Neotectonic extrusion of the Eastern Alps: Constraints from U/Th dating of tectonically damaged speleothems

Lukas Plan[1], Bernhard Grasemann[2], Christoph Spötl[3], Kurt Decker[2], Ronny Boch[3], and Jan Kramers[4]
[1]Department for Karst and Caves, Natural History Museum Vienna, Museumsplatz 1/10 A-1070 Vienna, Austria
[2]Department for Geodynamics and Sedimentology, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria
[3]Institute of Geology and Palaeontology, University of Innsbruck, Innrain 52, A-6020 Innsbruck, Austria
[4]Institute of Geological Sciences, University of Bern, Baltzerstrasse 1-3, CH-3012 Bern, Switzerland

ABSTRACT

We suggest that the Salzachtal-Ennstal-Mariazell-Puchberg (SEMP) fault, a major strike-slip system in the European Alps, is active. It has accommodated lateral extrusion of the central part of the Eastern Alps toward the Pannonian Basin. The main tectonic activity of this fault dates back to Oligocene and Miocene time, but until now it was largely unknown whether the fault was still active. We present here the first field evidence of neotectonic activity from a cave in the Hochschwab karst massif (Styria, Austria) that intersects a segment of the SEMP fault zone. Damaged speleothems in this cave include scratched flowstone (a hitherto undescribed feature), massive flowstone disrupted by a fault, and ruptured flowstone. The superposition of younger flowstone layers allows constraining the time frame of the tectonic events using U/Th dating. The youngest flowstone of the pre-damage generation is ca. 118 ka (end of the Last Interglacial) and the oldest post-event layer is ca. 9 ka (early Holocene). The tectonic event bracketed by these layers coincided with a growth hiatus during the last glacial period, consistent with the high alpine setting of the cave. Geologic evidence precludes deformation mechanisms other than tectonic. These new data are consistent with vectors of continuous global positioning system measurements as well as instrumental seismicity data, and collectively suggest that the SEMP is an active fault and that lateral extrusion of the Eastern Alps is ongoing.

INTRODUCTION

Caves and their sediments provide a unique archive of the past, being well shielded from the erosion that dominates the Earth's surface. Much work recently focused on paleoclimatic information encoded in speleothems (e.g., Schwarcz, 2006; Fairchild et al., 2006). These deposits also record paleoseismic events (e.g., Forti and Postpischl, 1984; Becker et al., 2006) and even provide constraints on their magnitude (e.g., Szeidovitz et al., 2008). Observed features include broken and tilted stalagmites, displacement of stalactite-stalagmite pairs, fallen stalactites, collapsed cave ceilings, and displaced gallery sections. Such features are sometimes referred to as seismothems (e.g., Delaby, 2001) or speleothem seismites (e.g., Kagan et al., 2005), if other causes of damage such as ice flow, human activity, or gravitational movements are ruled out (Gilli, 2004, 2005). Discriminating between seismic slip caused by an earthquake or aseismic creep along a fault can be problematic even in caves where deformation was clearly related to tectonic activity. Nevertheless, damaged speleothems provide an opportunity to constrain the chronology of tectonic (seismic) events as old as ca. 500 ka.

Here we report the first evidence of tectonically broken speleothems in the Eastern Alps (Austria) that have been studied in a cave within the sinistral Salzachtal-Ennstal-Mariazell-Puchberg (SEMP) fault zone. Together with the dextral Periadriatic fault zone in the south (Fig. 1), the SEMP facilitated lateral extrusion of the central Eastern Alps toward the Pannonian Basin to the east coeval with north-south shortening between the Adriatic and European plates (Ratschbacher et al., 1991).

