Abrupt glacial valley incision at 0.8 Ma dated from cave deposits in Switzerland

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ABSTRACT

Glacial erosion dramatically alters mountain landscapes, but the pace at which glaciers carve a previously fluvial landscape remains poorly defined because long-term valley incision rates are difficult to measure. Here we reconstruct the lowering history of the Aare Valley, Switzerland, over the past 4 m.y. by dating cave sediments with cosmogenic ^{26}Al and ^{10}Be. Incision accelerated from ~120 m/m.y. to ~1200 m/m.y. at 0.8–1.0 Ma, at least 1 m.y. after the onset of local glaciation. Rapid incision may have been triggered by lowering of the equilibrium line altitude at the mid-Pleistocene climate transition.

Keywords: glacial erosion rate, cave, Switzerland, speleogenesis, cosmogenic, burial age, glacial valley.

INTRODUCTION

The speed at which a landscape changes from a fluvial to a glacial morphology with deep U-shaped troughs remains poorly understood. On the basis of short-term sediment budgets (Hallet et al., 1996), long-term exhumation rates from thermochronology (Spotila et al., 2004; Farley et al., 2001; Shuster et al., 2005), and the morphometry of glaciated valleys (Montgomery, 2002; Brook et al., 2006), it has been suggested that glacial erosion can outpace fluvial erosion. However, whether the growth of glacial valleys occurs quickly or gradually is debated; until recently, there has been no long-term record of glacial valley incision.

Two lines of evidence suggest that glacial troughs may form quickly. Brocklehurst and Whipple (2004) found that although overdeepened glacial troughs are common, there are few transitional landscapes. They proposed that incision of large glacial troughs occurs rapidly and may be governed by a threshold behavior associated with lowering of the equilibrium line altitude (ELA). As tributary glaciers coalesce, nonlinear increase in ice velocity, improved subglacial drainage, and more frequent glacier sliding promote erosion well below the ELA, rapidly scouring a deep glacial trough. Recent application of $^4He/^3He$ thermochronometry has revealed that the glaciated Klinaklini Valley in the Coast Mountains, British Columbia, rapidly incised by as much as 2 km at 1.8 ± 0.2 Ma (Shuster et al., 2005). Marine records indicate that widespread glaciation in the region began 0.8 m.y. earlier, at 2.6 Ma (Rea and Snoeckx, 1995). Such an abrupt acceleration in erosion rates significantly postdating the onset of glaciation is consistent with a threshold behavior of glacial trough incision.

If the hypothesis of a threshold in the development of large glacial troughs is correct, then we would expect to observe abrupt acceleration of glacial valley incision elsewhere. Here we use a cosmogenic nuclide chronology of cave sediments to show that glacial valley incision rates in the northern Swiss Alps abruptly increased at 0.8 Ma, at least 1 m.y. after the onset of glaciation in the area.

SITE DESCRIPTION

We reconstruct the incision history of the Aare Valley, a major glacial trough in the northern Alpine front (Fig. 1), by dating the development and infilling of the Siebenhengste-Hohgant cave system. More than 290 km of cave passages are in the mountains between the glacially scoured Aare Valley and the Hohgant, 14 km to the north (Fig. 2), spanning a vertical range of 1340 m. The Siebenhengste-Hohgant cave system is a network of intersecting passages, some of which formed above the water table. Paleo–water tables can be identified by characteristic morphologic changes that occur near the vadose-phreatic transition (Haeuselmann et al., 2002; Palmer, 1991). The transition from vadose to phreatic morphology at multiple locations within the cave system can be correlated to reveal the paleo–water table (Ford and Williams, 1989). Extensive mapping and observation has led to the identification of 14 such speleogenetic levels in the Siebenhengste-Hohgant system (Fig. 2; Table 1). The uppermost five levels drained to springs in the Eriz Valley, to the north. The lower seven levels, including that of today, drained to the Aare Valley (Haeuselmann et al., 2002).

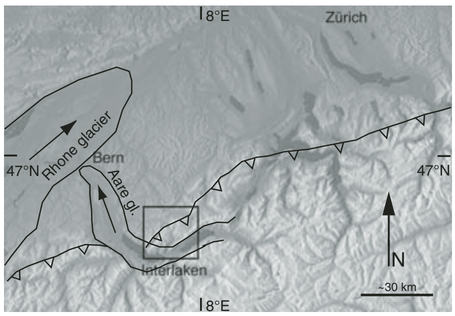

Figure 1. Digital elevation model of west-central Switzerland. Rectangle indicates study area. Last Glacial Maximum glacier extents are shown; arrows indicate glacier flow direction. Line with teeth is Alpine thrust front. Glacial troughs are visible. [Map modified from the Atlas of Switzerland (Institute of Cartography, 2004).]

