

Thermochronologic evidence for orogen-parallel variability in wedge kinematics during extending convergent orogenesis of the northern Apennines, Italy

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ABSTRACT

Analysis of 146 new apatite (U-Th)/He ages, six new apatite fission-track ages, and 165 previously published apatite fission-track (AFT) ages from the northern Apennine extending convergent orogen reveals a significant along-strike change in post-late Miocene wedge kinematics and exhumation history. East of ~11°30'E, age patterns and age-elevation relationships are diagnostic of ongoing frontal accretion and slab retreat consistent with a northeastward-migrating "orogenic wave." Enhanced erosion rates of ~1 mm/yr over a period of ~3–5 Ma are recorded on the contractional pro-side of the orogen and ~0.3 mm/yr on the extending retro-side. West of ~11°30'E, ongoing exhumation has been restricted to the range core since at least ca. 8 Ma at rates of ~0.4 mm/yr increasing to ~1 mm/yr in the Pliocene (ca. 3 Ma) accompanied by post-Pliocene tilting and associated faulting. This pattern can be attributed to either continued convergence (but a switch in the transfer of material into the wedge to a regime dominated by underplating or out-of-sequence shortening), or a slowdown or cessation of frontal accretion and slab retreat with enhanced Pliocene uplift and erosion triggered by a deeper seated process such as lithospheric delamination, complete slab detachment, or slab tear. These findings emphasize that no single model of wedge kinematics is likely appropriate

to explain long-term northern Apennine orogenesis and synconvergent extension, but rather that different lithospheric geodynamic processes have acted at different times in different lateral segments of the orogen.

INTRODUCTION

The northern Apennine mountain chain of Italy is an enigmatic orogen that exhibits orogen-parallel extension concomitant with crustal shortening and accretion. Numerous geodynamic models have been proffered to explain synconvergent extension, including processes as diverse as subducting slab retreat, slab breakoff, buoyant wedge escape, gravitational collapse, and extension of a critical orogenic wedge in response to crustal underplating (Willett, 1999b; Mantovani et al., 2001). The northern Apennine orogen is often cited as a type example of a retreating convergent subduction boundary (Malinverno and Ryan, 1986; Royden, 1993a, 1993b), but a number of fundamental questions regarding its orogenesis remain, and there are alternative models to explain extension in the Apennines, including slab detachment (Carminati et al., 1999; van der Meulen et al., 1999) and spreading of an overthickened critical wedge in response to underplating (Platt, 1986; Carmignani and Kligfield, 1990; Jolivet et al., 1998). The timing and nature of late Cenozoic topographic development of the northern Apennines is also controversial. Two competing views dominate the literature (Bartolini et al., 2003). One is that a topographic high has existed since at least late Miocene and that it has migrated east to northeastward as a "crustal orogenic wave" coincident with slab retreat (Cavinato and De Celles, 1999), with topography sustained either by

thermal or dynamic backarc mantle upwelling (Keller et al., 1994; D'Agostino and McKenzie, 1999). The alternate view is that uplift across the Apennines was symmetric and began later in the Pliocene, due to a slowdown or cessation of slab retreat and accretion caused by either lithospheric delamination (Carminati et al., 1999; D'Agostino et al., 2001; Argnani et al., 2003), slab tear (van der Meulen et al., 1999; Wortel and Spakman, 2000) or complete slab breakoff (Gvirtzman and Nur, 2001).

In an effort to better distinguish between contrasting models of Apennine erosional and topographic evolution, we have applied multiple low-temperature thermochronometers. In addition to providing erosion rate estimates over different time scales, using two or more thermochronometers with different closure temperatures allows constraints on material paths and deformational style within an orogenic wedge with time, which can constrain the relative roles of frontal accretion and underplating during wedge accretion (Batt et al., 2001; Batt and Brandon, 2002; Fuller et al., 2006). A detailed understanding of the surface erosion history ultimately provides a fundamental constraint to test coupled geodynamic and surface process models of synconvergent extension in the northern Apennines, which themselves provide insight into questions about the ultimate driving forces of slab retreat, synconvergent extension, and the interaction between lithospheric mantle and crustal dynamics.

In this study we present an extensive new regional apatite (U-Th)/He (AHe) thermochronometric database to augment preexisting apatite fission-track (AFT) data from the northern Apennines (Abbate et al., 1994, 1999; Balestrieri et al., 1996; Zattin et al., 2000, 2002; Ventura et al., 2001). The lower closure temperature of

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the AHe system compared to AFT provides new information on the cooling and erosion history of the less eroded parts of the orogen to enable the determination of better resolved denudation histories from age-elevation relationships. This is of particular importance given the relatively low (<2 km) local relief of the Apennines.

GEOLOGIC AND TECTONIC HISTORY

The geology and deformation of the northern Apennines can be understood in the context of the Cenozoic development of a convergent orogenic wedge developed above subduction of a remnant of the former Neotethys Ocean followed by collision with the western continental passive margin of the Adriatic microplate and the opening of the Tyrrhenian Sea backarc basin (see Malinverno and Ryan, 1986; Dewey et al., 1989; Boccaletti et al., 1990).

The oldest and uppermost tectonostratigraphic unit of the northern Apennines is the Ligurian unit: a complex mix of ophiolitic rocks, highly deformed pelagic sedimentary rocks, and partly terrigenous "Helminthoid" flysch deposits accreted during Late Cretaceous to Eocene subduction of oceanic crust of the Ligurian-Piedmont ocean basin below what is now Corsica and Sardinia (Elter, 1975; Marroni et al., 2001). The Ligurian unit rocks in the northern Apennines are unconformably overlain by Eocene to Pliocene sedimentary deposits known collectively as the Epiligurian unit (Ricci Lucchi, 1986; Barchi et al., 2001; Cibi et al., 2001, 2003). These rocks were deposited in marine thrust-top piggyback basins, demonstrating that much of the northern Apennine orogenic wedge was submarine during its accretionary history until its final full emergence between the Tortonian and Messinian (Ricci Lucchi, 1986). Both the Ligurian and Epiligurian units are disrupted by extensive tectonic and sedimentary mélange deposits commonly referred to as *argille scagliose* (Pini, 1999; Cowan and Pini, 2001; Pini et al., 2004). Immediately underlying the Ligurian unit is a thin tectonic unit known as the Subligurian, comprising Paleocene–Eocene shales and limestones (Bortotti et al., 2001) and thick early Oligocene siliciclastic turbidite rocks, regarded as the first and oldest Apennine foredeep deposits marking the onset of collision of the Ligurian accretionary wedge with the former continental passive margin of the Adria microplate (Catanzariti et al., 2003).

The Oligocene to Recent collisional history of the Apennine orogeny is characterized by thick and extensive synorogenic foredeep turbidite sedimentation. These deposits, along with their substrata of Paleozoic crystalline basement and Mesozoic–Cenozoic carbonate

and evaporite rocks of the former Adria continental margin (Barchi et al., 2001; Castellarin, 2001), were progressively deformed and accreted as a series of nappes into the northern Apennine orogenic wedge before being tectonically overridden by rocks of the Ligurian and Epiligurian units (Argnani and Ricci Lucchi, 2001). The turbidites of the northern Apennines are traditionally subdivided into different formations based on the ages of onset and cessation of sedimentation, as well as their paleogeographic position relative to the advancing thrust front. The Macigno (late Oligocene–early Miocene) and Cervarola (early Miocene) Formations (Ricci Lucchi, 1986; Sestini et al., 1986) form the earliest recognized deposits, with each formation likely representing an individual structural unit or nappe comprising turbidites deposited in the same foredeep basin (Argnani and Ricci Lucchi, 2001). Deeper metamorphosed and highly deformed foredeep rocks are exposed in the Alpi Apuane tectonic window (Fig. 1) and include the Pseudomacigno (the metamorphic equivalent of the Macigno) as well as Paleozoic basement and the Mesozoic Carrara marbles. These rocks underwent late Oligocene to early Miocene high-pressure–low-temperature (HP-LT) metamorphism (350–480 °C; 5–9 kbar) in a stacked duplex thrust system and were then progressively exhumed from midcrustal depths before being structurally juxtaposed against overlying nonmetamorphic rocks along a major low-angle detachment fault (Carmignani and Kligfield, 1990; Jolivet et al., 1998; Carmignani et al., 2001; Fellin et al., 2007). Tectonostratigraphically above the Cervarola Formation are extensive mid- to late Miocene turbidites of the Marnoso-Arenacea Formation. A distinct early Tortonian discontinuity in sedimentation records a change from a facies rich in mudstone, sand-poor turbidites, and basinwide carbonate-rich megabeds to a phase of coarser grained, sand-rich turbidites, with little or no mudstone and correlated with structural reorganization of the foredeep basin and initial emergence of the Apennine wedge (Ricci Lucchi, 1986, 2003; Boccaletti et al., 1990; Argnani and Ricci Lucchi, 2001; Cibi et al., 2004). The Marnoso-Arenacea Formation is capped by evaporite deposits marking the onset of the Messinian salinity crisis. Much of the syn- and post-Messinian sedimentary record of the northern Apennine accretionary wedge is currently buried beneath mid- to late Quaternary alluvial deposits of the Po Plain. Post-Messinian deposits comprise mainly deep marine clastic turbidites of the Fusignano, Porto Corsini, and Porto Garibaldi Formations. Late Pleistocene deposits record a shallowing upward trend, with marine sands (Sabbie Gialle Formation) grading

upward into alluvial clastic deposits of the Po River (Castellarin, 2001).

The largely in-sequence thrusting, accretion, and underplating of the northern Apennine orogen reached its maximum northward extent in the late Messinian–early Pliocene along the buried Monferrato, Emilia, and Ferrara-Romagna arcuate thrust fronts (Fig. 1). The early Pliocene also marks the final NE advancement of the Ligurian unit rocks to their current position tectonically overlying the foredeep deposits of the Marnoso-Arenacea Formation. Several authors have proposed that since the middle Pliocene shortening within the northern Apennines has become more complex with reactivation and out-of-sequence thrusting distributed across the more internal parts of the orogenic wedge (Castellarin, 2001; Ford, 2004) with emplacement of Macigno unit rocks over the Ligurian unit along the out-of-sequence Cervarola-Falterona thrust (Boccaletti and Sani, 1998) and shortening across the Apennine–Po Plain front (Montone and Mariucci, 1999; Argnani et al., 2003).

On the internal Tyrrhenian (SW) flank of the northern Apennines, the accretionary tectonostratigraphy is disrupted by later widespread Miocene to Recent extension. The most important mode of extension is characterized by ductile stretching and generally east-dipping, low-angle extensional detachment faulting that began in Burdigalian times in northeastern Corsica (Jolivet et al., 1990; Fellin et al., 2005), migrated eastward from the Tortonian to Pliocene (Carmignani et al., 1994; Keller et al., 1994; Jolivet et al., 1998) and is presently active along the Altotiberina low-angle normal fault system in the internal southernmost northern Apennines (Boncio et al., 2000; Collettini et al., 2006). Low-angle normal faulting and ductile thinning reflect between ~60% and 120% total extension since the early Miocene (Carmignani et al., 1994; Bartole, 1995). A second mode of extension is typified by high-angle brittle normal faults and the development of orogen-parallel, NNW-SSE–trending graben and half graben and represents total extension of ~6%–7% (Bartole, 1995). The age of the basal sedimentary deposits within these graben becomes younger in an eastward direction, ranging from Serravallian in the offshore northern Tyrrhenian Sea, to Pleistocene in the youngest graben located close to the current Apennine crest (Bartole, 1995; Boccaletti and Sani, 1998; Martini et al., 2001). Carmignani et al. (1994, 2001) have proposed that extension occurred as two discrete events, with core complexes related to thinning of an overthickened crust followed by later development of high-angle normal faults related to opening of the Tyrrhenian Sea. However, more recent analysis of the active

