Exhumation of the west-central Alborz Mountains, Iran, Caspian subsidence, and collision-related tectonics

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ABSTRACT

Crystallization and thermal histories of two plutons in the west-central Alborz (also Elburz, Elburs) Mountains, northern Iran, are combined with crosscutting relations and kinematic data from nearby faults to determine the Cenozoic tectonic evolution of this segment of the youthful Euro-Arabian collision zone. U/Pb, $^{40}Ar/^{39}Ar$, and (U-Th)/He data were obtained from zircon, biotite, K-feldspar, and apatite. The Akapol pluton intruded at 56 ± 2 Ma, cooled to ~150 °C by ca. 40 Ma, and stayed near that temperature until at least 25 Ma. The nearby Alam Kuh granite intruded at 6.8 ± 0.1 Ma and cooled rapidly to ~70 °C by ca. 6 Ma. These results imply tectonic stability of the west-central Alborz from late Eocene to late Miocene time, consistent with Miocene sedimentation patterns in central Iran. Elevation-correlated (U-Th)/He ages from the Akapol suite indicate 0.7 km/m.y. exhumation between 6 and 4 Ma, and imply ~10 km of Alborz uplift that was nearly synchronous with rapid south Caspian subsidence, suggesting a causal relation. Uplift, south Caspian subsidence and subsequent folding, reversal of Alborz strike-slip (from dextral to sinistral) and(?) eastward extrusion of central Iran, coarse Zagros molasse deposition, Dead Sea transform reorganization, Red Sea oceanic spreading, and(?) North and East Anatolian fault slip all apparently began ca. 5 ± 2 Ma, suggesting a widespread tectonic event that we infer was a response to buoyant Arabian lithosphere choking the Neo-Tethyan subduction zone.

Keywords: Iran, geochronology, collision, tectonics, exhumation, Caspian.

INTRODUCTION

The key area in which to study upper crustal response to early-stage continental collision is central Iran, the site of the most recent impact along the Alpine-Himalayan front. Alpine and Himalayan tectonics are better known, but older, and continued convergence has generally obscured their earliest features. We document the timing of collision-related deformation in the west-central Alborz Mountains, Iran, by integrating U/Pb, $^{40}Ar/^{39}Ar$, and (U-Th)/He apatite age results from deeply incised and strategically located plutons. The relations of these intrusions to major faults, their thermal histories, and their proximity to the super-deep south Caspian basin illuminate development of as much as 20 km of late Cenozoic structural relief in northern Iran.

GEOTECTONIC SETTING

The Neo-Tethyan ocean closed in late Neogene time along the Bitlis-Zagros suture (Fig. 1; Stöcklin, 1968; Dewey et al., 1973; Berberian and King, 1981; Alavi, 1994), which now accommodates dextral shear (e.g., Jackson and McKenzie, 1988). Suturing began ca. 12 Ma in Turkey and progressed southeast, but it has not yet occurred along the Gulf of Oman and the Makran, where subduction continues (McCall, 1998). The subduction-related Urumiyeh-Dokhtar magmatic arc (Fig. 1) had been active since the Early Cretaceous; prolific magmatism occurred in Eocene to Miocene time (Alavi, 1994). As the Neo-Tethys closed, the Zagros fold and thrust belt formed on the northern Arabian plate margin (Alavi, 1994). Plate-circuit reconstructions yield north-south Arabian-Eurasian convergence rates of 30+ mm/yr (DeMets et al., 1990). Iran consists of aseismic continental blocks surrounded by seismic belts; seismicity shows central Iran converging north-northeast with Eurasia (Jackson and McKenzie, 1988).