Cave system development is linked to glaciation in two ways. First, the altitude of the valley floor determines the altitude of the vadose-phreatic transition, because cave-forming waters

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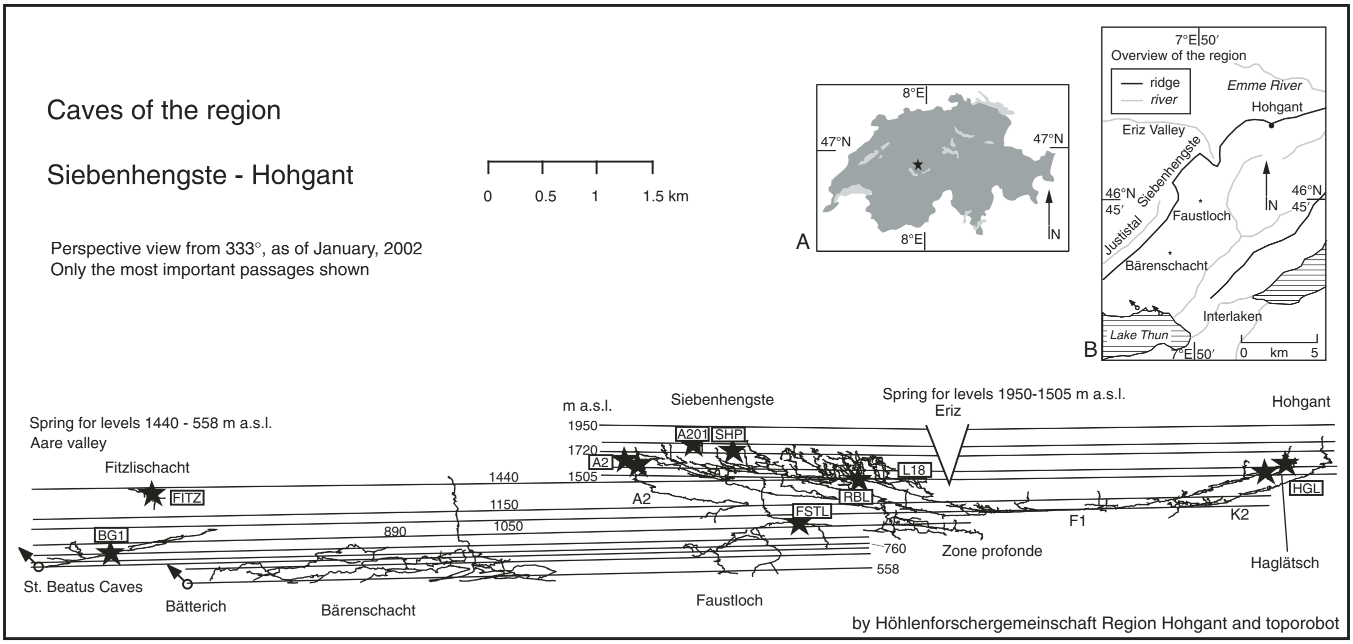

Figure 2. Projected view of Siebenhengste cave system. Subhorizontal lines show speleogenetic phases inferred from vadose-phreatic transitions (a.s.l.—above sea level). Inset A shows location of area within Switzerland; inset B is simplified geographic overview.