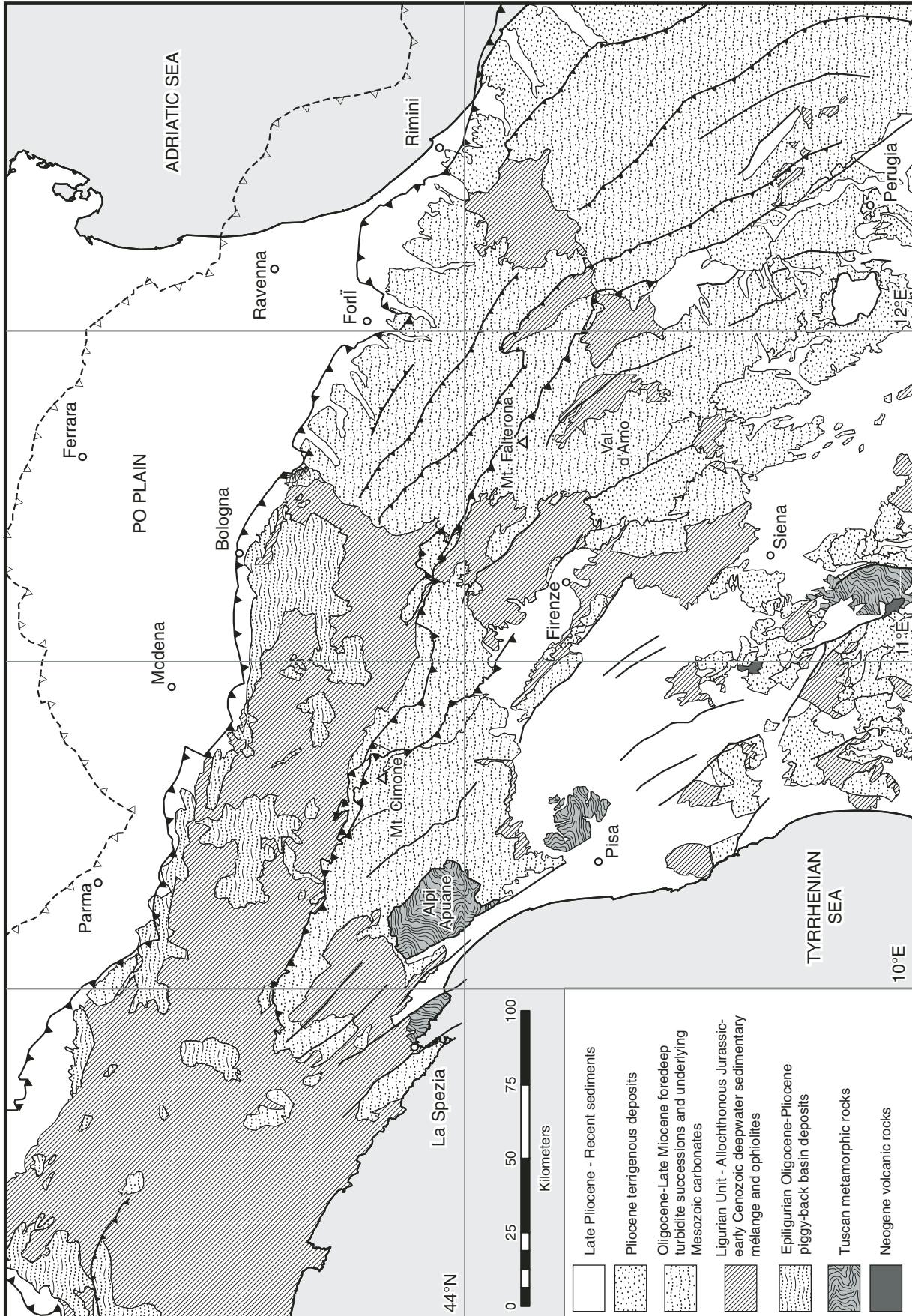


Figure 1. Geologic map of the northern Apennines, with location of the Mount Cimone, Mount Falterona, and Valdarno high-relief sample transects.

Altotiberina low-angle fault and exhumed low-angle detachments in the Alpi Apuane and Elba Island to the west (Boncio et al., 2000; Collettini et al., 2006) reveal that many of the high-angle brittle normal faults and their related half graben root into the deeper low-angle detachments and stretched ductile middle crust, supporting a cogenetic model for the two modes of extension (e.g., Bartole, 1995). To the south of the study area, the Neogene east-northeastward migration of extension is accompanied in its waning stages by significant magmatism that is lacking farther north (Serri et al., 2001).

SUMMARY OF RESULTS

This study presents 146 new AHe ages from 93 surface samples largely restricted to the late Cenozoic foredeep turbidite deposits of the Macigno and Marnoso-Arenacea formations. The extra 53 ages represent replicate analyses undertaken on 33 of the samples. Sixty-eight AHe ages are from apatite mineral separates with previously reported AFT ages (Ventura et al., 2001; Zattin et al., 2002; Balestrieri et al., 2003). Fresh samples for AHe dating were collected from the Macigno Formation close to Mount Cimone (Fig. 1) to provide a second NE-SW profile of samples across the northern Apennines. Ten AHe ages and six AFT ages are from the Ligurian nappe, including three samples from the Cretaceous–Paleocene Helminthoid flysch close to Mount Cervarola. The complete data set of AHe and AFT ages presented in this study are included in the GSA Data Repository¹. A map of the AHe ages obtained in this study, as well as those from collaborative studies by Balestrieri et al. (2003) and Fellin et al. (2007), is shown in Figure 2. The ages vary (with a few exceptions) from 19.1 Ma to a youngest age of 0.8 Ma. Older ages (generally > ca. 10 Ma) are obtained exclusively from near the present-day range front. The oldest AHe age of 47.3 Ma from sample MV1 comes from a lower Maastriichtian flysch sample of the Ligurian unit. Two anomalously old AHe ages of 15.8 and 20.3 Ma obtained from samples C52 and AP58 (not shown in Fig. 2) are presumed to have contained unobserved uranium-bearing inclusions. This is supported by a replicate age from sample C52A of 3.4 Ma. Close to the range front where less

post-depositional erosion was suspected (e.g., Zattin et al., 2002) multiple replicate single-grain analyses were performed to assess both detrital ages and the extent of partial resetting. Samples AP35, AP36, and AP42 have mixed ages between 9.5 Ma and 19.1 Ma, all of which are older than the late Miocene stratigraphic age of these rocks, confirming at least a partial detrital age signature. Samples AP5 and 1926, positioned slightly more toward the core of the orogen, give a mix of younger ages from 6.1 Ma down to 1.0 Ma, all significantly younger than the depositional age implying partial to total resetting. However, an expected correlation between age (lower extent of resetting) and U-Th concentration (e.g., Shuster et al., 2006) is weak at best in these samples. Apart from these few samples, all AHe ages (from both single and multiple grain analyses) are significantly younger than the corresponding stratigraphic age indicative of total resetting, hence the cooling and erosion history of the sampled rocks.

Six new AFT central ages from three clastic turbidite samples of the Helminthoid flysch of the Ligurian nappe show two age groups (Table DR2 [see footnote 1]). Samples 050320-2 and -3 show older mixed or detrital ages, with high age dispersion between 40.8 Ma and 76.3 Ma, close to, or slightly younger than the Late Cretaceous to Paleocene depositional age of these rocks. Sample 050320-1, on the other hand, yields two much younger single-population, low age dispersion AFT ages of 5.0 and 7.3 Ma, indicative of total resetting of this sample to temperatures >~120 °C due to greater post-depositional burial. Low track densities meant that no meaningful track length data could be obtained from these samples.

DATA INTERPRETATION

Determination of Exhumation Rates from Cooling Ages

To convert our new and previously published AHe and AFT cooling ages to exhumation rates, and to determine closure depths and temperatures for both systems given those exhumation rates, we have applied a simplified analysis to determine the upper crustal thermal field based on a one-dimensional, steady-state solution previously derived by Brandon et al. (1998). A closure temperature for each age is determined and then converted to a closure depth and time-averaged erosion rate. The modeling process accounts for isotherm advection, cooling rate, and thermochronometer temperature- and time-dependent diffusion or annealing properties. The model is based on thermal parameters applicable to the northern Apennine orogen (see

Reiners and Brandon, 2006; Fellin et al., 2007), with an estimated thickness to the base of the crustal layer $L = 30$ km, a thermal diffusivity $\kappa = 27.4$ km²/Ma (0.87 mm²/s), mean surface temperature $T_s = 14$ °C, a temperature at the base of the layer $T_L = 540$ °C based on the metamorphic pressure and temperature estimates of the deeply exhumed rocks of the Alpi Apuane, and an internal heat production $H_T = 4.5$ °C/Ma (equal to a volumetric heat production of ~0.3 μW/m³), which given the mean surface heat flow in the northern Apennines of ~40 mW/m² (Della Vedova et al., 1995; Pasquale et al., 1997) yields a realistic surface geothermal gradient of 20 °C/km. Thermochronometer closure temperatures determined with the model were based on He in apatite diffusion kinetics of Farley (2000) and average detrital apatite fission-track annealing data given in Carlson et al. (1999).

To account for the influence that surface topography can have on perturbing the topography of the closure isotherm for low-temperature thermochronometers (e.g., Stüwe et al., 1994; Mancktelow and Grasemann, 1997; Braun, 2002a, 2002b) we have applied a three-dimensional (3D) Fourier-based technique to calculate the downward continuation of the surface thermal field (Fellin et al., 2007; M. Brandon, 2009, personal commun.) where the depth to steady-state closure temperature isotherm surface is calculated from modern topography obtained from Shuttle Radar Topography Mission (SRTM) 90-m digital elevation data. The complete results of this analysis are included in the GSA Data Repository [see footnote 1]. The estimated closure depths and exhumation rates have all been corrected to account for differences between the actual sample elevation and mean elevation, as well as the difference between the mean closure depth and local relief of the closure depth (Fellin et al., 2007). Owing to the relatively limited local relief of the northern Apennines, this correction is generally small, with mean corrections of ~13% for the AHe system, and 7% for the AFT system.

Regional Cooling Age and Long-Term Exhumation Rate Patterns

To visualize the regional AHe and AFT cooling age patterns of the northern Apennines, age contour maps are presented in Figure 3. The AHe plot includes 86 of the 93 new AHe ages, as well as five AHe ages published by Balestrieri et al. (2003) and 11 AHe ages presented by Fellin et al. (2007). For contouring, the youngest replicate AHe ages were used for those samples close to the orogenic front that yielded mixed ages, with the assumption that the youngest age represents the maximum age at which these

¹GSA Data Repository item 2009284, Tables DR1 (Surface apatite (U-Th)/He data), DR2 (Apatite fission-track data), and Table DR3 (Closure depth and exhumation rate estimates using modified thermal model [after Brandon et al., 1998; Reiners and Brandon, 2006; Fellin et al., 2007] corrected for topographic relief), is available at <http://www.geosociety.org/pubs/ft2009.htm> or by request to editing@geosociety.org.

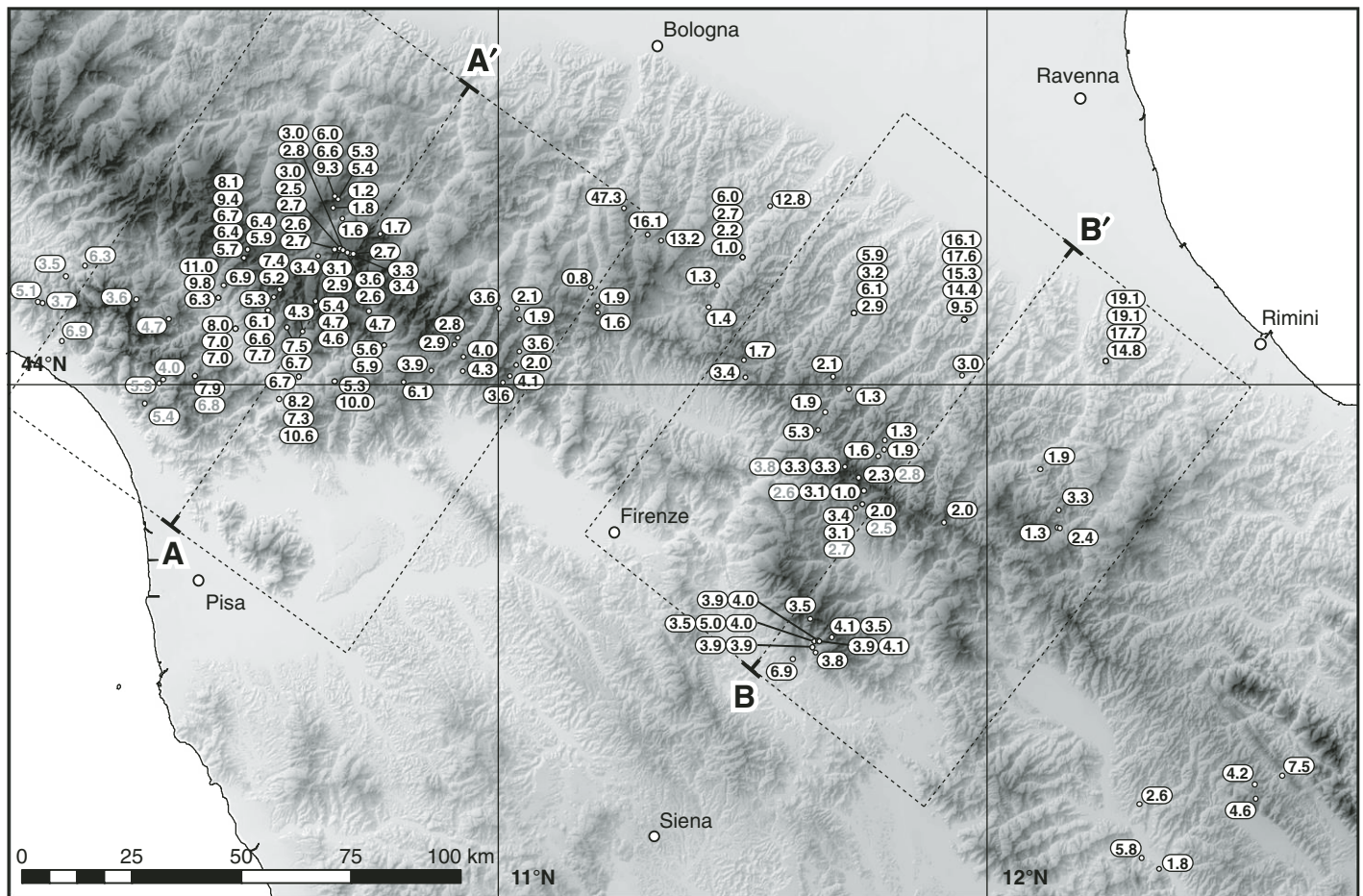


Figure 2. Geographic distribution of the surface apatite (U-Th)/He (AHe) ages. Ages in gray are published elsewhere (Balestrieri et al., 2003; Fellin et al., 2007). The position of two 100-km-wide swath, NE-SW profiles A–A' and B–B' in Figure 4 are also shown.

samples cooled through the representative closure depth. In addition, seven other sample ages outside the map area are included. Both the AHe and AFT age contours were constructed by converting the spatial point data into a raster surface using a natural neighbor interpolation algorithm with ESRI ArcGIS software. The AFT age contour plot (Fig. 3B) incorporates 165 AFT ages published by the Italian Bologna and Pisa thermochronometry groups (Abbate et al., 1994, 1999; Balestrieri et al., 1996; Zattin et al., 2000, 2002; Ventura et al., 2001; Fellin et al., 2007), as well six new AFT ages from the Helminthoid flysch (Table DR2 [see footnote 1]).

