Steady-state exhumation of the European Alps

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ABSTRACT

Fission-track grain-age distributions for detrital zircon are used in this study to resolve the late Cenozoic exhumation history of the European Alps. Grain-age distributions were determined for six sandstone samples and one modern river sediment sample, providing a record from 15 Ma to present. All samples can be traced to sources in the Western and Central Alps. The grain-age distributions are dominated by two components, P1 (8–25 Ma) and P2 (16–35 Ma), both of which show steady lag times (cooling age minus depositional age), with an average of 7.9 m.y. for P1 and 16.7 m.y. for P2. These results indicate steady-state exhumation in the source region at rates of ~0.4–0.7 km/m.y. since at least 15 Ma.

Keywords: Alps, steady-state, exhumation, erosion, fission-track.

INTRODUCTION

Previous studies of exhumation in the Alps have focused on reconstructing time-temperature-depth histories for currently exposed bedrock (see synthesis by Hunziker et al. 1992). We explore another approach here, using synorogenic sediments to reconstruct the evolution of surface cooling ages with time. Fission-track dating of detrital zircon is well suited for this approach because individual grains can be dated. Furthermore zircon is widely distributed in typical crustal rocks and is robust during weathering and transport (see review by Garver et al., 1999). We present fission-track grain-age distributions for 7 samples of detrital zircons derived from the Alps since 15 Ma. Approximately 80–100 grains were dated per sample, providing a detailed sampling of the distribution of bedrock cooling ages at the time that the sampled sediment was eroded from its source. These data are used to examine the late Cenozoic evolution of exhumation rates in the Alps.

LAG TIME

In orogenic settings, closure of low-temperature chronometers is commonly related to exhumation-related cooling caused by erosion or normal faulting. The lag time of a dated detrital mineral, defined as the amount of time between closure and deposition, provides a measure of the rate of exhumation. The lag time concept is illustrated in Figure 1B. At a closure depth Z_C, zircons pass through the closure temperature T_C and fission tracks are retained. Regional exhumation causes the zircons to move toward the surface where they are eroded at time t_e. Brandon et al. (1998) and Garver et al. (1999) summarized how Z_C for the zircon fission-track system varies as a function of erosion rate. Their calculations are based on a one-dimensional steady-state solution that accounts for the advection of heat and the influence of cooling rate on T_C. Relevant parameters for the European Alps, such as the initial thermal gradient, surface temperature, and crustal thermal diffusivity, are similar to those used in the Himalayan example in Garver et al. (1999). The model calculation predicts $T_C \approx 240–250$ °C for an exhumation rate of 0.5–1 km/m.y., which agrees with Hur-