Central Iran comprises narrow mountain ranges separated by wide lowlands, in contrast to the broad ~2000-m-high orogenic plateau in Turkey, Iraq, and western Iran. The Alborz Mountains (Fig. 1) are 200–500 km north of the Neo-Tethyan suture and wrap around the south Caspian Sea. Peaks are typically >3000 m, and elevation drops precipitously northward to −30 m at the Caspian. The south Caspian may be the deepest sedimentary basin in the world: as much as 25 km of post-Jurassic(?) sediments overlie oceanic basement (Neprochnov, 1968; Berberian, 1983; Priestley et al., 1994). Structural relief between the Alborz and the south Caspian is ~25 km; ~10 km is recorded by very rapidly deposited oil-bearing sediments younger than 6 Ma (Nadirov et al., 1997; Devlin et al., 1999).

The Alborz range consists mainly of late Precambrian to Eocene sedimentary and volcanic strata. These are intruded by Paleozoic to Pleistocene plutons and dikes (Annells et al., 1975, 1977; Stöcklin, 1974; Vahdati-Daneshmand, 1991). Structures are generally range parallel. Most faults dip into the range in a flower-structure geometry and have reverse separation, but some show normal separation (Gansser and Huber, 1962; Vahdati-Daneshmand, 1991; Annells et al., 1975),

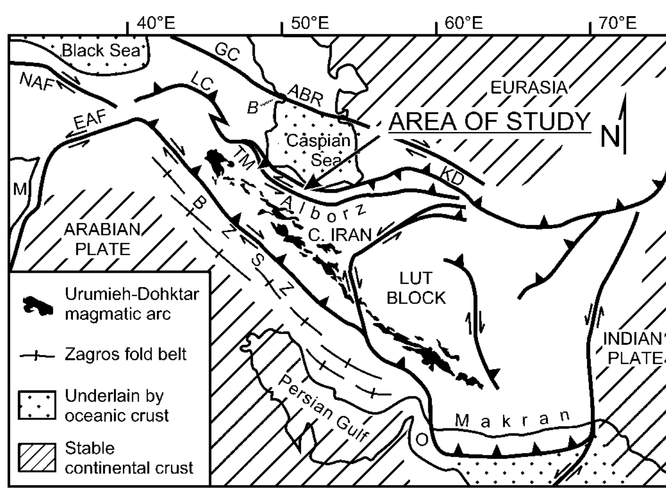

Figure 1. Tectonic map of Iran and surroundings (after Alavi, 1994; Berberian et al., 1999): ABR—Apsheron-Balkan ridge; B—Baku; BZSZ—Bitlis-Zagros suture zone; EAF—East Anatolian fault; GC—Greater Caucasus; KD—Kopet Dagh; LC—Lesser Caucasus; M—Mediterranean Sea; NAF—North Anatolian fault; O—Gulf of Oman; TM—Talesh Mountains.

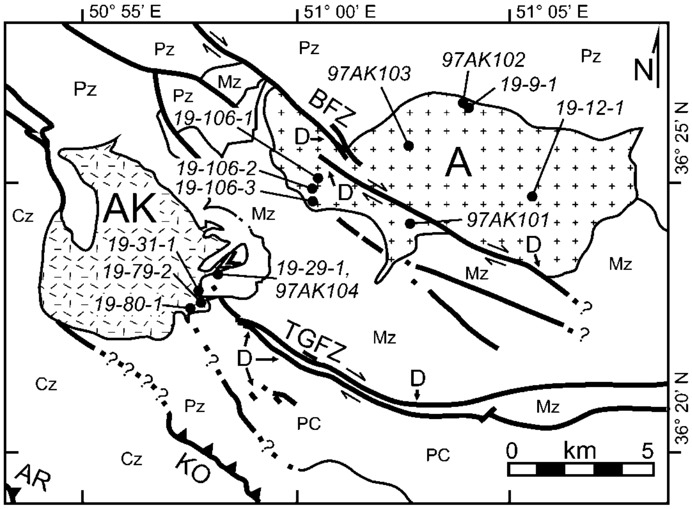

Figure 2. Map of Alam Kuh region showing sample sites and faults (modified from Annells et al., 1975; Vahdati-Daneshmand, 1991): A—Akapol pluton; AK—Alam Kuh pluton; BFZ—Barir fault zone; D—Dextral kinematic indicators on fault; KO—Kandavan 'overthrust'; AR—Alamut Rud thrust; TGFZ—Tang-e-Galu fault zone. Sedimentary strata: Cz—Cenozoic; Mz—Mesozoic; Pz—Paleozoic; PC—Precambrian.