Both the AHe and AFT ages show similar regional patterns. Close to the topographic front older detrital and mixed AHe ages occur, which then rapidly decrease to fully reset ages toward the core of the orogen. The youngest AHe ages (~1–2 Ma) are found close to the core of the range, although not necessarily at the highest elevations. On the Tyrrhenian (SW) retro-flank of the orogen, where post-Pliocene crustal ex-

tension is dominant, AHe cooling ages gradually increase southwestward to ~4–6 Ma. The age decrease from detrital and mixed ages to fully reset marks the thermochronometer reset front, defined here as the surface position where erosion of material accreted into the orogenic wedge has been sufficient to expose ages fully reset by post-deposition burial, that burial being both sedimentary and structural (i.e., by the emplacement of thrust sheets). The positions of reset fronts are located at the approximate position of most rapid age decrease (ca. 6 Ma for AHe, and ca. 10 Ma for AFT). In reality the exact position of the reset front is likely to be diffuse, as total resetting of apatite in both the AHe and AFT systems is not only influenced by temperature, but in detrital apatite populations such as those represented here, by factors such as variation in apatite chemistry and radiation damage. Furthermore the dip of this reset front is low (~1°–2°) and thus influenced by local topography. The thermal model outlined above predicts that the reset fronts of the

northern Apennines represent total depths of post-depositional erosion of between 2000 and 2150 m for fully reset AHe ages between 6 and 2 Ma. For the AFT system the equivalent values are 4250 m for a fully reset age of 10 Ma, and 3950 m for an age of 6 Ma.

A conspicuous feature of the age contour plots, especially the AHe age data, is the relatively abrupt change in the distance of the reset front from the topographic front at ~11°30'E. This coincides with a previously recognized NE-SW-trending feature labeled the Sillaro line (Bortolotti, 1966; Boccaletti et al., 1990) that marks the NW outcrop limit of accreted fore-deep deposits of the Marnoso-Arenacea Formation on the frontal flank of the orogen (Figs. 1 and 3). To the west of this line Ligurian unit rocks with much older AFT and AHe ages tectonically overlie rocks of the Marnoso-Arenacea Formation. AFT and vitrinite reflectance data (Zattin et al., 2000, 2002), sedimentary provenance studies (Cerrina Feroni et al., 2001), and borehole data (Anelli et al., 1994) demonstrate

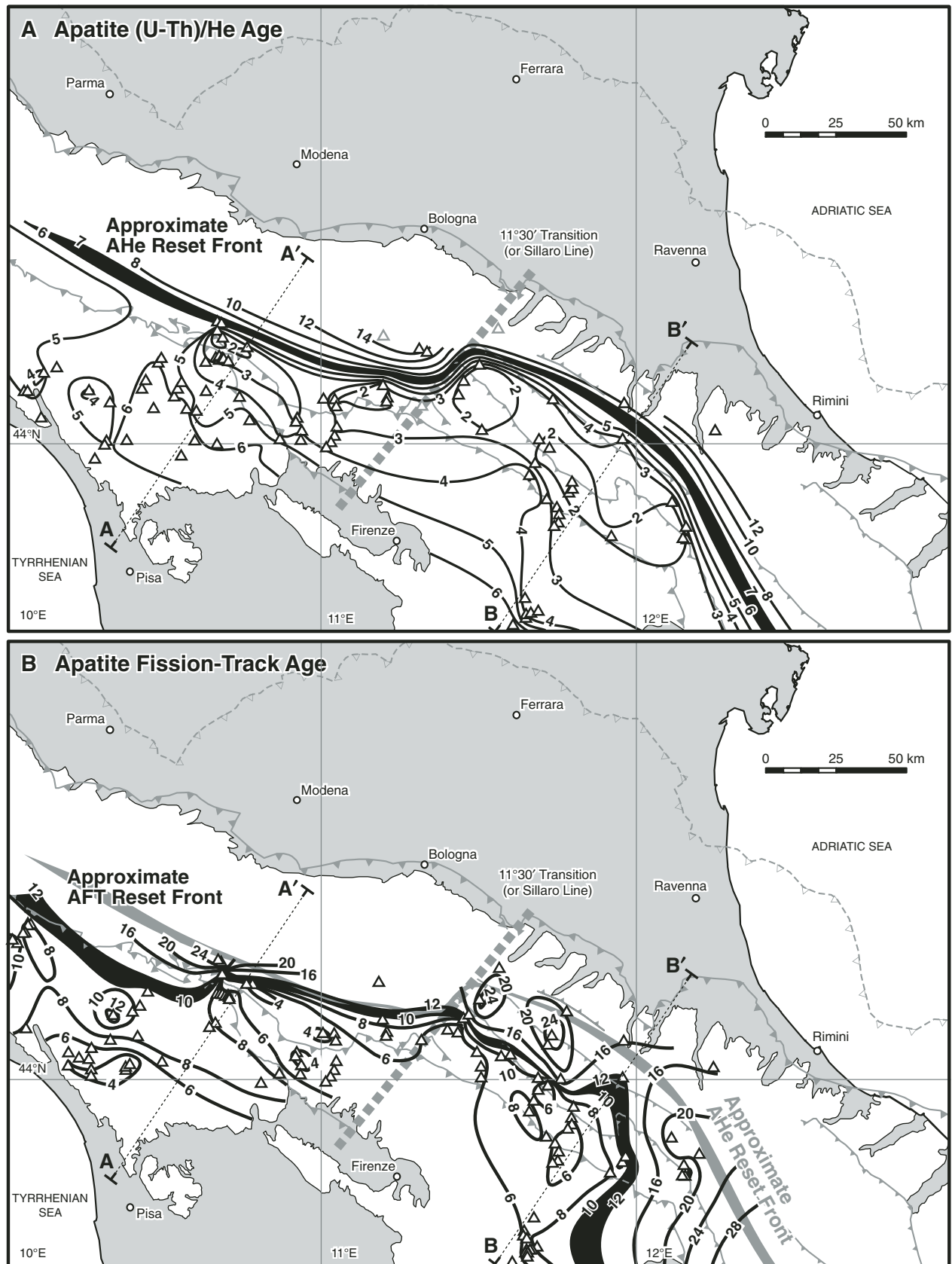


Figure 3. Map of contoured apatite (U-Th)/H (AHe) and apatite fission-track (AFT) ages, with approximate position of reset fronts (where ages are significantly younger than stratigraphic, and show no evidence of mixed ages)—for AHe between 6 and 7 Ma, for AFT between 10 and 12 Ma.

that the Sillaro line should really be thought of as simply a geographic feature or zone that splits the northern Apennines into two orogen-parallel (eastern and western) segments with different total amounts of post-depositional erosion (or missing section) in the frontal part of the orogen.

The transition to younger reset ages toward the center of the orogen can be seen more clearly in a 100-km-wide swath profile that plots age against distance parallel to the direction of convergence in the eastern segment of the northern Apennines, east of 11°30'E (Fig. 4B, profile B-B'). The AFT and AHe reset fronts and age minima are offset by ~20 km. Such offset is diagnostic of an orogenic wedge dominated by frontal accretion (Batt et al., 2001; Willett et al., 2001; Batt and Brandon, 2002). The direction of offset of the higher closure temperature thermochronometer (in this case AFT) marks the direction of accretion of material from the subducting plate to the overriding plate, while the extent of offset is dependent on the rate of frontal accretion or horizontal material motion within the wedge, as well as the erosion rate (vertical material motion). In a second swath profile across the western segment of the northern Apennines, west of 11°30'E (Fig. 4A, profile A-A') the transition from unreset and mixed AFT and AHe ages to reset ages is abrupt with no offset of reset fronts and age minima (see also Fig. 2B). Spatial coincidence of the age minima of different closure temperature thermochronometers is indicative of cooling and exhumation dominated by vertical material motion where either underplating is dominant (Willett et al., 2001; Fuller et al., 2006) or where frontal accretion is very slow or has ceased (e.g., Reinert et al., 2003). The abrupt age change in profile A-A' (Fig. 4A) likely reflects a structural discontinuity located at the contact of Macigno unit foredeep deposits against rocks of the Ligurian unit. This has been interpreted as either a Pliocene to Recent out-of-sequence thrust (Boccaletti and Sani, 1998; Cerrina Feroni et al., 2001; Pini et al., 2004), or a more recent normal fault (Remitti et al., 2007; Vannucchi et al., 2008; V. Picotti, 2007, personal commun.). A topographic profile across this contact shown with AHe ages (Fig. 5) favors the latter interpretation. Lines of constant AHe age (isochrons) imply a north upward tilt of the footwall block, with significant offset across the fault of >1000 m implied by the older AHe ages obtained from the Helminthoid flysch samples of the Ligurian unit in the downthrown hanging-wall block. The post-closure tilting of AHe isochrons of less than 2 Ma also imply that fault movement must be Plio-Pleistocene or younger in age, and may even indicate ongoing activity. Preferential uplift and exhumation to the south

of this structural discontinuity is also reflected by an ~1.0% increase in R_0 vitrinite reflectance values (Reutter et al., 1991).

Both profiles are characterized by a gradual increase in both AFT and AHe ages on the SW retro-flank of the orogen, the increase being more pronounced in the westernmost profile A-A' (Fig. 4A). An exception to this pattern is the region of anomalously young ages in the Alpi Apuane that reflect the presence of localized late Cenozoic extensional detachment faulting. These data and associated extensional detachment faulting are dealt with in detail in a companion study (Fellin et al., 2007). In typical convergent orogens, if the full orogen is in exhumational steady-state, the ages within the reset zone should reflect the synorogenic temperature field and erosion rates, with the reset ages generally similar or tending to decrease toward any retro-deformation front (Willett and Brandon, 2002; Willett et al., 2003). In profile A-A', however, the opposite pattern of increasing ages is observed. One interpretation for this anomalous pattern is that they reflect a decrease in long-term exhumation rates southwestward across the retro-flank of the orogen. Using the assumption of steady-state erosional exhumation for both the AHe and AFT age data, as done in our thermal model, would imply a pattern of increasing long-term exhumation rates toward the reset fronts from ~0.4 mm/yr on the SW flank to ~1.0–1.2 mm/yr close to the core of the range (Fig. 6; Table DR3 [see footnote 1]). The locally high exhumation rates on the AFT plot close to the Tyrrhenian Sea (Fig. 6B) relate to extensional unroofing in the Alpi Apuane (Fellin et al., 2007). The model also predicts spatially averaged model exhumation rates (equivalent to the long-term erosional flux from the northern Apennines) since ca. 8 Ma of ~0.66 mm/yr for AFT and ~0.67 mm/yr for AHe (excluding data from the Alpi Apuane). A shortcoming of this interpretation is that it relies on the often unrealistic assumption of a steady long-term erosion rate. If this were true, then the difference between the AFT and AHe age should increase with those areas with lower erosion rates. However, in both profiles the age difference across the retro-flank of the orogen is instead approxi-

mately constant at ca. 3 Ma (Figs. 6A and 6B). Furthermore, no other evidence for significant gradients in both short-term (modern fluvial) and long-term (thermochronometer-based) exhumation rates is observed across the range. For example, there is little change in mean local relief across the orogen (Fig. 4) that could explain differential erosion (Ahnert, 1970; Montgomery and Brandon, 2002).

