Journal of Structural Geology 110 (2018) 102–115

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Seismically-triggered soft-sediment deformation structures close to a major strike-slip fault system in the Eastern Alps (Hirlatz cave, Austria)

Martina Lan Salomon[a,b], Bernhard Grasemann[a,*], Lukas Plan[c], Susanne Gier[a], Martin P.J. Schöpfer[a]

[a] University of Vienna, Department for Geodynamics and Sedimentology, A-1090 Vienna, Austria
[b] NTNU, Department of Civil and Environmental Engineering, NO-7491 Trondheim, Norway
[c] Natural History Museum Vienna, Karst and Cave Group, A-1010 Vienna, Austria

ARTICLE INFO

Keywords:
Soft-sediment deformation
Liquefaction
Active tectonics
Northern Calcareous Alps
Speleoseismology

ABSTRACT

We investigate episodic soft-sediment deformation structures cross-cut by normal faults preserved in unlithified finely laminated calcite rich sediments in the Hirlatz cave in the Northern Calcareous Alps (Austria). These sediments comprise varve-like alternations of brighter carbonate/quartz rich layers, and darker clay mineral rich layers. The deformed sediments contain abundant millimeter to centimeter-scale soft-sediment structures (load casts, ball-and-pillow structures), sheet slumps (thrust faults and folds), erosive channels filled with slides and chaotic slumps. After deposition and soft-sediment deformation normal faults developed within the entire sedimentary succession, an event that probably correlates with an offset of c. 10 cm of the passage wall above the outcrop. Our major conclusions are: (i) The sediments have a glacial origin and were deposited in the Hirlatz cave under phreatic fluvio-lacustrine conditions. The deposition and the soft-sediment deformation occurred most likely during the last glaciation (i.e. around 25 ka ago); (ii) The liquefaction and formation of the soft-sediment structures in water-saturated stratified layers was triggered by episodic seismic events; (iii) The internally deformed sediments were later displaced by normal faults; (iv) A possible source for the seismic events is the active sinistral Salzach-Ennstal-Mariazeller-Puchberger (SEMP) strike-slip fault which is located about 10 km south of the outcrop and plays a major role in accommodating the extrusion of the Eastern Alps towards the Pannonian Basin. To our knowledge, the described structures are the first report of liquefaction and seismically induced soft-sediment deformations in Quaternary sediments in the Eastern Alps.

1. Introduction

In the Eastern Alps (Austria) and its Neogene basins only few direct geological or geo-archeological evidences are preserved that proof active tectonic processes (e.g. Decker et al., 2005, 2006; Beidinger and Decker, 2011; Beidinger et al., 2011). Although active crustal deformation in the Eastern Alps has been confirmed by numerous geophysical data sets (Reinecker and Lenhardt, 1999; Grenerczy et al., 2005; Tesauro et al., 2006; Brückl et al., 2010; Serpelloni et al., 2016), many geomorphological signals of active crustal deformation have been obliterated by (peri)glacial activity and intensive erosion during the last glacial period (Robl et al., 2008). Karst caves represent a unique environment that is capable to preserve proofs of past geomorphological and geological processes, even in terrains of high surface erosion rates. Especially for paleoseismic and neotectonic studies, this underground archive can play an essential role in deciphering past events (e.g., Postpischl et al., 1991; Lacave et al., 2004; Becker et al., 2006, 2012). Plan et al. (2010) described the first detailed and dated field evidence of neotectonic activity from a cave in the Northern Calcareous Alps (NCA) and showed that massive flowstones were scratched and ruptured between the last Interglacial and the Early Holocene. They concluded that the nearby Salzach-Ennstal-Mariazeller-Puchberg strike-slip fault (SEMP), which facilitates the extrusion of the Eastern Alps, must be an active fault. The present study supports these earlier findings and investigates liquefaction and complex soft-sediment deformation structures cross-cut by normal faults in the Hirlatz cave. The studied outcrop, which is about 100 km to the west of the studied fault segment of Plan et al. (2010), demonstrates the recurrence of seismic activity in that particular region close the SEMP fault system.