suggesting transpression. Steep strike-slip faults predominate over low-angle, dip-slip thrusts in the study area (Fig. 2). Geologically defined lateral offsets there are dextral. The Tang-e-Galu and Barir fault zones (new names) have outcrop-scale dextral kinematic indicators (Fig. 2). The latter offsets steep contacts of the Akapol pluton 2–4 km dextrally (Annells et al., 1977; Vahdati-Daneshmand, 1991). The Nusha fault, 25 km to the northwest, dextrally offsets a pluton by ~12 km (Annells et al., 1975). In contrast, seismicity reveals range-parallel sinistral faults within the Alborz, range-perpendicular thrusts along the southern margin, and thrusting of the northwest Alborz and Talesh Mountains to the east or northeast over the southwestern Caspian (Priestley et al., 1994).

U/Pb, $^{40}Ar/^{39}Ar$, AND (U-Th)/He RESULTS

Zircon (U/Pb), K-feldspar and biotite ($^{40}Ar/^{39}Ar$), and apatite ([U-Th]/He) were analyzed from the Akapol and Alam Kuh plutons.[1] Results are summarized in Table 1 and Figure 3. Zircon ion microprobe U/Pb ages (Dalrymple et al., 1999) from three Akapol suite samples are adversely affected by low U contents (50–150 ppm) and hence low radiogenic Pb (50%–60% radiogenic ^{206}Pb). Time-series measurements show that most common Pb is surface contamination, so regional anthropogenic Pb compositions are used in calculating a mean $^{206}Pb/^{238}U$ crystallization age for the three samples of 56 ± 2 Ma (1 σ). Reasonable variation of common Pb compositions alters this age by <2 m.y. Much higher U contents in Alam Kuh zircons (>1000 ppm) yield ~95% radiogenic ^{206}Pb, and concordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ crystallization ages of 6.8 ± 0.1 Ma (1 σ).

Step-heating of two Akapol pluton biotites yields weighted mean $^{40}Ar/^{39}Ar$ ages of 56–57 Ma (Table 1). Concordance of U-Pb zircon and $^{40}Ar/^{39}Ar$ biotite ages (Fig. 3) requires emplacement at depths with ambient temperature below 350 °C (McDougall and Harrison, 1999). The $^{40}Ar/^{39}Ar$ age spectrum from an Akapol pluton K-feldspar increases from ca. 25 Ma to 58 Ma after correcting for low-temperature Cl-correlated excess ^{40}Ar (Harrison et al., 1994; see footnote 1). Multidomain diffusion models assuming monotonic cooling (Lovera et al., 1997; see footnote 1) indicate cooling from 300 °C at 55 Ma to ~150 °C at 40 Ma (Fig. 3). These models also indicate that the Akapol pluton was nearly isothermal at ~150 °C from 40 Ma to at least 25 Ma. Transient reheating might alter this conclusion (Quidelleur et al., 1997), but reheating is unlikely because stable shelf sedimentation (e.g., Qom Formation) over much of Iran indicates tectonic quiescence during this interval (Berberian and King, 1981).

A nearly flat age spectrum from an Alam Kuh K-feldspar yields a total gas age concordant with that of the coexisting zircon (Table 1). Concordance is consistent with field evidence for shallow emplacement: relatively fine grained texture, common miarolitic cavities, and mineralogically similar glassy dikes in nearby country rocks (e.g., Gansser and Huber, 1962). Multidomain diffusion calculations are consistent with rapid cooling to 125–175 °C by ca. 6 Ma (Fig. 3).