SEMP FAULT ZONE

The east-northeast–striking SEMP extends from the Tauern Window in the west, along the southern part of the Northern Calcareous Alps, to the Vienna Basin (Ratschbacher et al., 1991). The fault has a length of ~400 km and a cumulative sinistral offset of at least 60 km (Linzer et al., 2002). The SEMP has attracted much interest because of the differential denudation along its strike with dominantly brittle structures in the eastern segments, whereas the Tauern segment exposes a mid-crustal shear zone dominated by ductile shear (Peresson and Decker, 1997a, 1997b; Linzer et al., 2002; Rosenberg and Schneider, 2008; Frost et al., 2009). Glodny et al. (2008) suggested that sinistral shearing at the SEMP was initiated 30–32 Ma and that transpressive deformation persisted, either continuously or intermittently, at least until the Middle Miocene (ca. 15 Ma). In the eastern part of the SEMP, ca. 17 Ma conglomerates record brittle deformation (Peresson and Decker, 1997a).

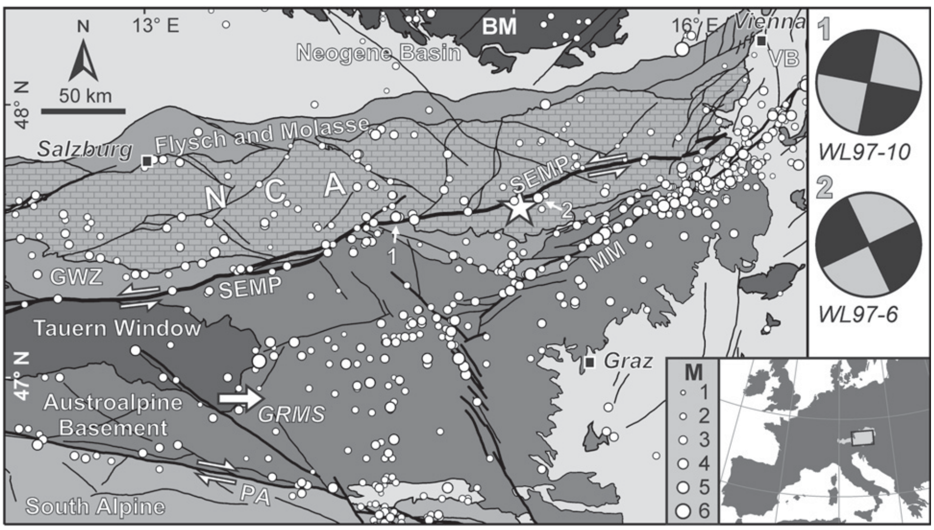

Figure 1. Geological map of Eastern Alps. SEMP—Salzachtal-Ennstal-Mariazell-Puchberg fault, PA—Periadriatic fault, MM—Mur-Mürz fault, BM—Bohemian Massif, GWZ—Graywacke Zone, NCA—Northern Calcareous Alps, VB—Vienna Basin. Open circles indicate epicenters of earthquake events since 1900 (Reinecker and Lenhart, 1999). Diameter of symbols is proportional to magnitude. Single arrow indicates 1.0 ± 0.6 mm/a east-directed movement of global positioning system station GRMS relative to Bohemian Massif (Grenerczy et al., 2005). Paired half-arrows give shear sense of SEMP and PA. Hirschgruben cave is indicated by white star. Two focal mechanism solutions available from SEMP indicate sinistral strike-slip movement at E- to ENE–striking faults (Reinecker and Lenhart, 1999).

Geology, June 2010; v. 38; no. 6; p. 483–486; doi: 10.1130/G30854.1; 2 figures; 1 table; Data Repository item 2010142.

Global positioning system (GPS) observations and seismicity data indicate ongoing eastward extrusion of the central Eastern Alps toward the Pannonian Basin (Reinecker and Lenhart, 1999; Grenerczy et al., 2005). As yet no direct geological field evidence of neotectonic movements has been uncovered to confirm whether the SEMP is an active fault. In this work we present field evidence and U/Th dates from tectonically deformed speleothems in Hirschgruben cave that indicate neotectonic deformation as recent as the late Pleistocene.