The observed pattern of ages across the orogen, especially east of 11°30'E, can be better predicted by a simple model of variable exhumation rates with time, whereby in the material reference frame a brief (~3–5 Ma) locus of high exhumation rates migrated NE with time preceded by foredeep sedimentation and was succeeded by much lower exhumation rates. This is demonstrated in a simple wedge model illustrated in Figure 7. To produce horizontal shortening in the frontal part of the wedge, a simple linear material velocity decrease is imposed (e.g., Willett et al., 2001) as well as an erosion rate of 1 mm/yr—similar to the rates inferred from the reset thermochronometric data closest to the reset fronts. On the retro-flank of the orogen a horizontal velocity increase is imposed to simulate extension in this part of the wedge, with the result that material is “excreted” out of the backside of the orogen, and hence a true backstop (e.g., Willett et al., 1993) is lacking. The balancing of these velocities, at least over the short term, is required, as global positioning system (GPS) determined far-field plate convergence rates between the internal part of the upper plate (Corsica) with respect to Eurasia are approximately zero (Serpelloni et al., 2005). The lower rate of erosion (0.3 mm/yr) on the retro-flank reflects a regional average rate that accounts for both areas of extension dominated by sedimentation (i.e., negative exhumation rate) and intervening areas of higher relief where erosion at relatively high rates is ongoing. The ages are calculated from the time to erode at the given erosion rates to the depths of the closure isotherm for each system, using values of 3720 m for AFT and 1730 m for AHe that represent regional average depths for the northern Apennines correcting for both heat advection and topographic bending of the isotherms

Figure 4. Figure showing age data from two NE-SW profiles A-A' (Cimone) and B-B' (Marnoso-Arenacea Formation). Top section shows maximum, mean, and minimum topography from a 50-km-wide swath profile, along with position (elevation) and apatite (U-Th)/He (AHe) age of each sample (only youngest age shown where replicate AHe ages were obtained from same sample). Bottom section shows apatite fission-track (AFT) ages and AHe ages. For Profile B-B', the approximate position of the reset fronts (and age minima) is shown relative to distance from thrust front, as well as position of the high-relief transects (Fig. 8). Depositional ages taken from Ventura et al. (2001) and Zattin et al. (2002).

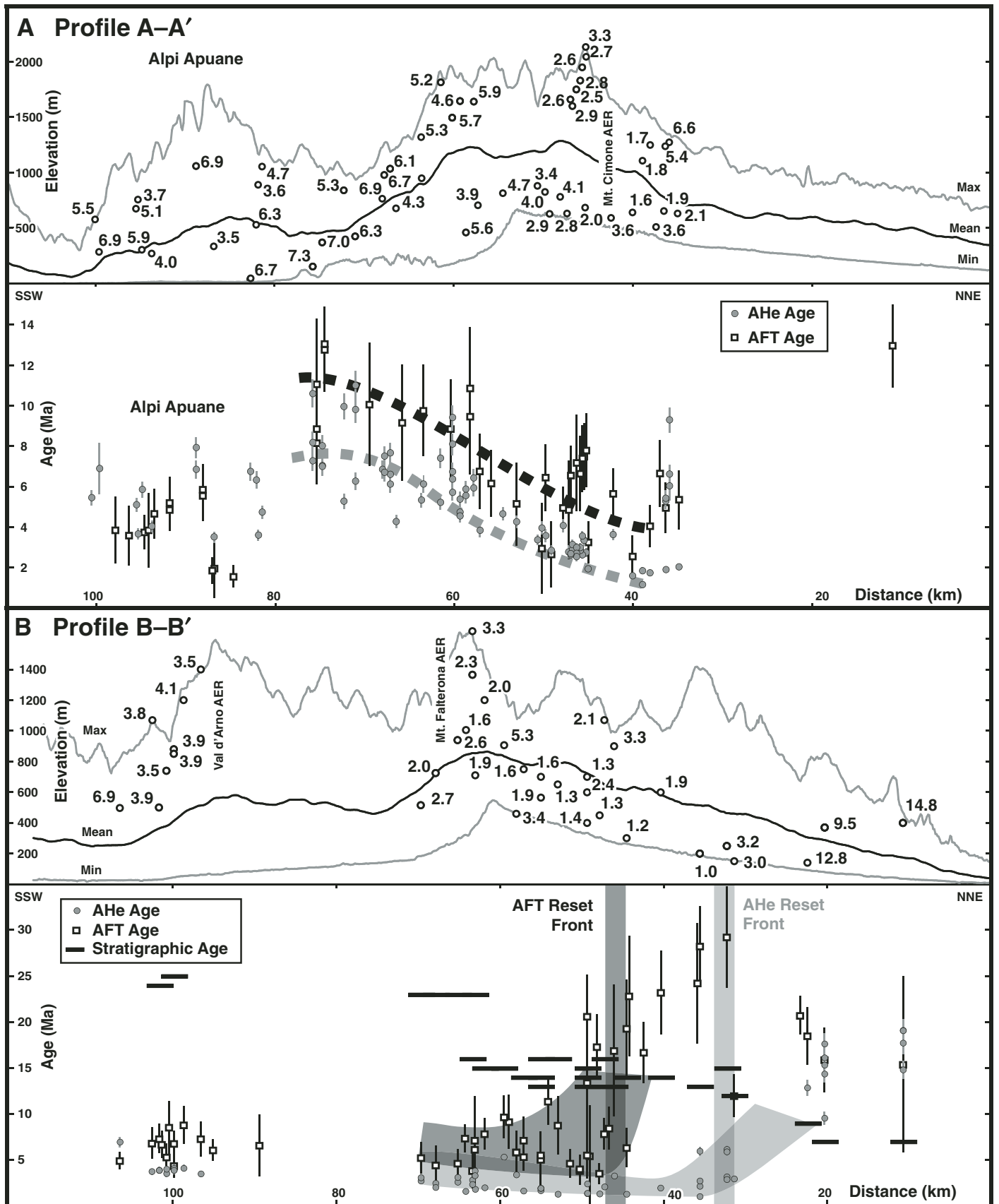


Figure 4.

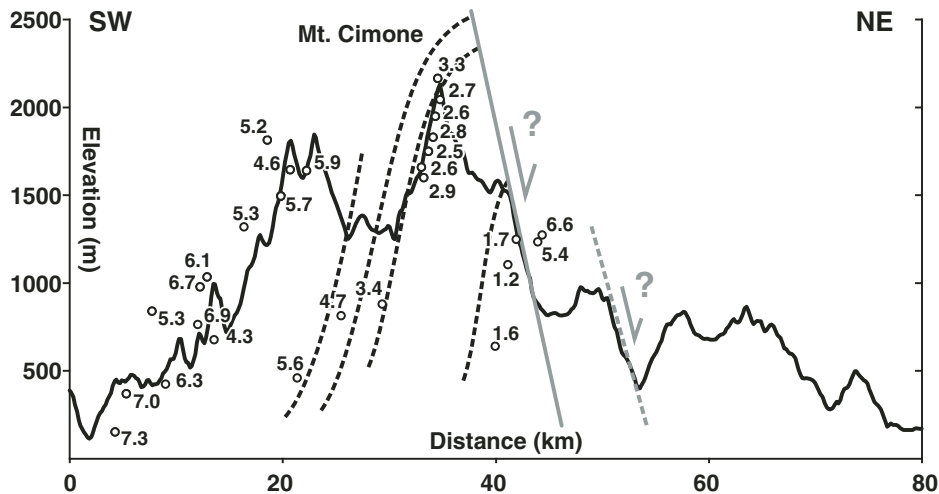


Figure 5. Topographic profile across Mount Cimone (along same line as profile A–A' shown in Figs. 2 and 4) showing apatite (U–Th)/He (AHe) ages, estimates of lines of constant (AHe) age (isochrons), and the inferred position of two normal faults. Note some data are projected from out-of-the-plane of profile and hence plot both above and below the topography.

using the approach outlined earlier. An erosion rate of 1.0 mm/yr gives a model minimum AHe age of 1.73 Ma, close to the minimum ages obtained. The “time of erosion” for any one point following its accretion into the wedge was calculated from the integrated horizontal velocity (in relation to the imposed velocity decrease and increase) over the distance of that point from the current wedge front. The modeled width of the wedge was taken to be close to its current size, being 120 km wide, subdivided into two equally wide “pro-” and “retro-” flanks of 60 km. For the given erosion rates, relative material velocities for frontal accretion of 17 km/Ma, excretion of 17 km/Ma, and 8 km/Ma horizontal velocity through the core of the orogen best simulate the observed relative offset of the AFT and AHe age minima and reset fronts, the AFT and AHe ages themselves, as well as the limited amount of total erosion implied by unreset zircon FT ages away from the Alpi Apuane (Balestrieri et al., 1996), vitrinite reflectance data (Reutter et al., 1983, 1991) and the gradual increase in ages of both thermochronometers on the retro-flank of orogen, particularly for profile B–B' (Fig. 4). Imposing slightly lower erosion rates of 0.8 mm/yr the frontal flank produces the observed spatial thermochronometer offset with slightly lower relative horizontal velocities of 13 km/Ma for frontal accretion and excretion, and 7 km/Ma horizontal velocity through the core of the orogen, but results in slightly greater total amounts of erosion and higher age minima (2.16 Ma for AHe and 4.65 Ma for AFT). Neither model fits the data from profile A–A', especially the age increase on the retro-flank of the orogen ~70–

90 km from the topographic front (Fig. 5). We attribute this disparity to along-strike variation in the style of accretion to a region dominated more by vertical material motion, as well as potential tilting of the upper crustal section related to Pliocene to Recent normal faulting (e.g., Fig. 5).

Thermochronometer Age-Elevation Relationships

Thermochronologic age-elevation relationships (AERs) for both AFT and AHe are presented from three different high-relief sample transects: Mount Cimone, Mount Falterona, and Valdarno (Fig. 8; see Fig. 1 for locations). The Mount Cimone transect is situated in rocks of the Macigno Formation little disturbed by later normal faulting. The other two transects are taken from Marnoso-Arenacea Formation rocks close to two well-developed Plio-Pleistocene extensional basins. Mount Falterona is bounded to the south by the Casentino-Mugello basin (Benvenuti, 2003), while the Valdarno transect is situated west of several normal faults with a combined throw of ~1.5 km (Martini et al., 2001). The Mount Falterona transect is disrupted by an important normal fault with ~500 m throw between the two lowermost samples (Balestrieri et al., 2003), thus the lowermost sample ages are excluded from any regression analysis. The AERs for each transect are plotted in unmodified form in Figure 8 (A–C). However, exhumation rates inferred from such plots can seriously underestimate or overestimate the true exhumation rate owing to a number of often inappropriate assumptions including (1) constant depth of

the closure isotherm (i.e., geothermal gradient) over time, (2) a flat closure isotherm at the time of closure, (3) steady-state relief over the areal extent of the transect following closure, (4) no tilting or folding of the sampled rocks after cooling through the closure isotherm, and (5) no residence for a significant time (>5–10 Ma) at temperatures within the fission-track partial annealing zone or helium partial retention zone (e.g., Stüwe et al., 1994; Brown and Summerfield, 1997; Mancktelow and Grasemann, 1997; Brandon et al., 1998; Moore and England, 2001; Braun, 2002a, 2002b; Ehlers and Farley, 2003; Ehlers, 2005; Reiners and Brandon, 2006).

We have corrected the AER for heat advection and topographic bending of the closure isotherms using the thermal analysis earlier (Brandon et al. 1998; Fellin et al., 2007) (Table DR3 [see footnote 1]). Instead of plotting sample ages against elevation and hence their relative height above an unperturbed horizontal isotherm, we use the results of the thermal analysis to plot sample ages against their relative height above the model-determined, perturbed closure isotherm surface at the time of closure (Figs. 8D–8F). Because the relative height of samples above the AHe and AFT closure isotherms are different, this allows data from both the AFT and AHe thermochronometers to be plotted on a single composite AER, providing a thermally robust long-term representation of the exhumation rate history for the region of each high-relief transect.