Six multigrain apatite separates from the Akapol granodiorite, analyzed following Stockli et al. (2000), yield very reproducible (U-Th)/He ages between 5.9 and 4.4 Ma that record rapid cooling below ~70 °C. These ages (except sample 19-106-3) correlate with elevation, increasing from 4.4 Ma at 1800 m to 5.9 Ma at 2880 m (Table 1; Fig. 3), giving an exhumation rate of 0.7 ± 0.1 km/m.y. (excluding sample 19-106-3). Alam Kuh apatites analyzed this way yield irreproducible (U-Th)/He ages that predate the crystallization age (Table 1). Backscattered electron imaging shows that grains that appear optically to be inclusion free commonly contain minute (<3 μm) U- and Th-rich zircon and monazite crystals. These likely survived nitric acid dissolution used for U and Th analysis, producing the anomalous ages (see House et al., 1997). Two inclusion-free single grains from the Alam Kuh samples analyzed by laser heating (House et al., 2000) yielded ages of 5.8 ± 0.3 and 6.3 ± 0.3 Ma (Table 1). We interpret these to record rapid cooling through ~70 °C due to final intrusive heat loss and(?) contemporaneous exhumation.

DISCUSSION

Our thermal history of the Alam Kuh area (Fig. 3) spans a key interval in Iranian tectonics. The Akapol granodiorite (56 ± 2 Ma) intruded during the main phase of subduction-related magmatism. Subsequent cooling to ~150 °C by 40 Ma probably reflects early exhumation due to crustal deformation also recorded by Eocene unconformities in central Iran (Berberian and King, 1981). Our multidomain diffusion thermal history models indicate nearly isothermal conditions at ~150 °C from 40 Ma to ca. 25 Ma, consistent with tectonic quiescence then (see above). Multidomain diffusion model results from the Akopol suite (Fig. 3) show that the area had cooled to 125 °–175 °C when the nearby Alam Kuh pluton intruded at ~6.8 Ma. This is supported by thermochronology (Fig. 3) and field observations (discussed above) from the Alam Kuh granite, so tectonic stability likely persisted in the study area into late Miocene time.

Elevation-correlated (U-Th)/He ages of 6 to 4 Ma from the Akapol pluton suggest that rapid denudation began about when the Alam Kuh granite was intruded (Fig. 3). Assuming a regional steady-state geotherm of ~25 °C/km implies that ~5–7 km of exhumation occurred after ca. 7 Ma. Including the ~3–4 km average elevation of the study area, total uplift may be 10–11 km since 7 Ma.

We infer that uplift of the high Alborz and Talesh Mountains loaded the south Caspian basin, causing accumulation of thick late Cenozoic deposits. Nadirov et al. (1997) showed that the south Caspian sedimentation rate near Baku (Fig. 1) increased more than tenfold ca. 6 Ma; >10 km of sediment has been deposited since then. They related this change to southward thrusting of the sub–sea level Apsheron-Balkan ridge (Fig. 1) over the south Caspian. However, it seems likely

[1]GSA Data Repository item 2001059, Methodology, tabulated analytical results, and additional figures, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org or at http://www.geosociety.org/pubs/ft2001.htm, or at http://oro.ess.ucla.edu.