DEFORMED CAVE FEATURES

The main strand of the SEMP cuts through the northern Hochschwab karst massif, which is part of the Northern Calcareous Alps. Although fault segments of the SEMP evolved primarily by progressive localization of a wide zone of deformation toward a high-strain fault core (Frost et al., 2009), the entire area is characterized by several parallel fault branches, which form a zone with a maximum width of ~10 km (Fig. DR1 in the GSA Data Repository[1]). The newly investigated Hirschgruben cave is located within this fault zone, 6.7 km south of the fault core of the SEMP at 1890 m above sea level (a.s.l.). The cave has a surveyed length of 4.5 km and consists mainly of galleries of phreatic (Tertiary) origin, which were later modified under vadose conditions. The cave formed within cataclastically deformed dolomitic limestone of the Upper Triassic Dachstein Formation and dolostone of the Middle Triassic Wetterstein Formation. Numerous generations of cohesive protocataclasites to ultracataclasites in the cave are cut by slickensides, suggesting episodic slip of the fault at upper crustal levels.

A WSW-ENE–trending, fault-controlled gallery 190 m below the surface shows several indications of neotectonic sinistral displacement (Fig. 2; Fig. DR2). In addition to broken speleothems and breakdown debris above flowstone, four different types of features indicate sinistral strike slip along the fault.

Scratched flowstone formed during movements of the fault (Fig. 2.3). We suggest that breakdown blocks were pinched between the two cave walls (which are part of both fault blocks) and scratched the flowstone cover during fault movement. Blocks that are still pinched are heavily crushed (Fig. 2.4), and others fell apart and exposed the scratches. The same scratches can also be found on the blocks. Within 12 m of the gallery ~20 subparallel scratches as long as 23 cm were identified (Figs. 2.2 and 2.3). On both the footwall and hanging wall the scratches