For the Mount Cimone transect (Fig. 8D) collected over a relief of 1524 m, our model predicts an AHe closure isotherm perturbation of 429 m, while the deeper AFT isotherm has a more dampened relief of 115 m. These values equate to ratios of isotherm relief over topographic relief (labeled the admittance ratio α by Braun, 2002a) of 0.28 and 0.08, respectively. For the AFT data, the corrected AER exhumation rate is adjusted downward from 253 ± 7 m/Ma to 223 ± 9 m/Ma (~12%), whereas the larger perturbation of the AHe isotherm results in a more significant correction from 721 ± 137 m/Ma to 576 ± 164 m/Ma (~20%). The data imply a twofold increase in exhumation rates ca. 3 Ma. Long mean AFT track lengths of >14 μ m (Abbate et al., 1999; Balestrieri and Ventura, 2000) confirm that the upper part of the AFT AER represents a period of exhumation that must have begun sometime before ca. 8 Ma, and does not represent the base of a fossil AFT partial annealing zone (e.g., Fitzgerald et al., 1995). This is supported by high post-depositional vitrinite reflectance values of the sampled rocks (Reutter et al., 1983, 1991) implying their deep burial following deposition during the early Miocene. The thermally adjusted composite AER plots also

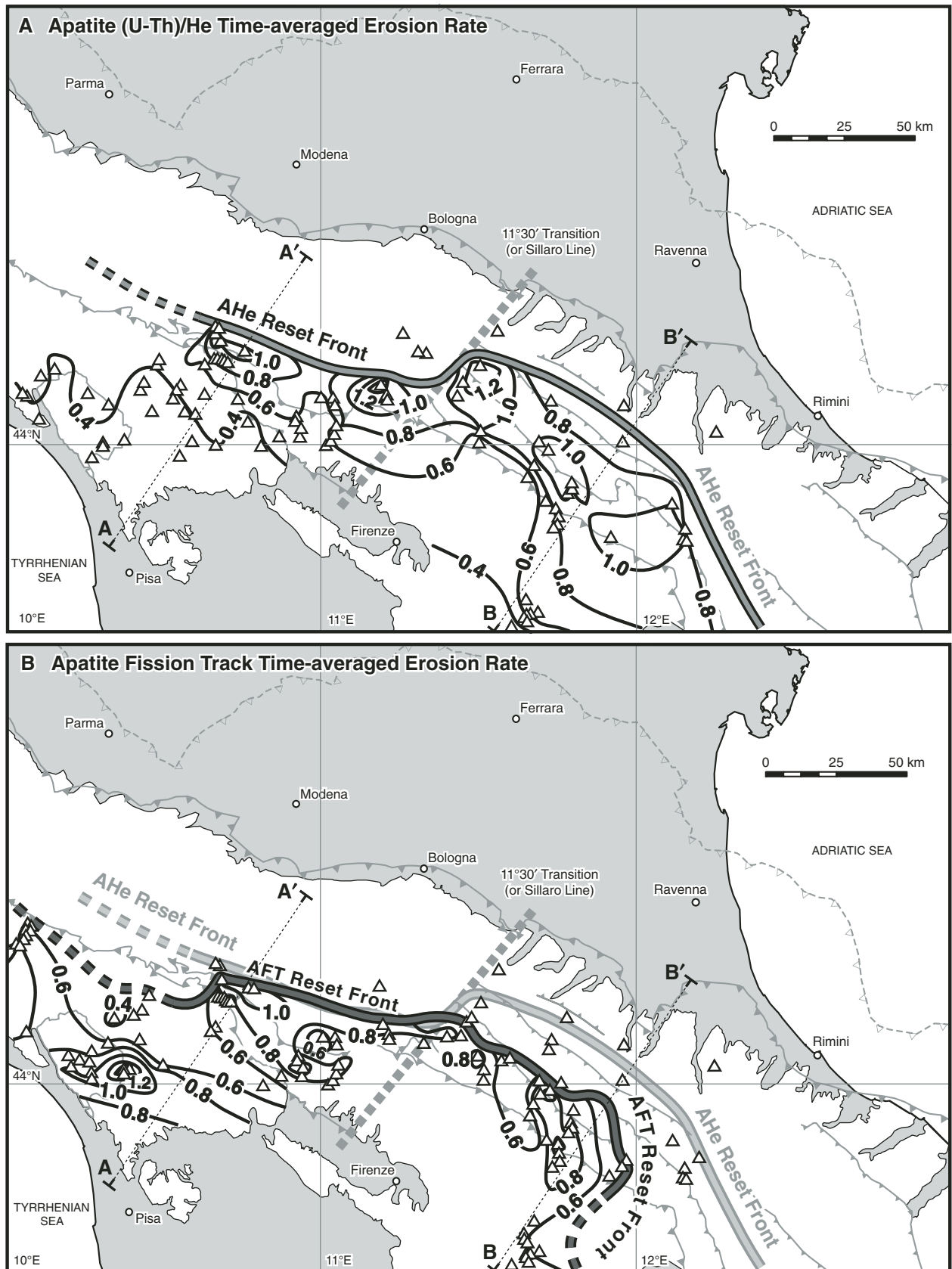


Figure 6. Map contour plots of reset fronts and time-averaged erosion rates corrected for both heat advection and 3D topographic perturbation of closure isotherms (see text or Fellin et al., 2007, for details of thermal correction).

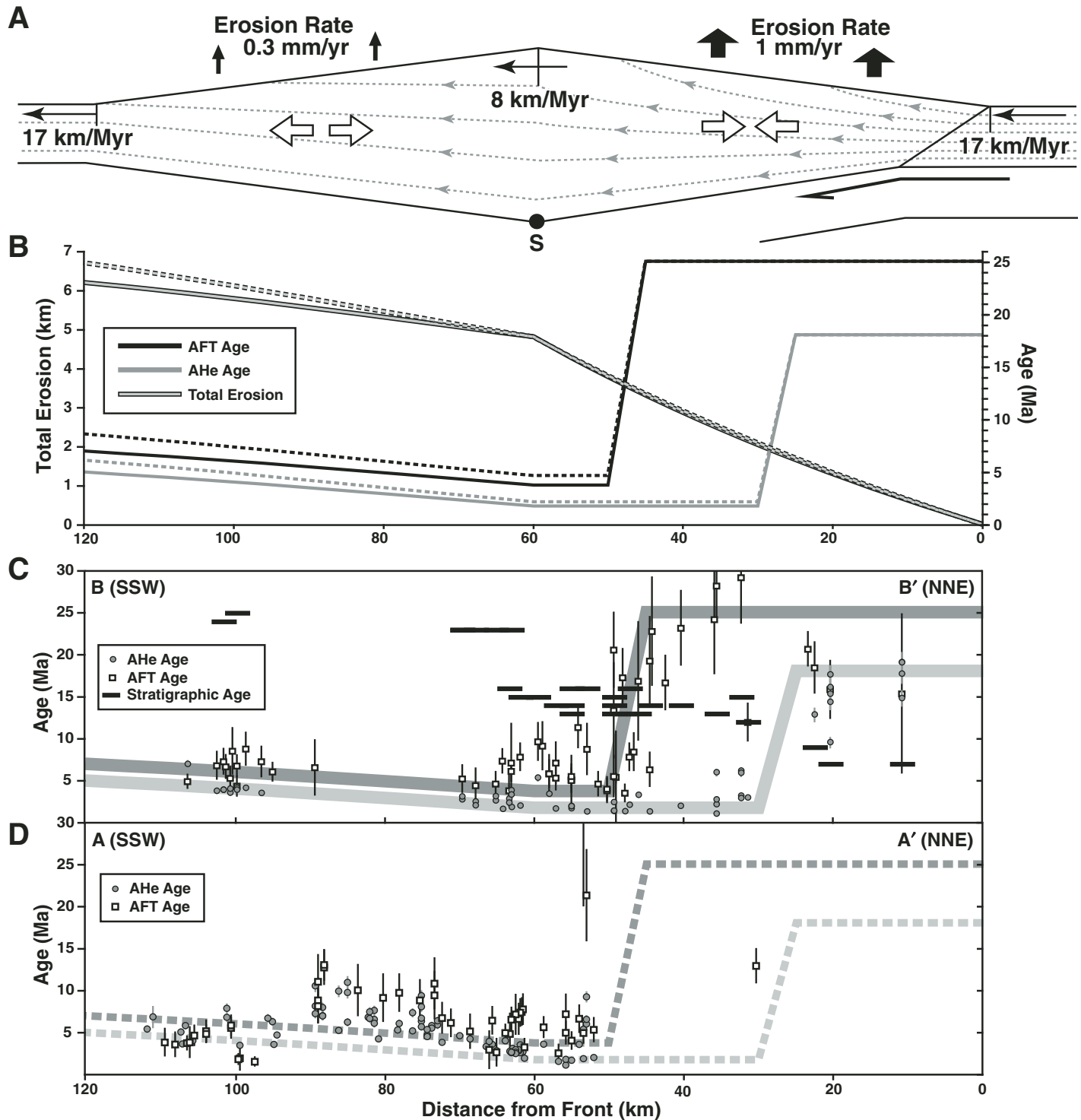


Figure 7. (A) Simple wedge model to predict apatite fission-track (AFT) and apatite (U-Th)/He (AHe) age data and total erosion estimate across northern Apennines shown in (B). Details of the variables used in the model are included in the text. Profile predicted ages are calculated from the time to erode to mean closure depth of 3720 m for AFT and 1730 m for AHe (as calculated using thermal model described in the text). Dotted lines in (B) are predictions for different velocity and erosion rate input values—see text for details. (C and D) Comparison of model predicted values with actual AFT and AHe age data obtained from NW-SE sample swath profiles B-B' and A-A' (Figs. 2 and 4), respectively.

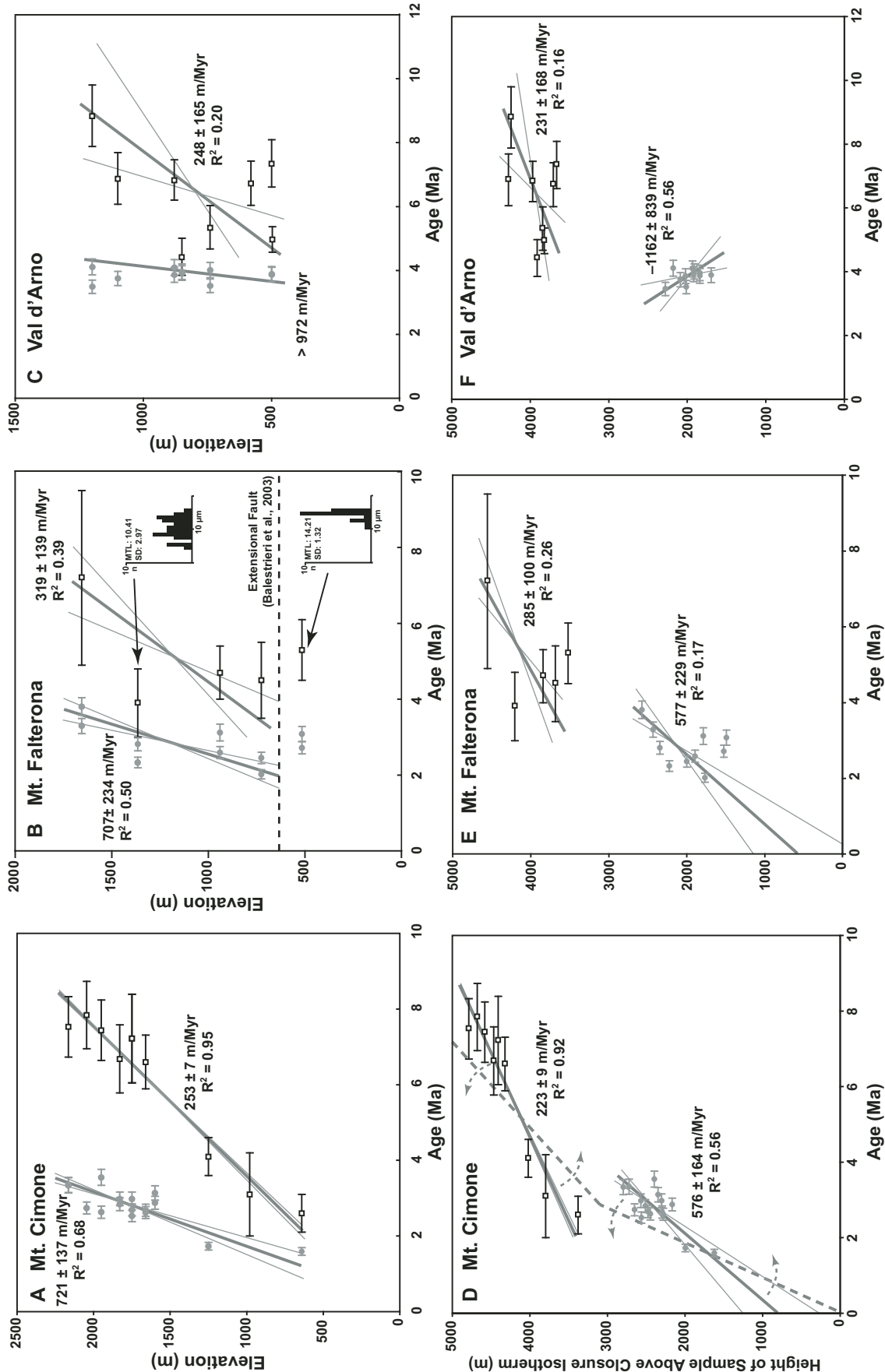


Figure 8. Apatite fission-track (AFT) and apatite (U-Th)/He (AHe) age-elevation relationships (AER) for three high-relief transects (Mount Cimone, Mount Falterona, and Valdarno). Upper plots (A–C) show unmodified AER. Best-fit exhumation rates and errors calculated from difference in slope from x on y , and y on x least-squares linear regression for each thermochronometer. Lower plots (D–F) show relationship between age and the height of each sample above the closure isotherm calculated using a 3D thermal model (Felin et al., 2007; M. Brandon, 2009, personal commun.). The slopes calculated from these plots give exhumation rates adjusted for both the 3D topography of the closure isotherm surface and the advection of heat during enhanced exhumation (see text for details).

provide a means to judge whether exhumation rates have changed from the time the samples passed through the AHe closure temperature to present day. If exhumation has remained steady, then the AHe regression line should intersect the origin (i.e., a rock at the depth of the closure isotherm will have zero age at the present day). If not, then the exhumation rate must have either decreased or increased since that time. The regression of AHe data from the Mount Cimone transect intersects the y-axis between 1246 m and 337 m indicating that the exhumation rate must have slightly increased since ca. 1.5 Ma.