TABLE 1. AGES FROM THE ALAM KUH AREA, WEST-CENTRAL ALBORZ MOUNTAINS, IRAN

Sample number	Location		Zircon* Pb/U ± 1 σ (Ma)	Biotite† $^{40}Ar/^{39}Ar$ ± 1 σ (Ma)	K feldspar† $^{40}Ar/^{39}Ar$ ± 1 σ (Ma)	Apatite (U-Th)/He ± 2 σ (Ma)	Elevation (m)	Rock type
	Lat (°N)	Long (°E)						
Alam Kuh Granite								
19-29-1	36°22′41″	050°58′09″	6.8 ± 0.1			7.6 ± 0.5§	4195	Fine-grained granite
97AK104	36°22′41″	050°58′09″			6.7 ± 0.1	5.8 ± 0.3#	4195	Fine-grained granite
19-31-1	36°22′34″	050°57′35″				8.1 ± 0.7§	4600 ± 50	Fine-grained granite
19-80-1	36°22′27″	050°57′18″				20.0 ± 1.0§	4620	Fine-grained granite
19-79-2	36°22′32″	050°57′44″				6.3 ± 0.3#	4880	Fine-grained granite
Akapol Suite								
97AK102	36°26′38″	051°03′54″	56 ± 2	56.8 ± 0.1		4.4 ± 0.2	1800	Foliated granodiorite
19-9-1	36°26′33″	051°03′58″				4.9 ± 0.2	1900	Foliated granodiorite
97AK103	36°25′54″	051°02′30″		56.0 ± 0.1	51.9 ± 0.4	4.8 ± 0.2	2150	Foliated granodiorite
19-12-1	36°24′40″	051°05′32″	54 ± 4				2620	Rapakivi granite
97AK101	36°24′11″	051°02′35″	58 ± 3				2650	Rapakivi granite
19-106-1	36°25′17″	051°00′46″				5.8 ± 0.3	2720	Granodiorite
19-106-2	36°24′58″	051°00′37″				5.9 ± 0.3	2880	Granodiorite
19-106-3	36°24′33″	051°00′34″				5.0 ± 0.3	3250	Granodiorite

*Weighted mean ages.
†Total gas ages. K-Feldspar ages are corrected for Cl-correlated excess ^{40}Ar (Harrison et al., 1994).
§Apparent (U-Th)/He ages with excess He derived from included zircon and monazite. Not shown in Figure 3.
#(U-Th)/He ages from inclusion-free single crystals heated by laser (House et al., 2000).

that much south Caspian subsidence was related to synchronous Alborz uplift. The southernmost Caspian sedimentary trough is ~20 km deep (Berberian, 1983), having >5 km of Neogene deposits (Huber, 1977). If ~10 km of post–6 Ma sediments are present in this trough too, then as much as 20 km (80%) of the structural relief (~25 km) between the high Alborz and the southernmost Caspian basement may be younger than ca. 6 Ma.

Unlike the overthrusting of the Talesh and northwest Alborz, the coupling between the central Alborz and the south Caspian is unclear. Huber (1977) showed Neogene beds, including a mid-Pliocene reflector at 2 to 3 km, lapping south onto metamorphic rock of the southeast Caspian coastal plain, and steep reverse- and normal-separation faults farther south at the Alborz range front. Berberian (1983) showed a major south-dipping reverse fault along the northern Alborz, but more detailed maps (Vahdati-Daneshmand, 1991; Annells et al., 1975) show discontinuous faults there, some dipping north. Alavi (1996) interpreted the Alborz as a south-vergent thin-skinned thrust belt. Folds in the southernmost Caspian (Berberian, 1983; Devlin et al., 1999) and in the Neogene of the northern Alborz foothills imply contraction there. We suspect that, as in our study area, transpression is important throughout the Alborz.

The Alborz Mountains lack a crustal root (Dehghani and Makris, 1984; Seber et al., 1997), so it is unclear what supports their topography. We argue that flexural support by the south Caspian basement is important, as indicated by the similar timing of Alborz uplift and Caspian subsidence. In addition, abnormal mantle (Kadinski-Cade et al., 1981) and common late Cenozoic alkaline igneous rocks in the Alborz (e.g., Annells et al., 1975, 1977; Berberian and King, 1981) suggest that buoyant mantle is also a factor.