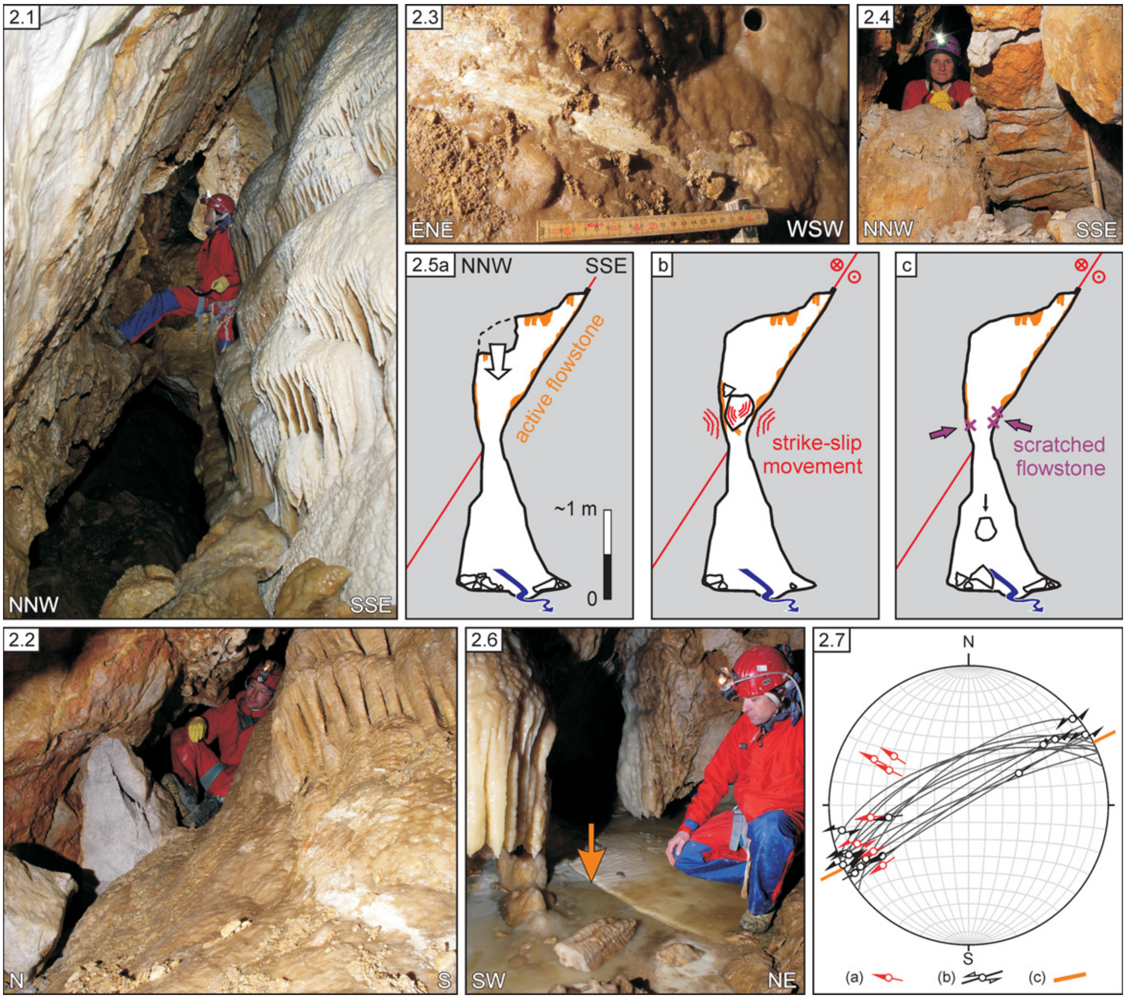

Figure 2. 2.1: Gallery cross section few meters away from scratched flowstone (2.2). Note fault-controlled gallery ceiling and undamaged flowstone. 2.2: Blocks (gray, partly cracked) stuck between gallery walls that were moved against each other. White stripes in lower right are scratches in flowstone (see 2.3). 2.3: Flowstone showing scratch marks partly overgrown by thin, transparent calcite layer (centimeter scale). Scratch marks are only developed on fault-parallel surfaces and on left sides of flowstone hummocks, indicating sinistral shear. Upper left: Sampling borehole of core H3 (Fig. DR3; see footnote 1). 2.4: Block that was pinched between two moving cave walls and broken into six parallel pieces. 2.5: Proposed mechanisms for origin of scratched flowstone: a—deposition of flowstone on walls of gallery showing hourglass-like cross section that developed along active fault (see 2.1); b—breakdown block gets pinched in neck of gallery (similar to block in 2.2 or 2.4). Differential movement of passage walls during fault displacement causes block to scratch surface of flowstone. c—Block breaks up as fault movement continues and its fragments fall down, exposing scratches (see 2.3). 2.6: Fault in massive flowstone partly sealed by post-event flowstone. Arrow indicates location of drill hole (core H5, Fig. DR3). 2.7: Equal-area stereographic projection (lower hemisphere): a—lineation of scratches in flowstone (note that they have no fault plane; see 2.3); b—slickenlines on faults that initiated origin of gallery (see 2.1); c—strike of fault in flowstone layer (see 2.6).

[1]GSA Data Repository item 2010142, additional data and figures, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

are present on fault-parallel flowstone surfaces, but only on the left sides of small flowstone hummocks; this indicates sinistral shear. The scratches are commonly overgrown by a few-millimeter-thick, younger (post-event) generation of flowstone (Fig DR2.4). Breakdown debris of various sizes was also covered by this post-event calcite layer.

Dislocated stalagmites and flowstone were sheared off or ruptured by the sinistral movement of the cave walls. One such feature allows us to reconstruct an offset of 20–30 cm (Fig. DR2.1).

There is offset of cave morphologic features that developed under phreatic conditions prior to the tectonic event. Whereas the floor of the gallery is covered by blocks or flowstone (see following), the ceiling often shows the sharp fault contact. Due to breakdown along the fault the original morphology is often crushed, but a few small ceiling pockets show sinistral offset. Their corners can be used as markers that allow determination of a sinistral offset of ~25 cm (Figs. DR2.2 and DR2.3).

Massive flowstone is disrupted by a WSW-ENE–striking fault (Fig. 2.6). A hole drilled into this flowstone and the corresponding core (Fig. DR3, cores H4 and H5) shows that only the lower flowstone generation, which formed prior to the tectonic event, was displaced, whereas the younger generation lacks deformation features.