TABLE 1. SAMPLE LOCATIONS, BRIEF DESCRIPTIONS, AND COSMOGENIC NUCLIDE DATA

Sample	Speleogenetic level	Notes	[^{26}Al] (10^3 at/g)	[^{10}Be] (10^3 at/g)	^{26}Al/^{10}Be*	Burial age† (Ma)	Inherited erosion rate (m/Ma)‡
SHP 1	1800	SHP 1–5 in stratigraphic order	196 ± 20	57.7 ± 1.6	3.40 ± 0.36	1.53 ± 0.22	85 ± 11
SHP 2	1800	SHP 6–7 collected nearby	94 ± 15	40.1 ± 1.3	2.35 ± 0.38	2.32 ± 0.33	81 ± 16
SHP 4	1800	SHP 7 is inferred to be stratigraphically older than SHP 1-5; the stratigraphic order of SHP 6 is unknown.	860 ± 60	175.2 ± 4.1	4.91 ± 0.36	0.72 ± 0.15	42 ± 4
SHP 5	1800		166 ± 17	55.7 ± 2.1	2.99 ± 0.33	1.80 ± 0.22	76 ± 10
SHP 6	1800		227 ± 21	66.2 ± 1.8	3.43 ± 0.33	1.51 ± 0.20	74 ± 9
SHP 7	1800		35 ± 11	37.9 ± 1.5	0.91 ± 0.29	4.35 ± 0.60	30 ± 11
A201	1800	Granitic pebbles indicate that sediments post-date glaciation.	237 ± 23	81.9 ± 1.7	2.89 ± 0.29	1.87 ± 0.21	50 ± 6
A2TR	>1585	Passage incised after sediment deposition.	544 ± 42	113.3 ± 2.8	4.22 ± 0.34	0.77 ± 0.17	64 ± 6
A2NS	1585		674 ± 49	140.3 ± 3.4	4.81 ± 0.37	0.77 ± 0.16	51 ± 5
A2CHU	1585		899 ± 58	186.8 ± 4.6	4.81 ± 0.33	0.76 ± 0.14	39 ± 3
L18	1585		284 ± 25	67.4 ± 1.9	4.21 ± 0.40	1.06 ± 0.19	92 ± 11
HGLS	>1585	Laminated silts above sediments indicate possible glacial origin.	309 ± 26	71.6 ± 1.8	4.32 ± 0.38	1.01 ± 0.18	89 ± 10
HGLP	1585	Deposited prior to HGLT	50 ± 10	15.1 ± 0.8	3.34 ± 0.71	1.57 ± 0.42	317 ± 81
HGLT	1585	Stratigraphically youngest sediment from Haglaetsch	66 ± 12	14.4 ± 0.6	4.56 ± 0.82	0.89 ± 0.36	472 ± 102
RBL1	1505	Fast-flow phreatic deposition in undulating passage	1726 ± 102	334 ± 11	5.17 ± 0.35	0.60 ± 0.14	23 ± 2
RBL2	1505	Fast-flow phreatic deposition in undulating passage	574 ± 44	117.9 ± 3.1	4.87 ± 0.40	0.74 ± 0.17	62 ± 6
FITZ	1440	Flowstone indicates air-filled passage prior to deposition.	1012 ± 69	152.8 ± 3.8	6.62 ± 0.48	0.08 ± 0.15	68 ± 6
FSTL	1050	Flowstone indicates air-filled passage prior to deposition.	387 ± 28	68.9 ± 1.8	5.61 ± 0.43	0.44 ± 0.16	124 ± 12
BG1	805	U-Th age of 160–235 ka	1120 ± 73	174.3 ± 4.3	6.43 ± 0.45	0.14 ± 0.15	57 ± 5
MWA		Confirms zero age at surface	491 ± 44	73.6 ± 2.0	6.67 ± 0.62	0.07 ± 0.19	141 ± 16

*Normalized for a ^{10}Be half-life of 1.34 Ma. To convert to a half-life of 1.51 Ma, multiply by 1.14.
†Uncertainties represent analytical error only. Burial ages calculated using a ^{10}Be half-life of 1.34 Ma.
‡Erosion rates approximate. Calculated using a local ^{10}Be production rate of 18 at/g/yr.

discharge at karst springs located in the main valley. Thus glacial incision promotes cave development at lower elevations (although it is generally not possible to associate each cave level to a particular glaciation). Second, the cave is formed preferentially during interglacials, when waters are more aggressive due to CO_2 production in soils, and therefore remain undersaturated with calcite in the main flow paths. During glacials, the groundwater carries finely ground calcite and is unable to dissolve new cave passages (Bini et al., 1998), and flow velocity is often low, impeding mechanical erosion. Glacial versus interglacial sediments can often be distinguished in the cave by the presence or absence of calcite glacial flour.

We dated 21 samples of quartz sediment (sand or sandstone and/or granitic pebbles) collected from 7 levels within the cave system (Table 1), using cosmogenic ^{26}Al and ^{10}Be burial dating. Each sample's location relative to the paleo–water table was inferred from passage geometry and sediment stratigraphy (Table 1). The burial dating method relies upon the differential radioactive decay of cosmogenic ^{26}Al and ^{10}Be, which accumulate in quartz grains near the ground surface at a constant ratio prior to emplacement in the cave. Measured [^{26}Al] and [^{10}Be] can thus be used to determine both the burial time and the inherited concentrations prior to burial,

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which depend primarily on the erosion rate in the sediment source area (Granger and Muzikar, 2001). To maximize the concentrations of ^{26}Al and ^{10}Be in the sediments, we chose sediments likely to have been deposited during interglacial episodes, as inferred from the lack of carbonate flour and oxidized sediments. The quartz sediment was derived from either a sandstone caprock or from remobilization of till containing granitic clasts.

