sufficient detail.

Yo-yo processes are expected to occur in the following tectonic settings:

(1) orogens (e.g., the North American Cordillera) that show major periods of orthogonal collision followed by oblique tectonics. If the episodes of orthogonal and

oblique tectonics are repeated, yo-yo tectonic motion is even more likely.

(2) collisional orogens in which the colliding continents or terranes are characterized by salients and reentrants (e.g., Appalachians; Alpine – Tauride belt; Himalayas), as these irregularities will enhance wrench tectonics along their margins.

(3) orogens with a significant component of oblique displacement (wrench). Wrench-dominated orogens will be characterized by multiple cycles of burial and exhumation because they commonly have steps and bends that evolve (move) through time along major orogen-parallel strike-slip zones. When large-scale translation along active margins follows collision, (scenario 1), wrenching will be prolonged and can contribute to both the exhumation of cycle 1 and the whole of cycle 2.

In contrast, regions dominated by purely extensional processes experience crustal thinning over large regions, and development of relatively shallow basins. Local areas may experience vertical motion, but exhumation of orogenic crust, particularly involving multiple cycles of burial and exhumation, is unlikely. Only in special types of extensional orogens – i.e., those with thick initial crust and/or high heat flow – will orogenic crust be exhumed (e.g., in metamorphic core complexes). In general, extension-dominated orogens are not good candidates for yo-yo tectonics.

Magnitudes and Rates of Vertical Motion in yo-yo Tectonics

In most cases of yo-yo tectonics, the first cycle may involve a greater magnitude of vertical displacement (burial and exhumation) than later cycles if it is related to collision and crustal thickening. The first cycle is not necessarily related to wrenching, but wrench zone tectonics can dramatically affect thickened crust because of the localized nature and capacity to rapidly thin (and thicken) crust. Subsequent cycles may be related to transpression-transtension during displacement of normal thickness crust in an intracontinental wrench zone. The expected pattern is major vertical motion followed by smaller cycles (Figure 4).

Although burial may be rapid, particularly for later cycles of the yo-yo, exhumation rates (> 1 mm/year) are

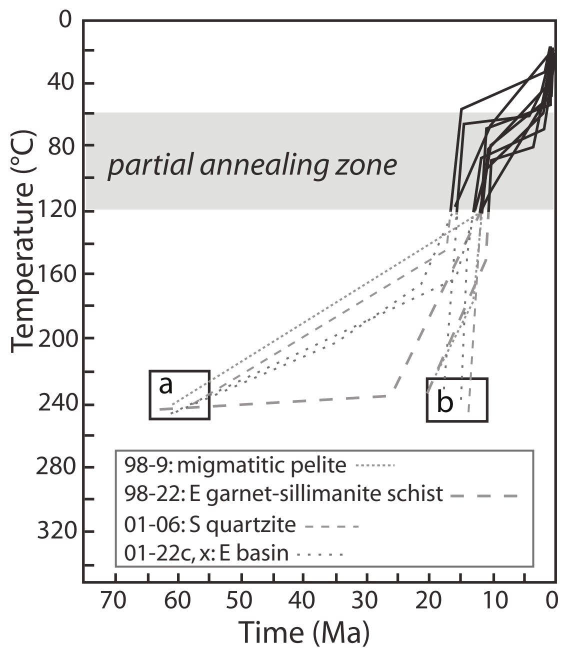

Figure 4. Results of AFT modeling for paths involving cooling from T= 220–250°C at different starting times: **(a)** 65–55 Ma, and **(b)** 20–10 Ma. Best-fit paths (>98% confidence interval) shown as lines: dashed grey at T > the partial annealing zone, solid black within/below the PAZ.

typically greater than burial rates (<1 mm/year), possibly because coupling between erosion and tectonic denudation accelerates exhumation and/or because buoyant rise of hot (and perhaps partially molten) orogenic crust assists exhumation. In the case of the Niğde Massif, exhumations were related to transtension and further enhanced by erosion and buoyancy of buried continental rocks relative to obducted ophiolites.

The deformation of basins and underlying basement during strike-slip displacement may be an important mechanism of basin inversion (e.g., De Paola *et al.* 2005); e.g., the second cycle of Niğde-Ulukışla Basin yo-yo history. More generally, yo-yo tectonics is a significant mechanism for alternately thickening and thinning orogenic crust. Wrench zone motion can periodically destabilize thickened crust, and the partitioning of deformation along intracontinental strike-slip faults concentrates vertical and lateral crustal motion. Both lateral and vertical displacements have consequences for surface processes and landscape development, and vertical motion of the magnitude documented in this study can influence the thermal structure of continental crust through time.

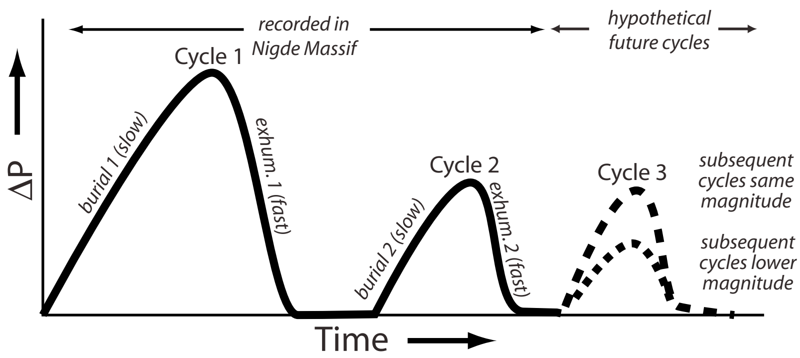

Figure 5. Conceptual model of a tectonic yo-yo through time. Schematic paths show possible path of a rock exposed at the surface by exhumation #1 (but not completely eroded) and reburied. The difference in magnitude of ΔP between the first and second (and subsequent) cycles of the yo-yo likely reflects a dramatic decrease in crustal thickness. Subsequent cycles may be of the same magnitude as the second cycle because they involve similar transpression-transtension switches in a strike-slip fault zone.

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