U/Th DATING

Drill cores were obtained from both the scratched flowstone in the hourglass gallery (Fig. 2.3; cores H1–H3) and the faulted flowstone (Fig. 2.5; cores H4 and H5). The flowstone covering the wall of the gallery shows a consistent internal stratigraphy of pre-event flowstone beneath (yellowish to brownish, irregularly laminated) and a thin veneer of rather clear and partly translucent post-event calcite above (Fig. DR3). The boundary between these two calcite generations is marked by a thin, discontinuous layer of white calcite in cores H1 and H2 (ground limestone powder). Core H3 penetrated a thicker layer of this tectonically disintegrated limestone material showing a porous, cataclastic fabric and a light brown stain (Fig. DR3).

Two cores drilled into the faulted horizontal flowstone penetrated the irregular fault plane, which is marked by a brownish-red loamy layer (Fig. DR3). The pre-event calcite is yellowish and is fractured, whereas the calcite above shows no deformation.

Samples for U/Th analysis were drilled from polished slabs of the drill cores using a dental drill. Details on the chemical preparation, measurements (by multicollector inductively coupled plasma–mass spectrometry), and correction for detrital Th were given by Boch et al. (2009).

U contents are low in all samples, reflecting the low U content of the host limestone (Table 1). U/Th ages of pre-event calcite of the flowstone covering the oblique wall were partly compromised by detrital Th and yielded (corrected) ages of 140.8 ± 9.5 (core H1) and 132.9 ± 5.2 ka (core H3; no dates are available for core H2; see Table 1). These dates are slightly older than those obtained from the pre-event calcite of the faulted flowstone that range from 118.0 ± 2.6 to 126.2 ± 4.2 ka. The calcite that grew across this fault yielded basal ages of 9.1 ± 0.5 (core H4) and 8.3 ± 0.3 ka (core H5). No reliable dates could be obtained from the thin post-event calcite of cores H1 to H3.

DISCUSSION

The U/Th ages of the two flowstone generations are internally consistent and indicate that the event or events that caused the deformation occurred after the Last Interglacial but prior to ca. 9 ka, i.e., during the late Pleistocene or the early Holocene. In order to verify a tectonic origin for this event, other mechanisms, which may also deform speleothems, i.e., subsidence, decompression, vandalism, gravity collapse, compaction and movement of sediments (Gilli, 2004, 2005), and, especially in Alpine caves, ice flow (Kempe, 2004; Becker et al., 2006), must be excluded.

The temperature inside the cave, which is located at 1890 m a.s.l., is 1.5 °C. Atmospheric cooling during the last glacial period, bracketed by the presented U/Th ages, resulted in freezing conditions, in particular in galleries located close to the surface. Some of these galleries show evidence that former frost wedging and cold-based ice may have been present in the cave during that time. The following observations, however, strongly argue against ice flow as the cause for the observed speleothem deformation in Hirschgruben cave. In the described passage all flowstones adjacent to the fault plane are damaged, even those formed in rather protected niches near the ceiling. Moving away from the fault, however, speleothems are undamaged and even locally protrude into the cave passage (Fig. 2.1). The fact that the scratches in the flowstones always (on the footwall and on the hanging wall) originated from left to right, which is evident from flowstone hummocks and thin section observations, rules out ice movement. Further, only speleothems close to the active fault show deformation features. Observations from a gallery 230 m to the northeast and 160 m higher than the gallery described above add support to these arguments. There, cave walls partly covered by millimeter-thick flowstone are displaced along a sinistral fault by a few centimeters (average orientation of fault planes: 080°, 87N; lineation 261°, 22°).