One unusual aspect of the Mount Cimone composite AER is the mismatch between the base of the AFT AER and the top of the AHe AER regression lines that cannot be reconciled without the need for a significant, and highly improbable, period of negative exhumation rate. This mismatch is most likely due to violation of the assumption of either constant topographic relief and/or lack of tilting following cooling through either the AFT or AHe closure isotherm. Recent relief change can strongly affect the slope of an AER (Braun, 2002a, 2002b). For example, a decrease in surface relief (i.e., the reduction of ridge height relative to the valley floor) results in ages at higher elevations having younger ages than would have been the case had relief remained constant. This leads to a counterclockwise rotation of the AER (and potentially even inversion of the AER slope) resulting in overestimation of the true exhumation rate. In the opposite case of increased relief the true exhumation rate will be underestimated. Post-closure tilting or folding of the sampled rocks can similarly affect the distribution of ages with elevation (Rahn et al., 1997; Thomson et al., 1998b; Rahn and Grasemann, 1999). In areas where younger ages are tilted upward, the slope of the AER will increase leading to overestimation of the true exhumation rate at the time of closure. For the Mount Cimone transect counterclockwise rotation of both the AFT and AHe AER to a similar degree, whether by relief increase or tilting, allows both slopes to intersect without the need for a negative slope (Fig. 8D). The resultant plot indicates a break in slope occurring at ca. 3 Ma with exhumation rate increasing from ~400 m/Ma to ~1 km/Ma. In addition, such rotation of the AHe slope causes it to intersect the y-axis at the origin, implying steady-state exhumation since this time. Later tilting of the Mount Cimone high-relief transect seems the most likely mechanism for causing rotation of the AER given its location in the hanging wall of a postulated major Plio-Pleistocene to Recent normal fault (Fig. 5) that is spatially coincident with the abrupt change in both AFT and AHe ages in profile A–A' (Fig. 4A). Such tilting also explains the pattern of increasing

AFT and AHe ages from the core of the range toward the more internal SW flank observed in the same profile (see earlier).

The corrected Mount Falterona AER (Fig. 8E) collected over a relief of 1140 m, has a predicted model closure isotherm relief of 284 m ($\alpha = 0.25$) for AHe, and 107 m ($\alpha = 0.09$) for AFT. The corrected exhumation rates of 285 ± 100 m/Ma (~11% correction) for AFT, and 577 ± 229 m/Ma (~18%) imply an increase in exhumation rates at ca. 4 Ma. The AHe regression line passes through the origin within error indicating steady exhumation since that time. The slopes of both the AFT and AHe AER show poor linear correlation with r^2 values of 0.28 and 0.17, respectively. The scatter of AFT ages has been attributed to post-cooling faulting (Zattin et al., 2002; Balestrieri et al., 2003), although tilting can also disrupt an AER (e.g., Rahn et al., 1997). Minor tilting or relief reduction associated with faulting may also explain the slight mismatch between the top of the AHe and bottom of the AFT AER. The AFT data from the higher elevations of Mount Falterona transect, in contrast to those from Mount Cimone, show a bimodal AFT track length distribution and an older mixed AFT age diagnostic of former residence near the base of a fossil AFT partial annealing zone (Zattin et al., 2002). This implies exhumation in this region has only been active since ca. 4 Ma following a period of relative thermal stability.

The model closure isotherm perturbations predicted for the 700 m Valdarno AER (Fig. 7F) are 363 m for AHe ($\alpha = 0.52$) and 123 m for AFT ($\alpha = 0.18$). The corrected exhumation rate determined from the AFT AER (231 ± 168 m/Ma) is similar to the rates obtained from both other transects. However, it has a very poor linear correlation ($r^2 = 0.16$). The wide variation in AFT ages at lower elevation is similar to patterns indicative of post-closure tilting in the Swiss Alps (Rahn et al., 1997; Rahn and Grasemann, 1999). This is consistent with the local geology of the Valdarno transect, as it is situated within a large, significantly tilted normal fault block. Unfortunately, no AFT length data were obtained from these samples owing to their low track density. Therefore, the possibility that the AFT AER represents a fossil AFT partial annealing zone cannot be discounted, and any inferred exhumation rate must be treated with caution. The corrected AHe AER shows an unusual negative slope that can most readily be explained by post-cooling tilting given the short horizontal distance over which the transect was collected. Over longer horizontal distances relief reduction can lead to similar AER inversion (Braun, 2002a, 2002b). With no information on the amount of tilting, relief change, and post-cooling faulting, further

interpretation of the Valdarno AER is difficult. However, the change in character between the AFT and AHe AER at ~4–5 Ma can best be interpreted as representing an increase or an onset of accelerated exhumation at this time. Also, the corrected AER must pass through the origin, requiring that exhumation rates slowed down appreciably to rates less than an absolute maximum of 0.5 mm/yr sometime between 4–5 Ma and present.

In summary, all three high-relief transects demonstrate apparent changes in exhumation rate with time. The Mount Falterona transect is consistent with an increased exhumation beginning at ca. 4 Ma. The initiation of exhumation can be interpreted as the time when the fore-deep deposits in this part of the orogen were accreted into the orogenic wedge and began to erode. This transect now lies ~60 km from the present-day topographic front of the orogen implying that the topographic front has migrated at an average rate of ~15 km/Ma since this time. The Valdarno transect can be similarly interpreted, although the AER is not so well defined. Here, ~80 km from the topographic front, exhumation began at ~4–5 Ma implying an average topographic front migration rate of ~16–20 km/Ma. In contrast, the Mount Cimone transect, situated a similar distance from the topographic front to the Mount Falterona transect, but west of $11^{\circ}30'E$, shows continuous exhumation since at least 8 Ma, with a twofold increase in exhumation rate at ca. 3 Ma. This equates to a much lower and longer term topographic front migration rate of <7.5 km/Ma.

Thermochronometer Pair Derived Exhumation Histories

Single-sample cooling and exhumation histories can be constructed using two or more mineral cooling ages of different closure temperature (Wagner et al., 1977; Mancktelow and Grasemann, 1997). This method avoids complications in the AER approach arising from topographic bending of isotherms, as well as post-cooling faulting and tilting, but is limited in its resolution to the number of different closure temperature cooling ages measured in each sample. As with the AER approach, inferring realistic exhumation rates from cooling ages requires detailed knowledge of the geothermal gradient over time (Moore and England, 2001), and its application is only appropriate if it can be demonstrated that the samples have not resided for any significant time at temperatures within the AFT partial annealing zone or AHe partial retention zone (Gallagher et al., 1998).

Seventeen single-sample, time-depth (exhumation) histories are plotted from a SSW–NNE

transect across the eastern segment of the northern Apennines east of $11^{\circ}30'E$ (Fig. 9). The closure depths are corrected for both isotherm advection and time-averaged exhumation rate dependent closure temperature variation (see earlier or Fellin et al., 2007). Most samples show a distinct variation in exhumation rate with time, with the time of maximum exhumation rates varying as a function of distance to the present-day topographic front. For samples from Valdarno, ~80 km from the front, maximum exhumation rates of ~1 mm/yr occurred at ~4–5 Ma, followed by a slowdown to rates of ~0.5 mm/yr or less up to the present day, consistent with the exhumation history inferred from the AER. The time-depth histories from the Mount Falterona area, ~60 km from the front, show maximum exhumation rates at ~3–4 Ma with only minor slowdown up to the present day, again consistent with the AER. In contrast, those samples slightly closer to the front (~45–50 km) show their fastest exhumation from ca. 2 Ma until the present day. Despite the poor time-depth resolution, the single-sample mineral cooling age data indicate the NE migration of a brief (~3–5 Ma) locus of enhanced exhumation at rates of ~1 mm/yr following a period with little or no exhumation east of $11^{\circ}30'E$. A distinct slowdown in exhumation rates appears to succeed the period of enhanced exhumation, particularly in the Valdarno samples that now reside in the extending part of the northern Apennine orogen. The implied rate of NE (NNE) migration is similar to that inferred from

the AER data at ~16–25 km/Ma relative to the position of the current topographic front. A slightly slower rate of ~10 km/Ma between ca. 6 and 2 Ma is implied by relating the NNE-SSW distance of the samples to each other.

DISCUSSION

Timing and Rates of Northern Apennine Topographic Development and Erosion

One of the most contentious debates regarding northern Apennine orogenesis has been whether the orogen has (1) existed as an eroding topographic high controlled by orogenic wedge dynamics since at least late Miocene times, which has migrated east-northeastward relative to the European or Adriatic plate as a “crustal orogenic wave” coincident with slab retreat, or (2) began uplifting in a more symmetric arch-like manner later in the Pliocene, controlled either by underplating during ongoing accretion, or a deeper seated process such as slab breakoff following a slowdown or cessation of slab retreat (Bartolini et al., 2003). Analysis of the new regional AHe data set presented here in conjunction with previous conclusions drawn from fission-track and other geologic studies, indicates that neither model is mutually exclusive, but rather that both were applicable at different times in different lateral segments of the orogen, with the timing of onset of erosion (as reasonable proxy for the onset of uplift or emergence of the orogenic wedge above sea level) varying

from late Miocene to Pliocene both parallel and perpendicular to the strike of the orogen.

In a regional synthesis of previous fission-track studies, Abbate et al. (1999) recognized a change to younger exhumation ages moving from the Tuscany (more internal and western) to Emilia-Romagna (more external and eastern) regions of the northern Apennines. For example, AFT ages from the western internal part of the orogen close to the Tyrrhenian coast indicate exhumation beginning at ~8–9 Ma at a rate of ~0.3–0.4 mm/yr for Ligurian unit rocks (Balestrieri et al., 1996), and between 5 and 8 Ma at a rate of ~0.7 mm/yr for underlying rocks of the Macigno Formation (Abbate et al., 1994). More external early Miocene Cervarola Formation turbidites close to the Apennine topographic divide west of $11^{\circ}30'E$ yield slightly younger AFT ages of between 4 and 7 Ma (Ventura et al., 2001). Here high vitrinite reflectance values (Reutter et al., 1983, 1991) indicative of maximum burial temperatures of ~190 °C led Ventura et al. (2001) to infer that accelerated cooling and exhumation started here even earlier at ca. 14 Ma. The youngest AFT ages are found in the foredeep turbidites exposed near the topographic divide on the external flank of the orogen east of $11^{\circ}30'E$ and are indicative of enhanced exhumation starting here at ca. 4.5 Ma (Zattin et al., 2000, 2002). The new AHe ages presented in this study and in a pilot study by Balestrieri et al. (2003) further constrain these findings and highlight the variability of the late Cenozoic exhumation history in different segments of the orogen. The corrected

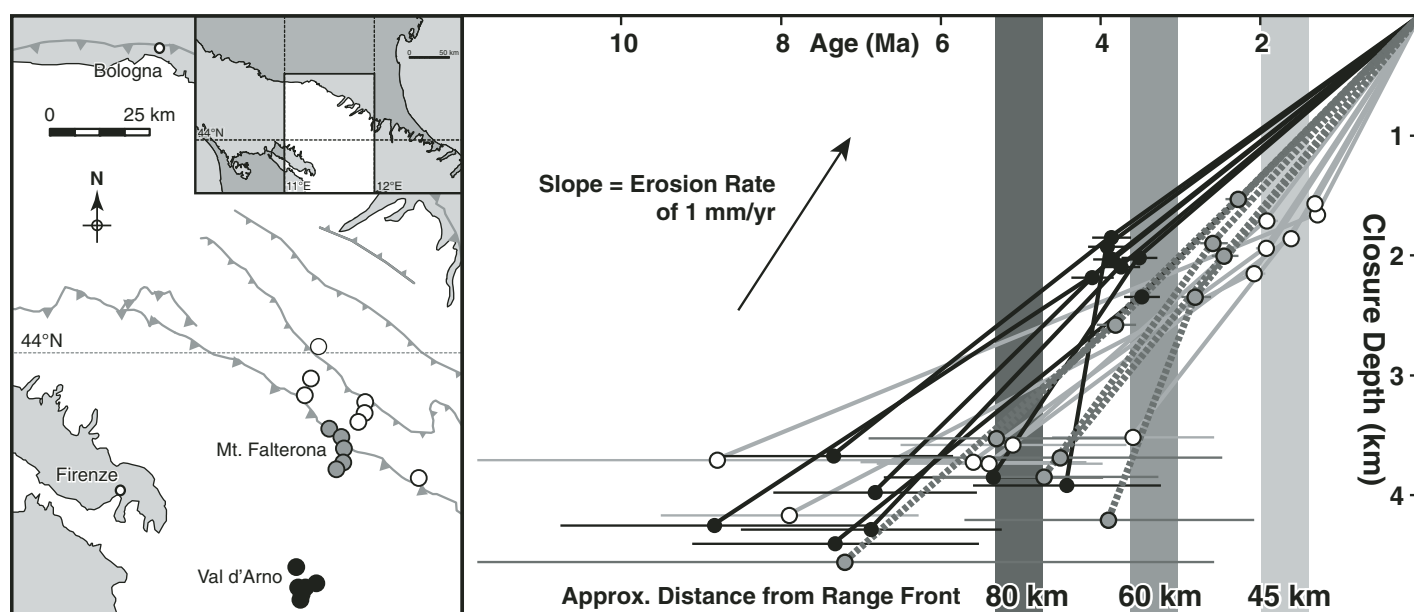


Figure 9. Paired apatite fission-track (AFT) and apatite (U-Th)/He (AHe) closure depth denudation (cooling) paths, showing apparent migration of locus of high denudation rates (~1 mm/yr = slope of arrow) toward present-day thrust front with time.