The nearly synchronous onset of (1) rapid south Caspian subsidence (Nadirov et al., 1997), (2) cooling, exhumation, and uplift of the west-central Alborz (this study), and (3) coarse molasse deposition in the Zagros foreland (Dewey et al., 1973; Beydoun et al., 1992) all record the widespread onset of rapid vertical motions in latest Miocene time. Apparently, these motions began suddenly over a broad area instead of migrating outward from the suture zone. This sudden onset probably was the result of buoyant continental crust finally choking the Neo-Tethyan subduction zone ca. 6 Ma, causing a change to widely distributed shortening and resultant vertical motions. These events may also be related to more widespread tectonic changes at ca. 5 Ma: reorganization of the Dead Sea transform and onset of oceanic spreading in the Red Sea along two boundaries of the Arabian plate (see Joffe and Garfunkel, 1987), and possible initiation of extrusion of western

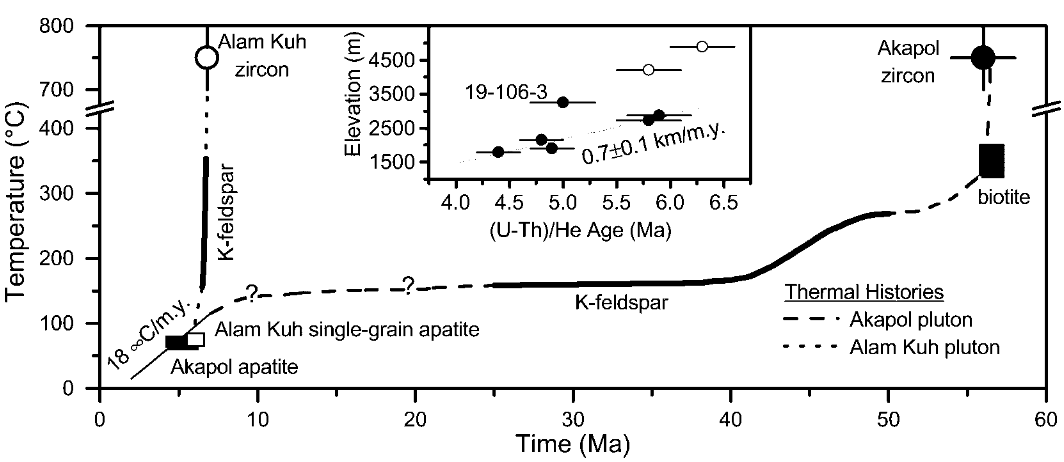

Figure 3. Thermal history results (ages from Table 1). Open symbols for Alam Kuh pluton; solid symbols for Akapol pluton. Biotite bulk closure temperature from Ar kinetics (McDougall and Harrison, 1999). K-feldspar multidomain diffusion model thermal histories (heavy lines) are calculated as discussed in text (see also text footnote 1) from ^{39}Ar release below melting. Inset plot of (U-Th)/He age vs. elevation yields 0.7 km/m.y. exhumation rate for the Akopol suite (sample 19-106-3 omitted). Apatite bulk He closure temperature based upon ~18 °C/m.y. cooling rate, 50 μm radius, and He diffusion properties (Farley, 2000).

Turkey from between the North and East Anatolian faults (Fig. 1) (Westaway, 1994).

Eastward extrusion of central Iran must occur between dextral faults of the Zagros (e.g., Alavi, 1994) and sinistral faults of the Alborz (Priestley et al., 1994) (Fig. 1). Sinistral transpression in the Alborz (and presumably extrusion) probably began in Pliocene time, reversing motion on older dextral faults of the same strike (Fig. 2). Dextral faults in the study area are younger than 56 Ma and older than 7 Ma: the Barir fault zone cuts the ca. 56 Ma Akapol pluton, but the Tang-e-Galu fault zone and the related(?) Kandavan ''overthrust'' are intruded by the ca. 7 Ma Alam Kuh granite (Fig. 2; Annells et al., 1975). Map relations (Annells et al., 1975, 1977; Vahdati-Daneshmand, 1991) suggest that late(?) Neogene synformal interior basins of the Alborz are also due to dextral transpression. In contrast, the modern tectonic regime—including sinistral faulting, overthrusting of the southwest Caspian (Priestley et al., 1994), and north-trending folding there—probably began ca. 3.4 Ma, when those folds began to grow (Devlin et al., 1999). Limited by the Indian plate on the east (Berberian and King, 1981), extrusion may be accommodated in the Makran or Kopet Dagh.

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