Deformation mechanisms other than ice flow are even less plausible. Deformation, subsidence, or creep of fine-grained clastic cave sediments are rejected because the scratched flowstone grew directly on rock wall. Collapse of karst cavities may result in damaged speleothems, but the subhorizontal nature of the slickenlines in Hirschgruben cave renders such a mechanism very unlikely. Gravitational slope processes can be safely excluded as the fault shows strike-slip displacement subparallel

TABLE 1. U-TH RESULTS OF DAMAGED SPELEOTHEMS

Sample	U		Th		$^{234}U/^{238}U$ initial		$^{234}U/^{238}U$		$^{230}Th/^{232}Th$		$^{230}Th/^{234}U$		Age (uncorrected)		Age (corrected)	
	(ppb)	(±1σ)	(ppb)	(±1σ)	(activity)	(±2σ)	(activity)	(±1σ)	(activity)	(±1σ)	(activity)	(±1σ)	(ka)	(±2σ)	(ka)	(±2σ)
H1A	32.4	0.1	13.581	0.054	2.386	0.040	1.9040	0.0064	11.2	0.2	0.8165	0.0132	151.4	9.1	140.8	9.5
H3D	40.2	0.1	13.634	0.047	2.447	0.026	1.9704	0.0053	13.8	0.1	0.7892	0.0083	141.2	5.4	133.0	5.2
H4D	89.3	0.1	0.340	0.003	2.381	0.013	1.9737	0.0023	1148.4	11.8	0.7304	0.0052	123.6	2.9	123.5	3.0
H4E*	49.3	0.1	0.924	0.004	2.255	0.006	2.2092	0.0029	30.3	0.7	0.0854	0.0021	9.64	0.50	9.11	0.48
H4G*	41.0	0.1	0.171	0.002	1.953	0.009	1.9371	0.0042	73.9	1.8	0.0526	0.0012	5.88	0.28	5.76	0.26
H5D	91.0	0.1	0.949	0.005	2.518	0.020	2.0627	0.0028	444.4	5.1	0.7429	0.0076	126.4	4.2	126.2	4.4
H5E	80.0	0.1	0.764	0.005	2.341	0.017	1.9563	0.0027	444.1	5.6	0.7165	0.0079	119.9	4.4	119.6	4.4
H5F	90.3	0.1	0.196	0.002	2.595	0.019	2.1298	0.0055	2145.3	26.6	0.7167	0.0049	118.0	2.6	118.0	2.6
H5H*	48.6	0.1	0.450	0.005	2.864	0.012	2.8199	0.0060	69.7	1.3	0.0759	0.0012	8.54	0.29	8.28	0.29
H5I*	58.2	0.1	0.177	0.002	2.613	0.012	2.5754	0.0058	190.5	5.7	0.0743	0.0021	8.37	0.47	8.27	0.45

Note: Ages were calculated using the decay constants of Cheng et al. (2000) and corrected for detrital ^{230}Th using initial $^{230}Th/^{232}Th$ activity ratio of 0.8.
*Post-damage event samples. H–drill cores (see text footnote 1).

to the cliff of the karst plateau, and the studied cave passage is located 190 m below the surface and 0.7 km off the margin of the plateau. As U/Th dates indicate that deformation occurred prior to ca. 9 ka and the speleothems are difficult to access (90 m shaft), vandalism can also be excluded.

We therefore conclude that the damaged speleothems in Hirschgruben cave were caused by one or more tectonic events during the last glacial period and/or the earliest part of the Holocene. Neotectonic activity along the SEMP fault is in good agreement with the recorded seismicity (Reinecker and Lenhart, 1999; Fig. 1), showing a match of epicenters along its fault trace. Two fault plane solutions of earthquakes close to the fault (Fig. 1) indicate coseismic sinistral strike-slip faulting along faults subparallel to the one observed in the cave.

GPS observations provide evidence for eastward displacement of the easternmost part of the Alps toward the Pannonian region at a rate of 1.4 ± 0.2 mm/a relative to the Bohemian Massif being part of the European Platform (Bus et al., 2009). This displacement is mainly accommodated at the seismically active Mur-Mürz fault (Decker et al., 2005; MM in Fig. 1). However, a GPS station (GMRS, Fig. 1) located on the extruding wedge west of the Mur-Mürz fault also shows an east-directed movement of 1.0 ± 0.6 mm/a (Grenerczy et al., 2005). More recent data from this station using a longer time series indicate a northeast-directed displacement of 1.2 ± 0.4 mm/a (G. Grenerczy, 2009, personal commun.).