Mount Cimone AER confirms that exhumation to the west of 11°30'E has been ongoing since at least ca. 8 Ma, but also reveals a previously unrecognized change in exhumation rates from ~0.4 mm/yr to ~1 mm/yr at ca. 3 Ma. New AHe and AFT ages from Ligurian unit rocks in the more external western segment of the orogen, although limited, are all unreset implying less than ~2–3 km total erosion here since the early Cenozoic. East of 11°30'E, the AHe data establish that erosion began later at ~4–5 Ma in the most internal sampled part of the orogen around Valdarno and at ca. 4 Ma close to the current topographic divide at Mount Falterona (see also Zattin et al., 2002; Balestrieri et al., 2003). The post-onset exhumation rates of ~0.6–1 mm/yr determined from thermally corrected combined AHe and AFT AER are, however, slightly lower than rates of 1.2 mm/yr previously proposed by Zattin et al. (2002). Close to the topographic front east of 11°30'E, both AFT and AHe ages in the late Miocene rocks of the Marnoso-Arenacea Formation are unreset indicating less than 2–3 km of total post-depositional erosion, despite high short-term (Pleistocene to Recent) erosion and uplift rates determined in this region using alternate methodologies. For example, measurements of the bed and suspended load of numerous Apennine Adriatic watershed rivers on the Adriatic (frontal) flank of the orogen imply modern basinwide erosion rates of ~0.77 mm/yr (Bartolini et al., 1996). Slightly lower, but longer term drainage basin erosion rates of between 0.20 and 0.58 mm/yr have been determined using cosmogenic isotopes (Cyr and Granger, 2008). Ongoing modern uplift close to the topographic front is reflected by late Pleistocene vertical fluvial incision rates along several major river profiles averaging ~0.8–2 mm/yr (Bierma et al., 2005; Wegmann et al., 2005). To preserve unreset AHe ages in the more eastern frontal parts of the northern Apennines and given that the present-day erosion rates have been ongoing since the Pliocene requires that uplift and erosion here began even later between ca. 3 Ma and present. The independently measured short-term erosion rates also agree well with the post-onset exhumation rates of between 0.3 and 0.7 mm/yr determined from both the AER and the single-sample apatite thermochronometer pair depth-time histories obtained in this study.

Sedimentary and geomorphic data in most cases support local variability in the timing and development of late Cenozoic orogenesis. For example, the lack of Messinian marine sedimentary rocks and evaporites within many of the Epiligurian unit rocks to the west of Bologna (Fig. 1) implies that the western part of the northern Apennine orogenic wedge was already elevated above base-level at this time, whereas

to the east rocks of the Marnoso-Arenacea Formation were still being deposited (van der Meulen et al., 1999). Arguments for later Pliocene emergence and onset of uplift and erosion of the whole northern Apennines independent of wedge dynamics are limited to geomorphic studies and extensional basin stratigraphy from the internal or retro-flank of the northern Apennines. Here Plio-Pleistocene marine sedimentary rocks are now at elevations of over 400 m, and locally up to 1000 m, requiring average surface uplift rates of ~0.3 mm/yr since the Pliocene to as high as 0.6 mm/yr since the middle Pleistocene despite ongoing extensional tectonism in the region (Bartole, 1995; Argnani et al., 2003; Bigi et al., 2003). Similar post-mid Miocene rates of 0.42 mm/yr are implied by elevated paleosurfaces assumed to be correlated to a mid-Pliocene unconformity (Coltorti and Pieruccini, 2000). The occurrence of enhanced Pliocene uplift and erosion in the western, more internal part of the orogen is reinforced by the Mount Cimone thermochronometric AER that records an approximately twofold increase in exhumation rates at ca. 3 Ma superimposed on a part of the orogen that was already emergent and had been undergoing exhumation at a slower rate since at least ca. 8 Ma. This timing correlates very well with the mid-Pliocene (~3–3.5 Ma) onset of continental terrigenous sedimentation in several basins in the western part of the northern Apennines south of Mount Cimone and around the Alpi Apuane (Argnani et al., 1997, 2003), as well as with the early to mid-Pliocene cessation of relative movement along the Alpi Apuane extensional detachment followed by common uplift and erosion of both the footwall and hanging wall (Fellin et al., 2007).

Orogenic Wedge Kinematics: Frontal Accretion and/or Underplating?

As described above, multiple thermochronometer analysis reveals a marked lateral (along-strike) transition in material motion within the northern Apennine orogenic wedge since at least latest Miocene times at ~11°30'E. The two NE-SW swath profiles described in this study are only 150 km apart, but show very distinct differences in age patterns (Fig. 7) with a western segment dominated by vertical material motion, and an eastern segment dominated by horizontal motion. The transition between the two segments occurs within ~50 km along strike of the orogen—especially with respect to surface distribution of AHe ages and their reset front (Fig. 6A).

In the eastern segment of the northern Apennines, higher closure temperature thermochronometric age minima (in this case AFT) are offset

by ~20 km in the direction of material transfer into the wedge compared to the lower temperature AHe system. This is a diagnostic indicator that this part of the orogen has been dominated by frontal accretion since at least the latest Miocene, especially given the apparent lack of significant spatial variations in erosion rates across the modern pro-side of the orogen (e.g., Bartolini et al., 1996; Cyr and Granger, 2008). The observed age pattern is well replicated by a model that simulates the idea of a northeast-migrating “orogenic wave” relative to a stable European or Adriatic plate similar to that proposed for the central Apennines by Cavinato and De Celles (1999) using erosion rates constrained by both thermochronometry and other independent methods outlined in the previous section. To reproduce the offset of thermochronometers requires relative horizontal velocities of frontal accretion of ~13–17 km/Ma, similar to migration rates implied by AER and thermochronometer pair data. Independently determined rates of thrust front advance, especially since the late Miocene, also compare favorably. Since the Oligocene, three main phases of accretion are generally identified (see Argnani and Ricci Lucchi, 2001): from the Chattian to Aquitanian at rates of ~12 km/Ma, from the Burdigalian to Tortonian at rates of ~7 km/Ma, and in the more eastern segments from the Messinian to Pliocene at much higher rates of up to 30 km/Ma. Over the same time (since ca. 25 Ma) total shortening across the northern Apennines has varied from ~40 km in the far west to ~300 km in the far southeast (Bally et al., 1986; Hill and Hayward, 1988; Boccaletti et al., 1990; Vai, 2001). West of 11°30'E, total long-term shortening has been significantly lower (40–100 km) than to the east (~170–300 km) (Boccaletti et al., 1990). Similarly fast Messinian to early Pliocene rates of advance of up to 30 km/Ma have been observed in the buried Ferrara-Romagna thrust front (Argnani et al., 2003; Ford, 2004), although here total shortening was less than 16 km over this time. In the central Apennines the rate of east to northeast migration of extensional graben formation is similar to the rate of thrust front migration at up to ~25 km/Ma, with onset of extension occurring ~3–4 Ma after and ~75–100 km behind the convergent front (Cavinato and De Celles, 1999). Comparable rates of late Miocene to Recent extensional front migration (~15–30 km/Ma) are implied by the timing of onset of synrift sedimentation in the internal extending parts of the eastern segment of the northern Apennines, south and east of 11°30'E (Bartole, 1995; Boccaletti and Sani, 1998).

The thermochronologically determined rates of accretion and erosion across the migrating eastern segment of the northern Apennines

provide important constraints in relation to the long-term erosional flux out of this part of the orogen. More accurate records of both erosional flux and its long-term relationship to accretionary flux can provide important information both on the maturity of an orogen (Willett and Brandon, 2002) and the relative roles of climatic or tectonic perturbations on orogen development (e.g., Willett, 1999a; Whipple and Meade, 2006), as well as being a valuable constraint for numeric models seeking to better understand the crustal dynamics of synconvergent extension (Waschbusch and Beaumont, 1996; Willett and Brandon, 2002). Assuming that the eastern segment of the northern Apennines has maintained a constant width of ~120 km during its NE-migration over the past ca. 5 Ma, then the long-term erosional flux from the frontal flank given a mean erosion rate of 1 mm/yr is 60 km²/Ma, while the retro flank, with its lower spatially averaged erosion rate of 0.3 mm/yr has had a flux of 18 km²/Ma. This equates to a total orogen-wide, long-term erosional flux of 78 km²/Ma. This compares to a significantly lower present-day estimated accretionary flux of only ~8 km²/Ma assuming an ~10 km thick incoming section (the maximum thickness of incoming accreted section of Adria Mesozoic–Cenozoic carbonates and Cenozoic foredeep deposits; Argnani and Ricci Lucchi, 2001; Barchi et al., 2001; Castellarin, 2001) and a modern GPS determined convergence rate of 0.8 mm/yr (Serpelloni et al., 2005). This mismatch has several possible explanations. (1) Convergence rates (and hence accretionary flux rates) could have slowed down since the time of the youngest exposed AHe age (ca. 1.3 Ma). However, this is unlikely, as modern erosion rates measured on the frontal flank of the orogen are similar to longer term rates estimated from thermochronology (see previous section) implying that no associated decrease in erosional flux rates has occurred, as would be required if the orogen has remained similar in size and hence maintained a balanced mass-flux into and out of the orogen. The lack of evidence for any slowdown in erosion rates in the past ca. 1 Ma also rules out the possibility of a delayed response in the decrease in erosional flux rates to any significant decrease in accretionary flux (e.g., Whipple and Meade, 2006). (2) The thickness of the incoming section could have recently increased so that the accretionary flux more closely matches the erosional flux. However, even if the whole crust of the Adria microplate were being accreted, it is only ~30–35 km thick (Finetti et al., 2001), implying a maximum modern accretionary flux of 28 km²/Ma given the modern GPS convergence rate of 0.8 mm/yr. (3) Perhaps most likely is that short-term GPS rates underestimate long-term convergence

owing to transient (interseismic) elastic strain from “competing” contractional and extensional faults reducing horizontal velocity gradients at the surface (Bennett, 2007, personal commun.) and that true modern convergence rates across this eastern segment of the northern Apennines remain relatively high, as is also implied by the dominance of thrust-related earthquakes to the south and east of 11°30'E (Chiarabba et al., 2005; Pondrelli et al., 2006).

