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A subaquatic moraine complex in overdeepened Lake Thun (Switzerland) unravelling the deglaciation history of the Aare Glacier

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ABSTRACT

To investigate the history of the Aare Glacier and its overdeepened valley, a high-resolution multibeam bathymetric dataset and a 2D multi-channel reflection seismic dataset were acquired on perialpine Lake Thun (Switzerland). The overdeepened basin was formed by a combination of tectonically predefined weak zones and glacial erosion during several glacial cycles. In the deepest region of the basin, top of bedrock lies at ~200 m below sea level, implying more than 750 m of overdeepening with respect to the current fluvial base level (i.e. lake level). Seismic stratigraphic analysis reveals the evolution of the basin and indicates a subaquatic moraine complex marked by high-amplitude reflections below the outermost edge of a morphologically distinct platform in the southeastern part of the lake. This stack of seven subaquatic terminal moraine crests was created by a fluctuating, “quasi-stagnant” grounded Aare Glacier during its overall recessional phase. Single packages of overridden moraine crests are seismically distuinguishable, which show a transition downstream into prograding clinoforms with foresets at the ice-distal slope. The succession of subaquatic glacial sequences (foresets and adjacent bottomsets) represent one fifth of the entire sedimentary thickness.

Exact time constraints concerning the deglacial history of the Aare Glacier are very sparse. However, existing ^{10}Be exposure ages from the accumulation area of the Aare Glacier and radiocarbon ages from a Late-Glacial lake close to the outlet of Lake Thun indicate that the formation of the subaquatic moraine complex and the associated sedimentary infill must have occurred in less than 1000 years, implying high sedimentation rates and rapid disintegration of the glacier.

These new data improve our comprehension of the landforms associated with the ice-contact zone in water, the facies architecture of the sub- to proglacial units, the related depositional processes, and thus the retreat mechanisms of the Aare Glacier.

1. Introduction

The evolution of the Quaternary landscape and the formation of Alpine valleys has been of scientific interest for generations of geologists over the last 200 years (e.g. Escher, 1820; Penck, 1905), seeking for explanations that elucidate the creation of perialpine lakes and overdeepened troughs (Bini et al., 1978; Finckh, 1978). In recent years, glacial overdeepenings attracted economic interest, since a majority of these troughs host aquifers with drinking water, and major engineering and tunneling projects across the Alps encountered unexpected challenges with the sedimentary infill and morphology of them (e.g. Lötschberg railway tunnel, Schlüchter, 1979). Furthermore, the Swiss nuclear waste disposal program aims at finding a safe repository for high-level nuclear waste that endures future glacial cycles, which requires an improved understanding of factors controlling glacio-fluvial erosion, overdeepening processes and glacial advances and retreat phases of the local Aare, Rhine and Rhone Glacier system (Preusser et al., 2010).

The important role of perialpine lakes for the unravelling of the

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(de-) glaciation history of the Alps was already recognized by Heim (1894) in Lake Lucerne (Switzerland). The detailed sedimentary archives of lakes serve as excellent trackers of glacial evolution. Moreover, morphological features, which are sometimes hard to identify on land, are perfectly preserved in lacustrine and marine environments, where erosional processes are strongly hampered. Examples of subaquatic glacial morphologies have been shown for example in the fjord basin of Lake Melville, southeast Labrador, Canada (Lønne and Syvitski, 1997), in Lago Fagnano, southern Patagonia (Waldmann et al., 2010), or in central Sweden, where a series of subaquatic end moraines is reported (Johnson et al., 2013).

The global Last Glacial Maximum (LGM, Mix et al., 2001; Clark et al., 2009; Hughes et al., 2013) does temporally fairly well coincide with the maximum reach out of Alpine piedmont glaciers into the northern foreland and the creation of the Italian amphitheatres in the south between 26 ka and 19 ka (Ivy-Ochs, 2015; Monegato et al., 2017, Fig. 1A). The maximum ice extent of the Rhone Glacier was reached at or slightly before 24.0 ± 1.1 ka, as reported by Reber et al. (2014). They dated the abandonment of the Rhone Glacier's maximum position to 19.1 ± 1.5 ka, in response to an initial pre-Bølling deglacial phase, which is in good agreement with the onset of deglaciation of the Aare Glacier (Akcar et al., 2011). It seems that Alpine glaciers act very sensitively to slight snowline changes and therefore respond rapidly to temperature changes, collapsing faster during warming pulses (Ivy-Ochs et al., 2004).