Although active tectonic deformation has been documented in the Vienna Basin at the eastern margin of the Alps (Decker et al., 2005), the subsurface observations in the Hirschgruben cave provide, to our knowledge, the first directly dated geological evidence of neotectonic activity in the Eastern Alps. The general lack of surface expressions of neotectonic activities in the Eastern Alps has been attributed to high erosion rates during the Pleistocene in this high-relief region (Plan and Decker, 2006), emphasizing the importance of paleoseismic records from caves.

CONCLUSIONS

Speleothems and the morphology of Hirschgruben cave show evidence of ~25 cm displacement associated with slip along an east-northeast–striking sinistral strike-slip fault that is part of the SEMP fault zone. The U/Th dating of pre-event and post-event calcite provides for the first time an absolutely dated time frame for this tectonic event, i.e., between ca. 118 ka (the end of the Last Interglacial) and ca. 9 ka. As mechanisms other than tectonic deformation can be excluded, these data confirm that the SEMP is an active fault. Seismicity data and vectors of GPS stations support this interpretation and demonstrate that extrusion of the Eastern Alps is an ongoing process. Tectonically damaged speleothems provide unique quantitative constraints on neotectonic activity, in particular in mountainous regions where glacial activity and intensive erosion have obliterated geomorphological evidence of recent faulting at the surface.

ACKNOWLEDGMENTS

The Vienna Waterworks supported the karst morphological studies. We thank M. Behm, A. Glitzner, and A. Klampfer for their support during cave exploration, E. Guggenberger, G. Wiesmayr, and M. Meyer for assistance in the cave, K.-H. Offenbecher for support in the isotope lab, C. Beybel and S. Hrabe for thin section preparation, and S. Martel, E. Kagan, and two anonymous reviewers for useful comments.

REFERENCES CITED

Becker, A., Davenport, C.A., Eichenberger, U., Gilli, E., Jeannin, P.Y., and Lacave, C., 2006, Speleoseismology: A critical perspective: Journal of Seismology, v. 10, p. 371–388, doi: 10.1007/s10950-006-9017-z.

Boch, R., Spötl, C., and Kramers, J., 2009, High-resolution isotope records of early Holocene rapid climate change from two coeval stalagmites of Katerloch Cave, Austria: Quaternary Science Reviews, v. 28, p. 2527–2538, doi: 10.1016/j.quascirev.2009.05.015.

Bus, Z., Grenerczy, G., Tóth, L., and Mónus, P., 2009, Active crustal deformation in two seismogenic zones of the Pannonian region—GPS versus seismological observations: Tectonophysics, v. 474, p. 343–352, doi: 10.1016/j.tecto.2009.02.045.

Cheng, H., Edwards, R.L., Hoff, J., Gallup, C.D., Richards, D.A., and Asmerom, Y., 2000, The half-lives of uranium-234 and thorium-230: Chemical Geology, v. 169, p. 17–33, doi: 10.1016/S0009-2541(99)00157-6.

Decker, K., Peresson, H., and Hinsch, R., 2005, Active tectonics and Quaternary basin formation along the Vienna Basin transform fault: Quaternary Science Reviews, v. 24, p. 305–320, doi: 10.1016/j.quascirev.2004.04.012.

Delaby, S., 2001, Palaeoseismic investigations in Belgian caves: Netherlands Journal of Geosciences, v. 80, p. 323–332.

Fairchild, I.J., Smith, C.L., Baker, A., Fuller, L.M., Spötl, C., Mattey, D., McDermott, F., and EIMF, 2006, Modification and preservation of environmental signals in speleothems: Earth-Science Reviews, v. 75, p. 105–153, doi: 10.1016/j.earscirev.2005.08.003.

Forti, P., and Postpischl, D., 1984, Seismotectonic and paleoseismic analyses using karst sediments: Marine Geology, v. 55, p. 145–161, doi: 10.1016/0025-3227(84)90138-5.