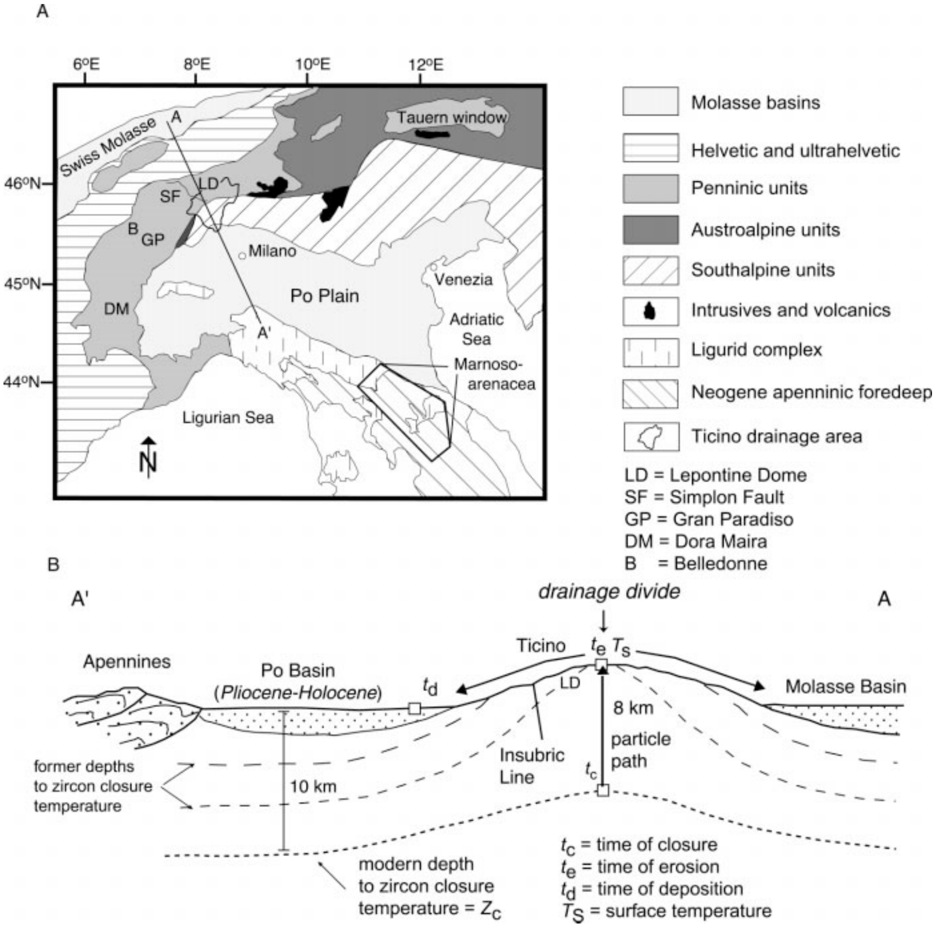

Figure 1. A: Simplified tectonic map of Alps and northern Apennine showing the study area. B: Lag time concept is illustrated using schematic profile (A–A′) through central Alps and adjacent sedimentary basins. Stippled line shows the zircon fission-track closure depth Z_C, where zircons cool through the effective fission-track closure temperature T_C at time t_c. Zircons reach the surface at time t_e and are transported and finally deposited in basin at time t_d.

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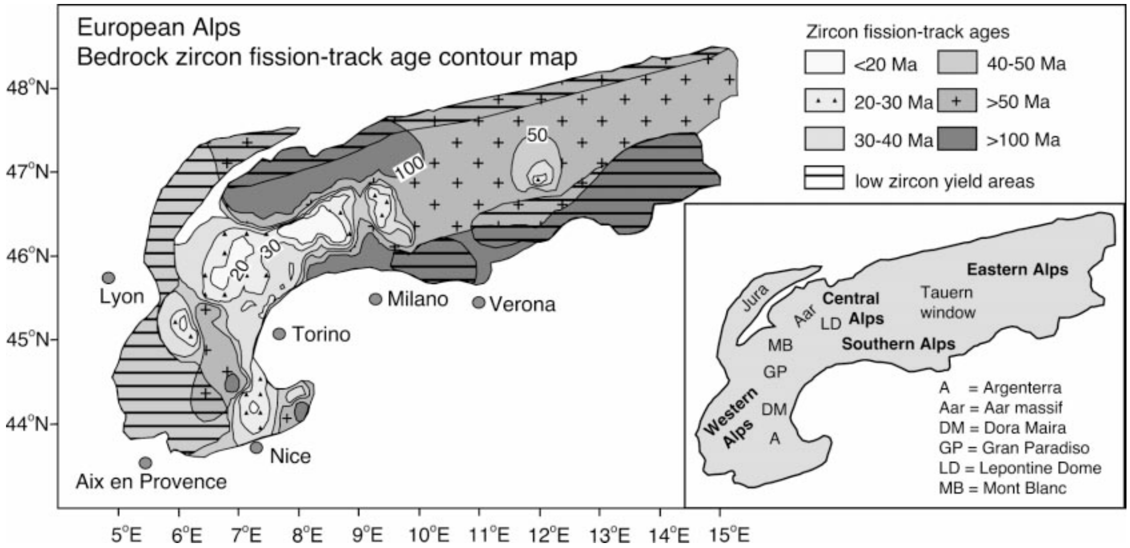

Figure 2. Contour map of zircon fission-track bedrock ages for the European Alps (see text for details). Only broad features are shown in the eastern Alps, southwest part of western Alps, and Jura Mountains because of sparse data coverage.

ford's (1986) field-based estimate for the central Alps. A typical value for Z_C for the central Alps is 5 km. We assume that most of the lag time is spent exhuming the rocks from Z_C. Sedimentary transport at the surface is negligible in comparison (e.g., Brandon and Vance, 1992).