2. Geological setting

The investigated Hirlatz cave is located at the northern rim of the Dachstein karst plateau with a peak elevation of almost 3000 m a.s.l.

* Corresponding author.
E-mail address: Bernhard.Grasemann@univie.ac.at (B. Grasemann).

https://doi.org/10.1016/j.jsg.2018.02.010
Received 1 September 2017; Received in revised form 14 February 2018; Accepted 22 February 2018
Available online 01 March 2018

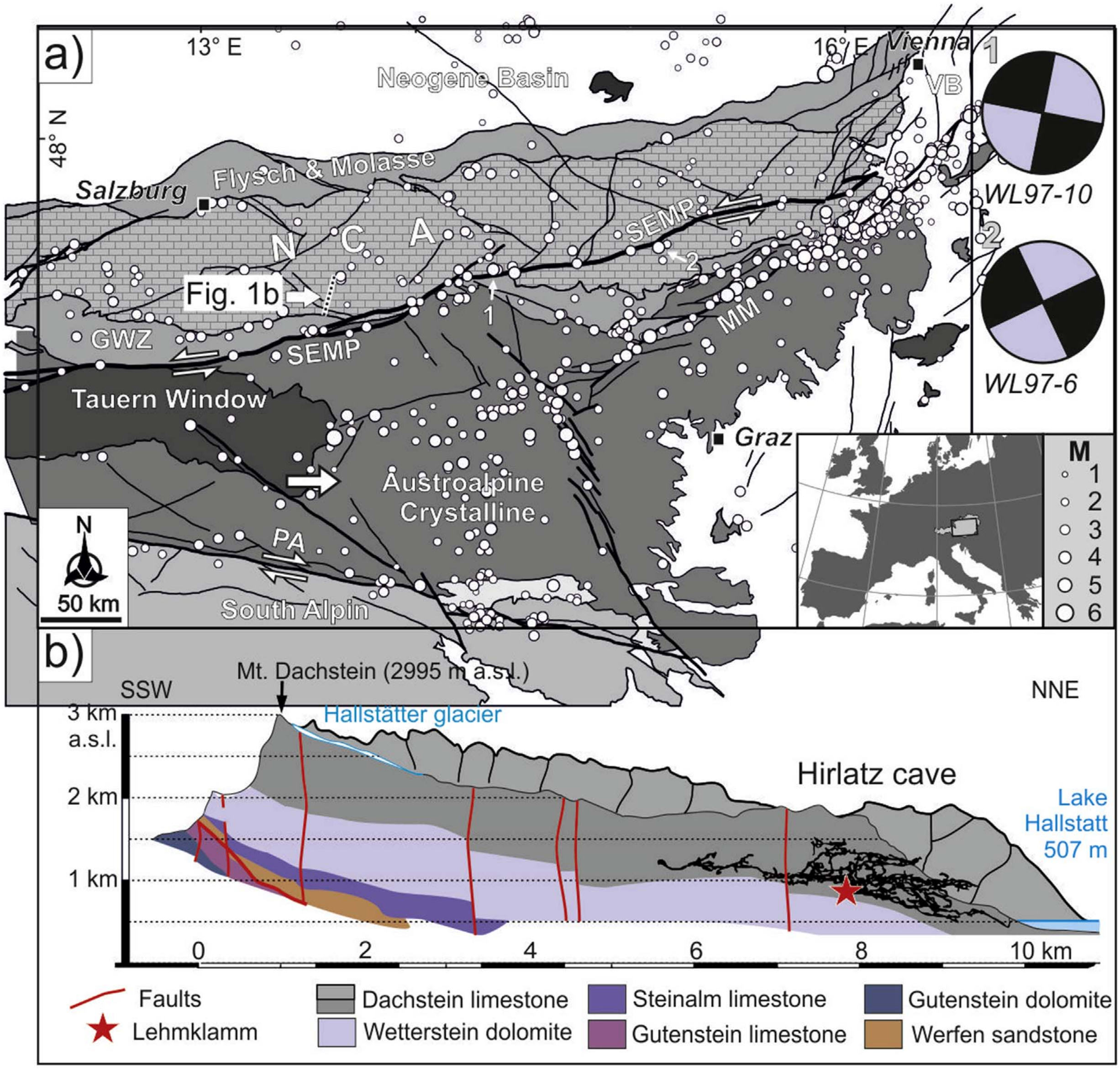

Fig. 1. a) Simplified geological map of the Eastern Alps (SEMP – Salzachtal-Ennstal-Mariazell-Puchberg fault; PA – Periadriatic fault; MM – Mur-Mürz fault; BM – Bohemian Massif, GWZ – Graywacke Zone, NCA – Northern Calcareous Alps; VB – Vienna Basin). White circles indicate epicenters of earthquake events since 1900 (Reinecker and Lenhardt, 1999). The size of the circles is proportional to their magnitude. Single arrow indicates 1.0 ± 0.6 mm/a E-directed movement of GPS station GRMS relative to Bohemian Massif (Grenerczy et al., 2005). Two focal mechanism solutions indicate sinistral strike-slip movement along active segments of the SEMP (Reinecker and Lenhardt, 1999). b) Geological section across the Dachstein plateau (modified after Seebacher, 2016 using Mandl, 1998). Black lines indicate the Hirlatz cave (cave survey data: VH Hallstatt-Obertraun).

(Fig. 1, Pohl and Greger, 2001). The Dachstein massif is part of the NCA, which constitute the uppermost tectonic unit in the Eastern Alps and form a 500 km long and 20–50 km wide thrust belt (Spengler, 1928; Tollmann, 1976). The strata record the history of the Eastern Alpine part of the Tethyan shelf from Permian to Eocene times (Mandl, 2000 and references cited therein). The cave is located in the Upper Triassic Dachstein Limestone formation (Simony, 1847), which represents a distal shallow marine shelf consisting of reef and lagoon facies (Haas et al., 2007). The