Frost, E., Dolan, J., Sammis, C., Hacker, B., Cole, J., and Ratschbacher, L., 2009, Progressive strain localization in a major strike-slip fault exhumed from midseismogenic depths: Structural observations from the Salzach-Ennstal-Mariazel Puchberg fault system, Austria: Journal of Geophysical Research, v. 114, B04406, doi: 10.1029/2008JB005763.

Gilli, E., 2004, Glacial causes of damage and difficulties to use speleothems as palaeoseismic indicators: Geodinamica Acta, v. 17, p. 229–240, doi: 10.3166/ga.17.229-240.

Gilli, E., 2005, Review on the use of natural cave speleothems as palaeoseismic or neotectonics indicators: Comptes Rendus Geoscience, v. 337, p. 1208–1215, doi: 10.1016/j.crte.2005.05.008.

Glodny, J., Ring, U., and Kühn, A., 2008, Coeval high-pressure metamorphism, thrusting, strike-slip, and extensional shearing in the Tauern Window, Eastern Alps: Tectonics, v. 27, TC4004, doi: 10.1029/2007TC002193.

Grenerczy, G., Sella, G., Stein, S., and Kenyeres, A., 2005, Tectonic implications of the GPS velocity field in the northern Adriatic region: Geophysical Research Letters, v. 32, L16311, doi: 10.1029/2005GL022947.

Kagan, E.J., Agnon, A., Bar-Matthews, M., and Ayalon, A., 2005, Dating large, infrequent earthquakes by damaged cave deposits: Geology, v. 33, p. 261–264, doi: 10.1130/G21193.1.

Kempe, S., 2004, Natural speleothem damage in Postojnska Jama (Slovenia), caused by glacial ice? A first assessment: Acta Carsologica, v. 33, p. 265–289.

Linzer, H.G., Decker, K., Peresson, H., Dell'Mour, R., and Frisch, W., 2002, Balancing lateral orogenic float of the Eastern Alps: Tectonophysics, v. 354, p. 211–237, doi: 10.1016/S0040-1951(02)00337-2.

Peresson, H., and Decker, K., 1997a, Far-field effects of Late Miocene subduction in the Eastern Carpathians: E-W compression and inversion of structures in the Alpine-Carpathian-Pannonian region: Tectonics, v. 16, p. 38–56, doi: 10.1029/96TC02730.

Peresson, H., and Decker, K., 1997b, The Tertiary dynamics of the northern Eastern Alps (Austria): Changing palaeostresses in a collisional plate boundary: Tectonophysics, v. 272, p. 125–157, doi: 10.1016/S0040-1951(96)00255-7.

Plan, L., and Decker, K., 2006, Quantitative karst morphology of the Hochschwab plateau, Eastern Alps, Austria: Zeitschrift für Geomorphologie, v. 147, supplement, p. 29–56.

Ratschbacher, L., Frisch, W., Linzer, H.G., and Merle, O., 1991, Lateral extrusion in the Eastern Alps. Part 2: Structural analysis: Tectonics, v. 10, p. 257–271, doi: 10.1029/90TC02623.

Reinecker, J., and Lenhart, W.A., 1999, Present-day stress field and deformation in eastern Austria: International Journal of Earth Sciences, v. 88, p. 532–550, doi: 10.1007/s005310050283.

Rosenberg, C.L., and Schneider, S., 2008, The western termination of the SEMP fault (Eastern Alps) and its bearing on the exhumation of the Tauern Window, *in* Siegesmund, S., et al., eds., Tectonic aspects of the Alpine-Carpathian-Dinaride system: Geological Society of London Special Publication 298, p. 197–218.

Schwarcz, H., 2006, Speleothems, *in* Elias, S.A., ed., Encyclopedia of Quaternary science: Amsterdam, Elsevier, p. 290–300.

Szeidovitz, G., Surányi, G., Gribovszki, K., Bus, Z., Leél-Össy, S., and Varga, Z., 2008, Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact speleothems in Hungarian caves: Journal of Seismology, v. 12, p. 21–33, doi: 10.1007/s10950-007-9068-9.

Manuscript received 11 November 2009
Revised manuscript received 16 December 2009
Manuscript accepted 20 December 2009

Printed in USA