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Mineralogical composition of the Baumkirchen lacustrine sequence (Würmian, Inn Valley, Tyrol): provenance and palaeogeographical implications

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Abstract

The Baumkirchen palaeolake sequence east of Innsbruck, Tyrol, is a well-known and studied Late Pleistocene sequence of key importance for Alpine Quaternary stratigraphy. Recent luminescence dating and geochemical analysis revealed that the sequence is made up of two compositionally slightly different phases representing sedimentation during Marine Isotope Stages (MIS) 3 and 4 separated by a ca. 7-15 ka-long hiatus. We investigated the bulk mineralogical composition of the sediment to better characterise the compositional differences, and analysed modern stream sediments to constrain the provenance from different catchments. The modern stream sediments closely match expectations based on catchment geology besides an overrepresentation of dolomite in several catchments, likely attributable to the greater sediment generation potential of dolostone based on its physical and petrographic properties. The Baumkirchen sediments show a high inter-lamina heterogeneity in terms of their mineralogical composition. The event layers form two clusters that largely overlap with clusters of similar grain-size from the modern Sill and Inn sediments and stream sediments from the Wattenbach. This implies that the differences in event layers are due to different sediment sources. The majority of these laminae in the lower lake phase 1 are of the Sill and Inn source type, while the majority in the upper lake phase 2 are of the Wattenbach source type. This indicates a change in sediment delivery between the lake phases and implies a change in catchment configuration. We propose a model whereby the Inn and Sill flowed into the lake during both lake phases with the different sediment supply being controlled by the difference in distance between Baumkirchen and these inflows, being closer during lake phase 1 and further away during the younger lake phase 2. A subtle and gradual change in mineralogy and bulk chemistry is seen within lake phase 2, although the change does not appear to be a distinct change in lake/catchment conditions, but more likely a gradual shift in sediment transport patterns due to basin filling and/or climate change.

Die lakustrinen Baumkirchner Bändertone östlich von Innsbruck, Tirol, stellen eine bekannte und mehrfach untersuchte spätpleistozäne Abfolge von großer Bedeutung für die Quartärstratigraphie der Alpen dar. Lumineszenz-Datierungen und geochemische Analysen haben jüngst gezeigt, dass diese Sedimente in zwei leicht unterschiedliche Sequenzen gegliedert werden können, die im Zeitraum der Marinen Isotopenstufen 3 und 4 abgelagert wurden und durch einen ca. 7-15 ka-langen Hiatus getrennt sind. Wir untersuchten die Gesamtmineralogie um diese kompositionellen Unterschiede zu charakterisieren. Zudem analysierten wir rezente Flusssedimente um die Herkunft aus den verschiedenen Einzugsgebieten einzugrenzen. Die modernen fluviatilen Sedimente entsprechen in ihrer Zusammensetzung gut den vorherrschenden Lithologien ihrer Einzugsgebiete, sieht man von einer Dolomit-Überrepräsentation in einzelnen Gebieten ab, welche auf das höhere Sedimentproduktionspotential von Dolomit aufgrund seiner petrophysikalischen Eigenschaften zurückgeführt wird. Die mineralogische Zusammensetzung der Baumkirchner Bändertone weist eine hohe inter-Lamina-Heterogenität auf. Die Ereignislagen bilden zwei Cluster, die in ihrer Korngröße weitgehend mit den rezenten Sill- und Innsedimenten und jenen des Wattenbachs überlappen. Die Unterschiede in den Mittelsilt- bis Sandlagen dürften daher unterschiedliche Sedimentliefergebiete widerspiegeln. Die meisten dieser Laminae der älteren Seephase 1 entsprechen dem Sill- und Inntypus, während die der jüngeren Seephase 2 zum Wattenbachtyp zu zählen sind. Somit deutet sich eine Änderung in der Sedimentzufuhr zwischen den beiden Seephasen an, die eine Änderung der Flusseinzugsgebiete impliziert. Es wird ein Modell vorgestellt, in dem Inn und Sill während beider Seephasen in diesen See mündeten. Die unterschiedlichen Sedimente werden durch die Distanz zwischen diesen Flussmündungen und Baumkirchen erklärt, welche in der Seephase 1 geringer und in der Seephase 2 größer war. In der jüngeren Seephase erkennt man eine weitere, graduelle Änderung in der Zusammensetzung der Sedimente, welche jedoch keine markante Änderung des Sees bzw. seines Einzugsgebietes belegt, sondern eine allmähliche Änderung der Sedimenttransportmuster im Zuge der Auffüllung dieses Beckens und/oder bedingt durch eine klimatische Veränderung.