NCA have been subjected to several tectonics phases, starting with initial nappe stacking in the Upper Jurassic followed by major W-directed thrusting in the Cretaceous. After drowning and deposition of the Upper Cretaceous clastic sediments of the Gosau Group, the NCA were thrusted towards the north into a thin-skinned fold and thrust belt (Frisch and Gawlick, 2003). Sinistral strike-slip movements along the SEMP fault system, which is located along the southern margin of the NCA, commenced in the Miocene and accommodated since then about 60 km extrusion of the central parts of the Eastern Alps towards the Pannonian Basin (Linzer et al., 2002).

The main entrance of the Hirlatz cave is located at 870 m a.s.l. in the Echern Valley, below the 900 m vertical north face of Mount Hirlatz (Buchegger and Greger, 1998; Austrian Cave Register #1546/7). With a length of 105 km and a depth of 1070 m, this karstic cave is the third longest cave system known in Austria. The investigated structures are exposed on a 5.5 m long and 2.5 m high NE-SW striking outcrop wall of cave sediments along a section called *Lehmklamm*, which is located about 2.8 km SE of the cave entrance at 1005 m a.s.l. Fig. 2 shows an orthomosaic of the outcrop, which was created from 24 individual pictures using the photogrammetric software Agisoft PhotoScan Vers. 1.2.4 (www.agisoft.com). Karst hydrological investigations have demonstrated a complex drainage system from the Dachstein plateau through parts of the cave generally directed towards the N, which corresponds to the dip direction of the bedded limestone (Völkl, 1998). At the present time phreatic (completely water filled) and epiphreatic (only filled during floods) conditions are found at different altitude levels within the cave. The investigated sedimentary succession in the Lehmklamm is nowadays located in the vadose zone (water unsaturated