The Quaternary landscape created by the Aare Glacier between Bern and the accumulation area at Grimselpass was first described by Penck and Brückner (1909). Beck (1920–1922) noticed that the complete excavation of sedimentary infill in an overdeepened valley during the Würmian glaciation is rather unlikely. The records from drilling sites at Meikirch NW of Bern (Welten, 1988) and at Thalgut (Schlüchter, 1989b, Fig. 1B) north of Thun serve as ideal Quaternary archives to support his claim. The latter reveals top of Molasse bedrock at 147 m depth below surface with at least three glacial cycles covering it (Schlüchter and Kelly, 2000). A basal glacial unit is followed by the lowermost lacustrine clays being indicative for the Holstein Interglacial associated with MIS 9 (Schlüchter, 1989b, 1989a). This implies that bedrock erosion to the current level occurred during the glaciation in MIS 10 or even earlier at Thalgut. The sequence is topped with a basal lodgment till deposited during LGM (Preusser and Schlüchter, 2004). At Meikirch, deposits of previous glacial cycles are preserved as well, and the last time bedrock experienced ice contact was during MIS 8 or earlier based on the re-interpretation of sediment logs, palynological correlation and luminescence dating (Preusser et al., 2005). Other drill holes within overdeepened basins revealed similar deposits of previous glacial cycles and showed their preservation potential over several glaciations (e.g. Niederweningen, Switzerland: Anselmetti et al., 2010; Dehnert et al., 2012; Salzach, Austria/Germany: Fiebig et al., 2014; Lower Glatt Valley, Switzerland: Buechi et al., 2017).

In contrast to our fairly good understanding of the ice extent during LGM along the Alps (Fig. 1A), the deglaciation history of the LGM is still poorly constrained and mostly based on ice-marginal landforms, trimlines, striae, roches moutonnées, polished bedrock and erratic boulders (e.g. Jäckli, 1962; Schlüchter, 1988). More recent studies in the Upper Aare Valley incorporate surface exposure ages derived from in-situ produced cosmogenic nuclides such as ^{10}Be in boulders and bedrock (e.g. Ivy-Ochs and Kober, 2008; Akcar et al., 2011). Kelly et al. (2006) and Wirsig et al. (2016) reconstructed the retreat and stagnant episodes of the Aare Glacier during its recessional phase from the abandonment of its LGM position northeast of Bern to its accumulation area at Grimselpass using ^{10}Be. The rapid ice decay in the northern foreland (Schlüchter, 1988) hardly left any obvious moraines hinting at a stabilization of the ice front or a Late-Glacial readvance beyond the inner-Alpine regions (Kelly et al., 2006; Reitner et al., 2016). Ivy-Ochs et al. (2006) also noted that, despite detailed geologic mapping for more than 100 years, Gschnitz moraines (Kerschner et al., 1999) have not been found yet in major longitudinal valleys within the Alps.

Our extensive multi-channel reflection seismic survey combined with multibeam swath bathymetry on Lake Thun enable us to perform a detailed study of the bedrock topography and the sedimentary infill of its overdeepened basin, both containing several glacial features. We present the seismic stratigraphy displaying the detailed internal structure of a previously unknown large subaquatic moraine complex, including a model that gives a relative chronology of its build-up. Our findings shed new light on the understanding of the deglaciation history of the Aare Valley, and will address some challenges associated with the often poorly constrained estimation of overdeepening in perialpine lakes.

1.1. Geological setting

Perialpine Lake Thun lies at the northern front of the Alpine nappes and is situated in the Upper Aare Valley between Interlaken and Bern (Fig. 1A). Its overdeepened basin is located within sedimentary Penninic and Helvetic thrust nappes and the Subalpine Molasse outcropping on the southwest, northeast and northern shores, respectively. The main part of the Lake Thun basin is elongated orthogonal to the general strike direction of the Alpine front (WSW-ENE).

During the Pleistocene glaciations, subglacial erosion formed overdeepenings and shaped the study area (Haeuselmann et al., 2007; Reber and Schlunegger, 2016). Ice thickness of the valley glacier may have varied between these different glaciations, but must have reached several hundred meters of ice (ice elevation at ~1200 m a.s.l at Thun and 3000 m a.s.l. at the accumulation area of the Aare Glacier) during the LGM (Bini et al., 2009). Prominent glacial landforms attributed to the last glacial period are limited to the southern shoreline of the lake (Fig. 1C), where a number of relatively continuous lateral moraine ridges run parallel to the lake axis. Furthermore, a drumlin field and ribbed moraines have been described in the area W of Thun (Beck, 1933; Fiore, 2007).

1.2. Previous seismic surveys

A first seismic study on Lake Thun was performed by Matter et al. (1971), following the technical recommendations of Hinz et al. (1970) who had previously used the same equipment to investigate Lake Zurich in 1968. The successful imaging and interpretation of the bedrock surface in Lake Thun resulted in a structural map of the basin. They noticed that the deepest part of the lake coincides with a local, spatially well confined depression in bedrock topography to more than 500 m below lake level, adjacent to a shallow-water platform towards Interlaken, where bedrock was interpreted at ~100 m depth below water surface. Drill hole lithology at Interlaken Hospital, however, revealed at that depth the transition between lake sediments and older gravels and sands (Bodmer et al., 1973). In contrast, Bodmer et al. (1973) interpreted bedrock at 300 m below surface in their onshore seismic refraction campaign on the western edge of the Interlaken plateau. Independent of the bedrock depth underestimation, Matter et al. (1971) recognized in their seismic data a few distinct seismic stratigraphic horizons: a shallow one between 7 and 10 m below the lake bottom, which was attributed to the impact of the Kander deviation from 1714 CE, and two additional ones at 90 and 130 m in the northwestern part of the lake and 100 and 190 m in the deep lake basin. They suggest that the oldest deposits in the Lake basin have