RESULTS

Results are shown in Table 1 and Figure 3. Burial ages range to 4 Ma, spanning the entire history of Pleistocene glaciation in the Alps. It is apparent from the burial ages that young sediment may be emplaced in old caves; thus the burial ages are minima for cave formation. For example, sample SHP6 is in the same cave as SHP7, yet it is nearly 3 m.y. younger. We believe that the burial age of SHP7 is reliable and that it is closer to the true age of the cave, because this sediment is stratigraphically oldest and contains redox weathering fronts that are absent in the younger sediments. Remobilization of old sand and deposition in a younger passage is also possible, although it is only confirmed in one case: SHP4 is stratigraphically older than SHP5, but the ages are inverted. Sediment from the surface (MWA) has a burial age indistinguishable from zero, and sediment from St. Beatus Cave (BG1) has a young age that agrees with previous U-Th data from intercalated flowstone (Haeuselmann, 2002).

Paleo-erosion rates determined for these samples range from 30 to 470 m/m.y.; all but two of the samples have paleo-erosion rates <150 m/m.y., consistent with deposition during interglacials, rather than glacial times, for which cosmogenic nuclide concentrations are generally much lower (Riihimaki et al. 2005; Hebdon et al., 1997). These paleo-erosion rates should be considered approximate, because the elevation of the sediment source area is difficult to define, leading to uncertainty in cosmogenic nuclide production rates.

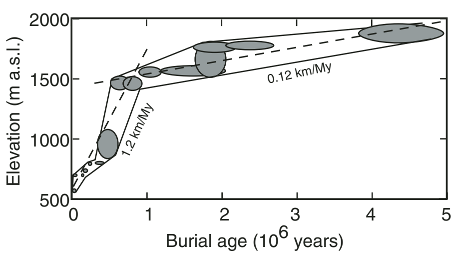

Figure 3. Valley incision history determined from envelope of oldest burial ages for each speleogenetic level (a.s.l.—above sea level). Shaded ellipses indicate analytical uncertainty in burial ages and conservative uncertainty of one speleogenetic level in elevation. U/Th ages (Haeuselmann, 2002) are between 0 and 0.35 Ma. Incision rates are ~0.12 km/m.y. prior to 0.8 Ma, and 1.2 km/m.y. thereafter.

DISCUSSION AND CONCLUSION

To reconstruct valley lowering rates, we restrict ourselves to the envelope of the oldest burial ages obtained for each cave level. We combine the cosmogenic nuclide ages reported here with cave level ages obtained by U-Th data (Haeuselmann, 2002). The inferred valley lowering history is shown in Figure 3. The data show that an abrupt increase in valley lowering rates occurred at 0.8–1.0 Ma. Prior to this transition the valley lowering rate was ~120 m/m.y., in approximate equilibrium with the paleo-erosion rates (Table 1). Subsequently, the water table lowered by nearly 1 km to its present position, at a rate of ~1.2 km/m.y. This tenfold increase in valley incision rates corresponds to changes in cave morphology and to the piracy of drainage from the Eriz to the Aare Valley. We interpret this transition to be due to rapid glacial deepening of the Aare Valley and lowering of the regional karst water table. The incision rates reported here seem to be typical for valley-forming glaciers, which can erode at rates of several millimeters per million years (Hallet et al., 1996; Riihimaki et al., 2005; Hebdon et al., 1997).

Accelerated valley lowering at 0.8–1.0 Ma significantly postdates the onset of glaciation inferred from older moraines downvalley (Schluechter, 2004). Moreover, sample A201, with an age of 1.91 ± 0.17 Ma, contains granitic clasts from the Aar massif that were likely transported to the site by glaciers, as inferred from the presence of glacial till close to the same altitude nearby (Jeannin, 1991). The inferred history of valley incision therefore supports the hypothesis that glacial erosion follows a threshold behavior, in which rapid valley incision occurs much later than the onset of glaciation. Our data and the incision history of the Klinaklini Valley (Shuster et al., 2005) provide, to our knowledge, the only long-term records of glacial trough incision that span the onset of Pliocene–Pleistocene glaciation. It is compelling that both of these records indicate that rapid valley incision commenced well after glaciation began.