The transition in the spatial pattern of thermochronometric ages going from east to west at ~11°30'E is marked. Since the latest Miocene, no relative offset of the AFT and AHe age minima and reset fronts is observed in the western segment of the northern Apennines implying very little horizontal material motion over this time. Any minor frontal accretion was restricted to the buried thrust front in the Po plain, where estimated total shortening over this time is somewhat less than 15 km, or less than 3 km/Ma (Boccaletti et al., 1990; Ford, 2004). Significant accretion must have taken place before this, however, as earlier major thrusting and folding is evident in accreted Oligo-Miocene foredeep deposits now exposed in the more internal parts of this segment of the orogen (Ricci Lucchi, 1986; Argnani and Ricci Lucchi, 2001; Carmignani et al., 2001) along with Miocene advance of the Ligurian unit (Zattin et al., 2002), and the migration of the piggy-back basins of the Epiligurian rocks (Cibin et al., 2003). The change to dominantly vertical material motion in the western segment of the northern Apennines in the late Miocene has caused exhumation to become concentrated and restricted to the core of the range. This is supported by continuous exhumation since at least ca. 8 Ma recorded by the Mount Cimone thermochronometric AER. Sustained exhumation near the range crest is also reflected in higher post-depositional vitrinite reflectance values of ~1.8% R_0 in the Oligo-Miocene foredeep rocks compared to ~0.6%–0.8% R_0 close to the topographic divide east of 11°30'E (Reutter et al., 1983, 1991). Marine deposition of Epiligurian rocks in thrust-top basins at the thrust front (Ricci Lucchi, 1986; Cibin et al., 2001, 2003) implies some pre-late Miocene subaerial exposure, with exhumation and erosion restricted to the more internal parts of the orogen. The post-latest Miocene history and pattern of erosion and material motion in the western segment of northern Apennines has several potential causes. (1) Overall convergence continued, but transfer of material into the wedge switched to a regime dominated by underplating below the current core of the range. In orogens close to topographic steady state, the zone of maximum exhumation tends to be focused above the zone of maximum under-

plating, with relatively little erosion close to the wedge front (Batt et al., 2001; Konstantinovskaia and Malavieille, 2005; Fuller et al., 2006). Formation of underplated crustal duplexes at depth has been proposed in this segment of the orogen to explain earlier Oligocene shortening and HP-LT metamorphism in the Alpi Apuane followed by later Miocene gravitational collapse of the consequent overthickened unstable wedge and extensional unroofing along the Alpi Apuane detachment (Carmignani and Kligfield, 1990; Jolivet et al., 1998; Carmignani et al., 2001). (2) Overall convergence continued, but shortening was concentrated in the more internal parts of the orogenic wedge in the form of out-of-sequence thrusts (e.g., Boccaletti and Sani, 1998). Internal shortening in a critical orogenic wedge can be caused by changes in boundary conditions such as an increase in basal friction (e.g., Nieuwland et al., 2000; Konstantinovskaia and Malavieille, 2005) or climatically increased erosion rates (Willett, 1999a; Stolar et al., 2006). Removal of material from the hanging wall of an out-of-sequence major thrust fault within an orogenic wedge can result in the continued preferential activity along that fault (e.g., Hardy et al., 1998) leading to the observed long-term, but spatially restricted erosion and exhumation. (3) A slowdown or cessation of slab retreat and hence frontal accretion occurred during the late Miocene to early Pliocene, with subsequent erosion and rock uplift being dominated by an isostatic response. However, given such a large decrease in the accretionary flux, erosion and rock uplift rates would be expected to decrease significantly right across the orogen, even allowing for relatively long response times (e.g., Whipple and Meade, 2006) and not increase, as is observed. (4) A slowdown or cessation of slab retreat occurred with related enhanced uplift and erosion triggered by a deeper seated process such as lithospheric delamination, complete slab detachment (Reutter et al., 1980; Boccaletti and Sani, 1998; Carminati et al., 1999; Argnani, 2002), or earlier late Miocene slab tear migrating from west to east (van der Meulen et al., 1999; Wortel and Spakman, 2000). Such a process explains well the ca. 3 Ma increase in exhumation rates recorded in the Mount Cimone AER, as well as cessation of extensional detachment faulting in the Alpi Apuane (Fellin et al., 2007). However, slab detachment or delamination has been inferred to have contributed to late Pliocene and Pleistocene uplift throughout both the northern and central Apennines (e.g., Carminati et al., 1999) implying that this deeper seated process, if real, may have been decoupled from higher level wedge dynamics (Bartolini, 2003). Alternatively, lithosphere delamination may be occurring across the whole orogen, with

true slab detachment or “breakoff” having occurred only west of the erosional transition seen at $11^{\circ}30'E$ resulting in the slowdown and cessation of slab retreat in this western segment of the northern Apennines. To the east, on the other hand, ongoing slab retreat and hence frontal accretion may be achieved through delamination by separation of the crust and mantle such that the denser mantle continues to subduct, as has been suggested for both the Apennines (Reutter et al., 1980), as well as the Aegean (Deboer, 1989; Wijbrans et al., 1993; Thomson et al., 1998a). The idea of slab tear (van der Meulen et al., 1999; Wortel and Spakman, 2000), although similar, predicts an ongoing orogen-parallel migration of the zone of slab breakoff, and does not explain the apparent late Miocene to Recent stability of wedge kinematics east and west of the Sillaro line indicated by the thermochronologic data.

Orogen-Parallel Differences in Post-Miocene Northern Apennine Orogenesis

The subdivision of the Apennines by a number of orogen transverse lineaments into several segments exhibiting independent tectonic behavior has long been recognized; the Sillaro (or Livorno-Sillaro) line—geographically coincident with the transition in AFT and AHe ages at $11^{\circ}30'E$ —being of particular prominence (e.g., Signorini, 1935; Boccaletti et al., 1990; Bartole, 1995). Many earlier studies interpret these lineaments as near-surface transverse shear zones or strike-slip faults. However, more recent studies (e.g., van der Meulen et al., 1999; Cerrina Feroni et al., 2001; Zattin et al., 2002) have demonstrated that the Sillaro line in particular actually represents an orogen-parallel change in erosion level, with the preferential late Miocene to Pleistocene removal of material from the frontal flank of the Romagna Apennines to its east. This fits with the idea of the frontal part of this segment acting as a critical taper orogen dominated by frontal accretion during this time. Where an orogen is close to flux and topographic steady-state, then ongoing accretionary and erosional flux will force the wedge to deform internally to maintain its critical taper. This will lead to enhanced tectonically forced uplift to balance removal of material by erosion and hence the removal of significant material from the frontal flank. Boccaletti et al. (1990) have further speculated that the Sillaro line has represented a deep crustal element since at least late Oligocene times, with the segment north and west of the line related to opening of the Ligurian-Tyrrhenian basin, whereas south and east of the Sillaro line migration was con-

trolled by rotation of the Corsica-Sardinia block and opening of the Ligurian-Balearic basin and later the opening of the Tyrrhenian sea. Along-strike variation in the foredeep basin system and Bouguer gravity field has led Royden et al. (1987) to alternatively propose Pliocene and later subduction of segmented lithosphere at depth, such that different slab segments are separated from one another at depth by a transverse “tear,” but are assumed to be continuous at shallower depths in the foreland. New observations of upper mantle anisotropy from the northern Apennines including both quasi-Love (QL) surface waves (Levin et al., 2007) and SKS shear-wave splitting measurements (Plomerova et al., 2006; Salimbeni et al., 2007, 2008) provide further support for an orogen-parallel transition in the nature of slab subduction and subduction retreat. Both QL waves and SKS measurements show an abrupt change in mantle anisotropy at $\sim 44^{\circ}N$, close to the position of the Sillaro line. This has led Levin et al. (2007) to suggest that to the south and east the pattern of mantle flow is consistent with ongoing slab retreat, while to the north the subducted slab has begun to detach from the surface lithosphere. They also note that this coincides spatially with a change in the nature of crustal seismicity across the frontal flank of the orogen from dominantly thrust events to the south and east, a seismic gap near Bologna, and dominantly strike-slip earthquakes to the north and west (see also Chiarabba et al., 2005; Pondrelli et al., 2006).

SUMMARY AND CONCLUSIONS

Combined and complementary interpretation of an extensive regional data set comprising two independent low-temperature thermochronometers (apatite (U-Th)/He and fission track) has highlighted previously unrecognized post-Miocene orogen-parallel variation in upper crustal kinematics of the northern Apennine orogen, with a western segment being dominated by vertical material motion; the eastern segment being dominated by horizontal motion. The transition occurs over a relatively short distance parallel to the main trend of the orogen at $\sim 11^{\circ}30'E$ and is approximately coincident with a transverse feature that has previously been labeled as the Sillaro line. Lateral differences in wedge kinematics also better explain previous observations using AFT thermochronologic data alone that erosional exhumation becomes younger moving not only from the more internal to more external regions of the orogen (e.g., Abbate et al., 1999), but also from west to east parallel to the orogen.

The pattern and age-elevation relationships of dual thermochronometers in the eastern segment of the northern Apennines (south and east

of $\sim 11^{\circ}30'E$) is diagnostic of ongoing frontal accretion and hence slab retreat since latest Miocene times. The data are best replicated by a model of a northeastward-migrating “orogenic wave” with respect to the European and Adriatic plates with associated migrating locus of enhanced erosional exhumation. Enhanced spatially uniform exhumation occurs on the transient migrating frontal flank of the orogen, and lasts for ~ 3 – 5 Ma at rates of ~ 0.8 – 1 mm/yr, followed by a slowdown to spatially averaged rates of ~ 0.3 – 0.5 mm/yr once material passes into the extending internal (retro) flank of the orogen. The best-fit frontal accretion and retro-flank excretion rates are ~ 15 – 20 km/Ma, and ~ 7 – 10 km/Ma for the rate of horizontal material motion through the core of the orogen.

In the western segment of the northern Apennines, the post-late Miocene AFT and AHe age pattern and age-elevation relationships are diagnostic of dominantly vertical material motion, and little or no frontal accretion and local post-Pliocene tilting likely related to late normal faulting. Ongoing exhumation is recorded in the more internal parts of this segment since at least ca. 8 Ma at rates of 0.4 mm/yr, increasing to ~ 1 mm/yr in the Pliocene (ca. 3 Ma). Over the same time the frontal flank saw less than ~ 2 km of erosion. Enhanced post-late Miocene erosion and uplift restricted to the core of the western segment of the northern Apennines can be attributed to either (1) a continuation of overall convergence, but a switch in the transfer of material into the wedge to a regime dominated by underplating or shortening in the form of out-of-sequence thrusts; or (2) a slowdown or cessation of slab retreat and hence frontal accretion with related enhanced uplift and erosion triggered by a deeper seated process such as lithospheric delamination, complete slab detachment, or earlier late Miocene slab tear.

These findings emphasize that no single model of wedge kinematics is likely appropriate for the northern Apennines over the long term, but rather that either (1) slab retreat accompanied by frontal accretion or (2) vertical material motion including underplating and/or internal wedge deformation following a slowdown or cessation in slab retreat have each played a dominant role in transferring material into the orogenic wedge and explaining synconvergent extension at different times and different lateral segments of the orogen.

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APPENDIX

Apatite (U-Th)/He Dating

Dated crystals were handpicked and inspected under a high-powered binocular microscope with cross-polarization to eliminate grains with inclusions. Suitable grains were then measured in two orientations for later alpha-ejection correction, and loaded either as single or multiple grains into 1 mm Pt tubes. Degassing of He was achieved by heating with a Nd-YAG laser in a high-vacuum laser cell connected to the He extraction and measurement line. Concentration of ⁴He was determined by spiking with a known volume of ³He and analyzing the isotope ratio in a quadrupole mass spectrometer according to the procedure outlined in Reiners et al. (2003). For U and Th analysis, degassed apatite grains were dissolved in situ from Pt tubes in HNO₃ and spiked with a calibrated ²²⁹Th and ²³³U solution. U and Th concentrations were determined by inductively coupled plasma mass spectrometry. Alpha ejection was corrected using the formula of Farley (2002). Based on the long-term reproducibility of Durango apatite standard analyses at Yale University, an analytical uncertainty of 6% (2σ) was applied to the apatite (U-Th)/He age determinations. Radiogenic He accumulated in apatite is lost by diffusion at even lower temperatures than the annealing of fission tracks in the same mineral. Extrapolation of laboratory He diffusion experiments in apatite to geologic time (Farley, 2000), supported by evidence from borehole data (House et al., 1999), shows that He begins to be measurably lost above ~45 °C, and entirely lost above ~85 °C for a typical grain with radius of 60 ± 20 μm (Wolf et al., 1998). This range of temperatures—labeled the helium partial retention zone—is analogous to the apatite fission-track partial annealing zone (e.g., Wagner and Van den haute, 1992; Gallagher et al., 1998; Reiners and Brandon, 2006). The closure temperature for He in apatite of typical grain radius (60 ± 20 μm) is ~70 °C at a cooling rate of ~10 °C/Ma (Farley, 2000).

Apatite Fission-Track Analysis

The methodology follows that outlined in Thomson and Ring (2006). CN5 glass was used to monitor neutron fluence during irradiation at the Oregon State University TRIGA reactor, Corvallis, Oregon (United States). A CN5 apatite zeta calibration factor (Hurfurd and Green, 1983) of 342.5 ± 3.8 was used in age calculation. For apatite of typical Durango composition (0.4 wt% Cl), experimental and borehole data (Green et al., 1989; Ketcham et al., 1999) show that over geologic time tracks begin to anneal at a sufficient rate to be measurable above ~60 °C, with complete annealing and total resetting of the apatite fission-track age occurring at between 100 °C and 120 °C. This range of temperatures is labeled the apatite fission-track partial annealing zone. For samples that have undergone moderate to fast cooling, a closure temperature of 110 ± 10 °C can be reasonably assumed for the most common apatite compositions (e.g., Reiners and Brandon, 2006).

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