Convergent orogenesis can be divided into idealized phases of construction, steady state, and decay (Jamieson and Beaumont, 1989). The constructional phase involves the growth of topography and an increase in erosion rates, which would be represented in the stratigraphic record by an upsection decrease in lag time. In some cases, the erosional outflux may become large enough to balance the accretionary flux into the orogen. This steady-state phase would be recorded by a stratigraphic interval where lag time remained approximately constant. When convergence stops, the orogen moves into a decay phase, marked by a reduction in topography and a decrease in erosion rates. The decay phase would be recorded by an upsection increase in lag time.

Tectonic exhumation by normal faulting can also influence lag times. If tectonic exhumation is persistent over millions of years, we might expect to see upsection changes in lag time similar to those outlined above for erosional exhumation. An important distinction is that tectonic exhumation does not produce sediment. Thus, a change in the rate of tectonic exhumation will cause a change in lag time, but no direct changes in the flux of eroded sediment.

Alternatively, if tectonic exhumation were rapid and short lived, as is commonly proposed for cases of orogenic collapse, then the grain-age distributions would show an abrupt upsection decrease in lag time. Rapid normal faulting would allow the exhumed footwall to quench to a nearly constant cooling age, extending down to the closure depth. This source region would deliver a relatively constant source of grain ages (static peak of Brandon and Vance, 1992) until erosion had stripped away a thickness equal to the closure depth. The grain-age component from this source would show a steadily increasing lag time, with the increase equal to the amount of time since the exhumation event.

The upsection change in lag time recorded in sediments derived from an active volcanic source might appear similar to that produced by rapid normal faulting. Regional geologic relationships and sedimentary petrography are usually successful in distinguishing between volcanism and rapid exhumation.

TECTONIC SETTING

The Central and Western Alps formed by Cretaceous to present convergence between a subducting European plate and an overriding Adriatic plate (e.g., Frisch, 1979; Platt, 1986). Continental collision started in the Eocene, and led to development of a subaerial orogenic wedge. Surface exposures of the Alpine metamorphic core record peak conditions ca. 35–30 Ma in the Central Alps (Steck and Hunziker, 1994). There was almost no magmatism associated with Alpine convergence. The only significant event was the emplacement of the Periadratic intrusions ca. 33–28 Ma. Siliciclastic sediments of that age show significant volcanogenic detritus (e.g., lower Oligocene Taveyannaz sandstone). Other than this example, sediments derived from the Alps show little to no volcanic influence.

The present pattern of exhumation in the Alps is illustrated in Figure 2, which shows a contour map of bedrock cooling ages compiled from approximately 205 zircon fission-track ages[1]. The youngest ages are associated with the Central Alps. Large volumes of synorogenic sediment provide clear evidence that erosion was an important exhumation process in the Alps (England, 1981). More recent work has demonstrated the importance of tectonic exhumation in the Alps (e.g., Simplon fault: Mancktelow, 1992; Turba mylonite: Nievergelt et al., 1996; Tauern window: Selverstone, 1985; Ratschbacher et al., 1991).

FISSION-TRACK SAMPLES AND RESULTS

Our samples come from 6 localities in the Miocene Marnoso-Arenacea Formation of the Northern Apennines, Italy, and from modern sediments from the lower reach of the Ticino River, which drains the source area for the Marnoso-Arenacea Formation (Fig. 1A). All sediments have an arkosic composition. Zircons are generally subhedral to rounded. Depositional ages are based on biostratigraphy, and are generally known to ±1 m.y.

As summarized by Ricci Lucchi (1986), the lower part of the Marnoso-Arenacea Formation(<5 Ma) records a flysch stage of deposition in a deep marine foredeep that bordered the east side of an active but otherwise submerged Apennine convergent wedge. Heavy mineral assemblages and paleocurrent directions indicate sedimentary sources in the Central and Western Alps (Gandolfi et al., 1983;

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[1] GSA Data Repository item 20019, Zircon fission-track ages of the European Alps, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