Although our data cannot distinguish a trigger for rapid glacial incision, the timing corresponds to the global mid-Pleistocene event, when glacial cycles changed from 41 k.y. to 100 k.y. periodicity (Ruddiman et al., 1986). Numerous changes in climate at this time might have influenced glaciation in the Alps, including changes in ocean circulation (Raymo et al., 1997), the degree of open water in the Norwegian-Greenland Sea (Henrich et al., 2002), and increased amplitude of climate variability (Zhang et al., 2001). Other glaciers in and around the Alps apparently increased their erosion rate at the same time, indicated by an increase in sediment supply to the Po Basin to the south (Muttoni et al., 2003), changes in sediment deposition in the Bohemian massif (Tyracek, 1997), and a transition from piedmont style to incisive glaciation elsewhere in the northern Swiss Alps (Schluechter, 2004). We suggest, following Brocklehurst and Whipple (2004), that a significant lowering of the ELA in the Alps occurred in the mid-Pleistocene, and that the Aare Valley passed a threshold condition under which downvalley convergence of glacier ice caused a nonlinear increase in glacial erosion rates.

The data reported here and our interpretation have implications for the Pliocene–Pleistocene tectonic history of the Alps. It has been suggested that uplift of the Alps was driven by rapid erosion beginning during the early Pliocene. Cederbom et al. (2004) used fission track data in Molasse basin sediment to suggest that as much as 6 km of material was removed over the Pliocene–Pleistocene. Our data are difficult to reconcile with such extensive erosion of the Molasse basin, because early Pliocene sediments are found in caves only 1.3 km above modern base level. Willett et al. (2006) argued that increased erosion of the Alps during and after the Messinnian salinity crisis led to a transition from orogenic wedge growth to destruction, with deformation and uplift shifting toward the core of the mountain range. Our data cannot provide any constraints on erosion and uplift of the central Alps. Although neotectonic motion can be observed in the cave system (Haeuselmann et al., 1999), there are no discernible signs for regional uplift.

Kuhlemann (2000) documented a large increase in sediment flux from the Alps beginning in the early Pliocene, at rates to 400 m/m.y., although such regional sediment budgets are highly uncertain. Our data point instead to a long period of steady erosion in the northern Alps during the Pliocene and early Pleistocene. Any increase in sediment flux must have come from elsewhere in the Alps. We find that prior to rapid glacial incision, local erosion rates and valley incision rates remained remarkably similar at ~120 m/m.y. (Table 1). These erosion rates are consistent with long-term exhumation rates of 300 ± 100 m/m.y. over the past 30 m.y., determined from fission tracks and the timing of peak metamorphism in the nearby Penninic crystalline nappes (Schlunegger and Willett, 1999). They are also roughly consistent with sediment budgets for the Alps calculated from basin fills, which indicate rates of 200 m/m.y. for the Pliocene–Pleistocene, and 350–400 m/m.y. for the Pleistocene (Guillaume and Guillaume, 1982). Thus the erosion rate of the northern Alps does not seem to have changed substantially over several million years prior to glaciation. This is consistent with the northern

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Alps being in an erosional or flux steady state (Bernet et al., 2001) that was only disrupted by rapid incision of glacial valley troughs beginning in the mid-Pleistocene.

ACKNOWLEDGMENTS

The study was supported by the Swiss National Science Foundation and the Forschungskommission University of Freiburg (81FR-68830), and the U.S. National Science Foundation (grant EAR-0092459). We acknowledge the help of the mapping cavers (mainly Alex Hof) as well as Bob Finkel for measurements. Constructive reviews of D. Shuster, M. Bernet, and C. Cederbom improved the paper.

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Manuscript received 14 June 2006
Revised manuscript received 12 September 2006
Manuscript accepted 25 September 2006

Printed in USA

ERRATUM

High-precision U-Pb zircon age from the Triassic of Italy: Implications for the Triassic time scale and the Carnian origin of calcareous nannoplankton and dinosaurs

Stefano Furin, Nereo Preto, Manuel Rigo, Guido Roghi, Piero Gianolla, James L. Crowley, Samuel A. Bowring

Geology: Vol. 34, No. 12, pp. 1009–1012 (December 2006)

On page 1010, center column, middle of paragraph: "The ash bed is thus within the P. carpathica or the Eokochapsis nodosa zones of Channell et al. (2003)" should be "The ash bed is thus within the P. carpathica or the E. nodosa zones of Channell et al. (2003)."

On page 1011, the authors omitted the following sentence from the end of the Discussion section: "In addition, the eruption of the Ontong-Java plateau (the largest preserved LIP on Earth) is thought to have triggered a major radiation of calcareous nannoplankton (Erba, 2006)."

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