1. Introduction

The pre-Last Glacial Maximum (LGM) Baumkirchen lacustrine sequence in the central Inn Valley (Fig. 1) is a classic and well-studied sequence in Alpine Quaternary stratigraphy. While known and investigated on a limited basis earlier (Ampferer, 1908; Penck and Brückner, 1909; Zoeke, 1944), the surface outcrops were subject to detailed investigation in the 1960s and 70s (see also Spötl et al., 2014). Much effort was put into determining the chronology of the sediments through radiocarbon dating (Fliri, 1970; Fliri et al., 1972) and palaeomagnetism (Mayr, 1976; Koci, 1981), as well as into the sedimentology, geochemistry (Felber, 1971; Maurer and Nabholz, 1972; Fliri, 1973, 1976; Köhler and Resch, 1973), and palaeontology (Resch, 1972; Bortenschlager and Bortenschlager, 1978). Together this work contributed significantly to the scientific understanding of the last glaciation in the Alps during the 1970s. As a result of this work, more recent luminescence dating (Klasen et al., 2007), and the recent renewed research effort (Spötl et al., 2013; Barrett et al., 2017), the Baumkirchen sequence is the best studied lacustrine succession of glacial age in the Eastern Alps. Furthermore, the transition from lacustrine to overlying fluvioglacial sediments is the type locality of the Middle to Upper Würmian boundary in the Eastern Alps (Chaline and Jerz, 1984).

Several authors have investigated the composition of the sediments at Baumkirchen and similar lacustrine sediments elsewhere. Zoeke (1944) investigated the heavy mineral composition, and Horvacki (1982) studied the bulk mineral composition using qualitative X-ray diffraction. Their data is not conclusive, but has informed the discussion of potential sediment sources and catchment, lake, and dam configuration. Two main models exist to explain the occurrence of the lacustrine sediments in the Inn Valley:

1. The "fjord model", where the different localities represent deposits of a single large fjord-like lake. This was originally argued by Penck (1890), was further assessed by Zoeke (1944) and Heissel (1954), and has more recently been discussed by Sarnthein and Spötl (2012). The dam for such a lake is not clear but has been variously suggested as an alluvial fan/sediment wedge or glacier at the confluence of the Ziller and Inn Valleys. On the basis of some apparently anomalous results indicating a sediment source from the Ziller, Zoeke (1944) further suggested that the lake was primarily fed from the East, in the opposite direction to the modern drainage pattern.