TABLE 1. DETRITAL ZIRCON FISSION-TRACK DATA

Sample	Approximate depositional age (Ma)	N	P1	P2	P3	P4
Ticino River	0	95	8.6 ± 1.4	15.6 ± 1.5	25.6 ± 4.8	140.1 ± 20.1
			15.3%	56.5%	19.8%	8.4%
			8.6	15.6	25.6	140.1
1	7.5	102	15.2 ± 1.5	24.7 ± 2.2	—	106.7 ± 13.7
			39.8%	51.1%		9.1%
			7.7	17.2		99.2
2	12.0	102	20.4 ± 1.7	34.2 ± 3.6	69.5 ± 8.1	131.2 ± 20.6
			49.2%	25.4%	16.8%	8.6%
			8.4	22.2	57.5	119.2
3	12.5	105	18.9 ± 2.4	28.8 ± 3.2	51.7 ± 6.0	115.6 ± 14.8
			29.3%	44.3%	14.0%	12.4%
			6.4	16.3	38.8	103.1
4	13.8	78	19.5 ± 2.5	27.7 ± 4.2	51.7 ± 12.4	94.9 ± 14.6
			28.2%	39.8%	8.7%	15.9%
			5.7	13.9	37.9	81.1
5	13.9	101	20.7 ± 3.6	29.9 ± 4.9	49.9 ± 8.8	114.1 ± 20.6
			33.4%	50.0%	9.8%	6.7%
			6.8	16.0	36.0	100.2
6	15.0	85	23.5 ± 2.1	—	43.9 ± 4.5	110.6 ± 9.6
			35.1%		24.3%	40.6%
			8.5		28.9	95.6

Note: N is the total number of grains counted; binomial fitted peak ages (Galbraith and Green, 1990) are given in Ma with a 95% confidence interval. The relative size of the specific peak is in percent, and the lag time in m.y. The depositional age is known to ±1 Ma and lag time is calculated by cooling age minus depositional age. Sample treatment is described in Garver et al. (2000).

Valloni and Zuffa, 1984; Cibin et al., 2000). Sandstones with local Apennine sources are present, but they are restricted to rare isolated beds that are easily distinguished by their petrographic composition and a difference in paleocurrent directions (Gandolfi et al., 1983).

Grain-age distributions were decomposed into significant components or peaks using the binomial peak-fitting method (Table 1). Errors are cited at the 95% confidence level. The grain-age distributions are generally dominated by two young peaks, P1 and P2, which are the focus of our analysis here. Older peaks are present but they generally represent <15% of the distribution. P1 varies from 8.6 to 23.5 Ma and P2 from 15.6 to 34.2 Ma (Table 1) but both show nearly constant lag times (Fig. 3).

DISCUSSION

Test for Steady State

Changes in peak age t_c with depositional age t_d can be approximated by a linear relationship, $t_c = A + B\, t_d$ where A and B are fit parameters. Conversion to lag time gives $(t_c - t_d) = A + (B - 1)\, t_d$, which shows that A is the present lag time and $(B - 1)$ is the change in lag time with depositional age. Thus, the upsection trends in lag time discussed above can be represented by B, with $B < 1$ associated with construction, $B > 1$ with decay, and $B = 1$ with steady state. The linear relationship fits the P1 data well ($R^2 = 0.96$); the residuals are the same size as the uncertainties of the peak ages (reduced $\chi^2 = 1.04$). The best-fit estimate of $B = 0.92 \pm 0.128$ (2 standard error) indicates a steady-state trend. The average lag time is 7.9 m.y. (determined at midpoint of the data distribution).

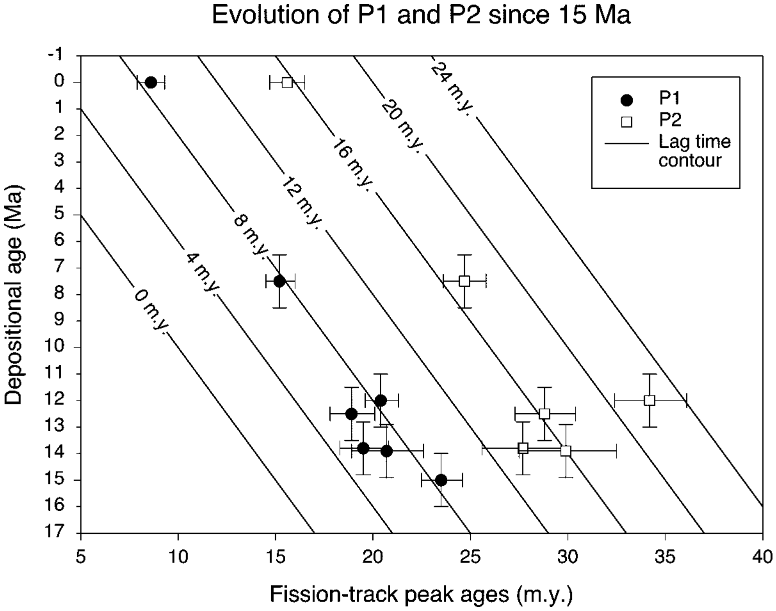

Figure 3. Plot showing the evolution with time of the P1 and P2 component ages. Contours show lines of constant lag time. Error bars show ±1 standard error for peak ages and ±1 m.y. uncertainty for depositional ages.

The linear relationship provides a reasonable fit for the P2 data ($R^2 = 0.86$). The residuals show no systematic variations. Their large size (reduced $\chi^2 = 2.87$) indicates other sources of variance in addition to those related to fission-track measurement of age. The best-fit estimate of $B = 1.13 \pm 0.185$ (2 standard error) is also consistent with a steady-state trend. The average lag time is 16.7 m.y.

Ideally, during steady-state exhumation, the relative sizes of peaks should remain constant. The ratio of peak sizes for P1 and P2 are similar for 4 out of 7 of our samples. We note, however, that lag times provide an estimate of exhumation rate averaged over the lag time (>5 m.y.), whereas the relative peak size is controlled by short-term erosion rates with an averaging constant much less than 1 m.y. We emphasize here the lag time estimates of exhumation rate because they are more relevant to the long-term evolution of the orogen.

Source Areas

The contour map (Fig. 2) provides a basis for resolving where the P1 and P2 zircons came from. A viable source area for a component must have a modern zircon fission-track age that is equal to the estimated lag time of the component.

Our P1 ages indicate that the source of these zircons must have a modern bedrock age ca. 8 Ma. This requirement restricts our search to two closely spaced areas in the Alps: (1) the Pennine front in the Aar Massif region (Seward and Mancktelow, 1994), and (2) the Lower Pennine nappes of the Lepontine Dome in the footwall of the Simplon fault (Hunziker et al., 1992; Seward and Mancktelow, 1994). The P1 component is present in our oldest samples, which indicates that by ca. 15 Ma young reset zircons were already eroding from this source.

The modern age of the P2 source is estimated to be ca. 15–20 Ma. In the Central Alps, candidates include the southern and eastern parts of the Lepontine Dome (Hurford, 1986; Hunziker et al., 1992) and the hanging wall of the Simplon fault and in the Western

Alps the Pennine front in the Mont Blanc–Belledonne Massif region (Seward and Mancktelow, 1994; Fügenschuh et al., 1999).

Comparison with Bedrock Studies

The lag time versus erosion rate relationship from Garver et al. (1999) predicts an approximate exhumation rate of ~0.7 km/m.y. for P1 and ~0.4 km/m.y. for P2. These rates are similar to those estimated by the modeling study of the Simplon normal fault by Grasemann and Mancktelow (1993). The youngest cooling ages in the Central Alps occur in the footwall of the Simplon normal fault. Part of the Ticino drainage is eroding the Simplon fault footwall. Grasemann and Mancktelow (1993) indicate a short interval of rapid normal faulting from 18 to 15 Ma with fast rates of tectonic exhumation of the footwall, ~4.6 km/m.y, followed by slower normal faulting from 15 Ma to at least 3 Ma. After 15 Ma, the total exhumation rates were estimated to be 0.6 km/m.y. in the footwall and 0.4 km/m.y. in the hanging wall, which matches the rates estimated for P1 and P2. Grasemann and Mancktelow (1993) attribute the difference in exhumation rates between the footwall and hanging wall to a regional erosion rate of 0.4 km/m.y. and a 0.2 km/m.y. rate of tectonic exhumation for the footwall.

CONCLUSIONS

Detrital zircon fission-track grain ages with depositional ages ranging from 15 to 0 Ma indicate steady lag times for the most rapidly eroding sources. This result indicates that the Alps were being exhumed at a steady rate, and that sediments delivered from Alpine sources came from areas where zircon fission-track ages were set by a combination of tectonic and erosional cooling. Exhumational steady state has been observed in some modern orogens, such as Taiwan (Dahlen and Suppe, 1988), the Southern Alps of New Zealand (Adams, 1980), and northern Cascadia in the northwestern United States (Brandon et al., 1998). Erosion dominates exhumation in those cases. The Alps appear to be another example where erosion and tectonic exhumation are operating together in an approximately steady-state fashion.

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