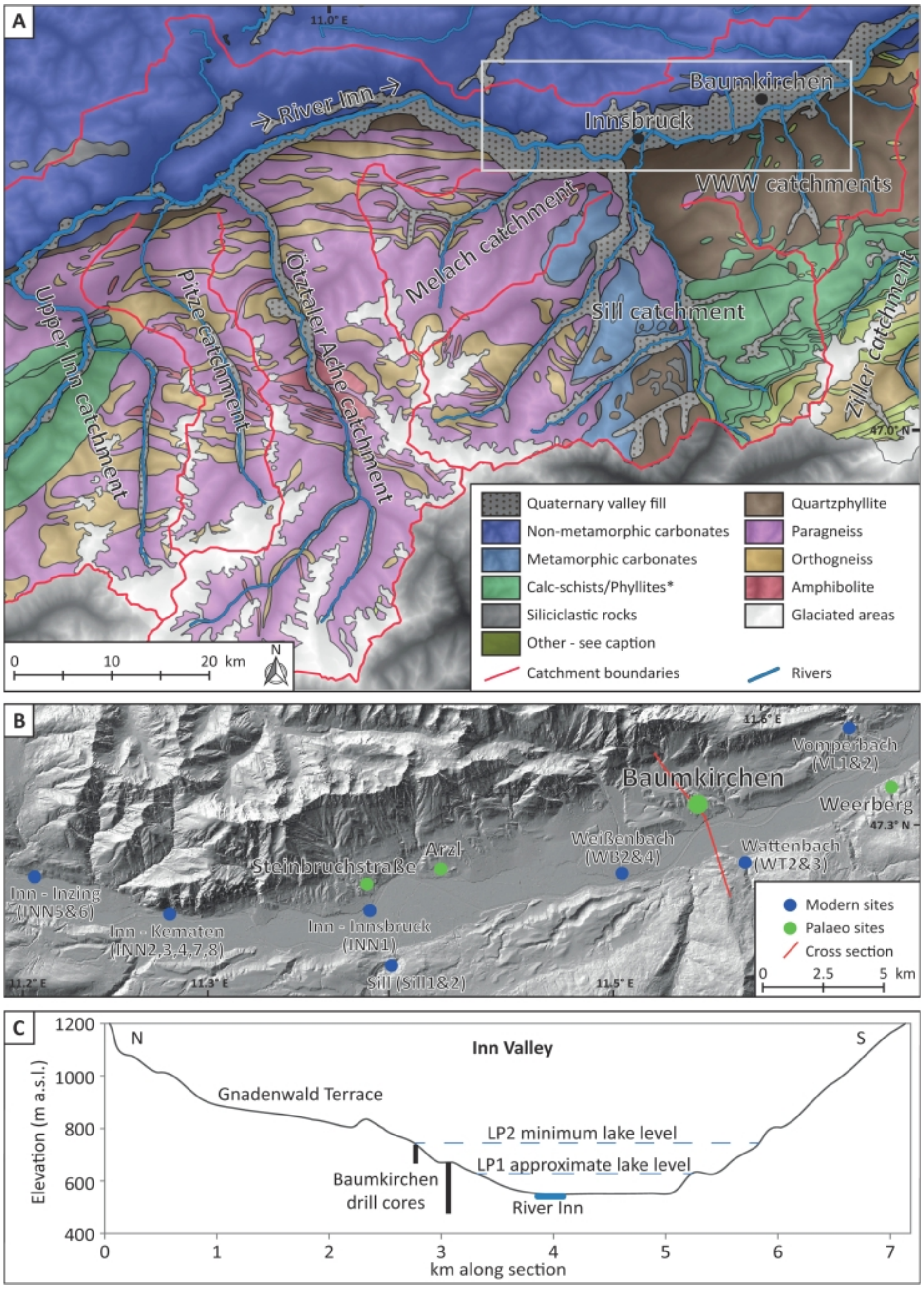

Figure 1: A: Generalised geological map of the central Inn Valley and surrounding valleys showing the watersheds between different catchments. "Other" within the Sill and VWW catchments (Voldertalbach, Wattenbach and Weerbach) includes migmatites, greenschists, serpentinite, basic volcanics and metapelites. * includes diverse calcareous meta-sediments including schists, phyllites, dolomites and marbles. Source of geological base map: Geological Survey of Austria 1:500,000 geological map of Austria based on Weber (1997). B: Inset of A, laserscan topography (TIRIS hillshade) with sample site locations. C: Topographic cross section across the Inn Valley (indicated in B) through the Baumkirchen site and Gnadenwald terrace showing the drill core locations and approximate palaeo-lake levels after Barrett et al. (2017).

2. The "many lakes model", where the different localities largely represent the deposits of individual lakes separated geographically and/or temporally. This model was most notably suggested by Ampferer (1908). Two main variations of this hypothesis exist where the lakes are largely caused by either:
   a. Sediment damming (the "alluvial fan" model), where alluvial fans or similar sediment wedges from side valleys dam the main valley. This hypothesis was elaborated by van Husen (1983, 2000), who suggested that lakes are dammed during periods of rapid aggradation.
   b. Glacial ice damming, either where the ice from tributaries dams the main valley or forms local water bodies at the ice margins. Mayr (1968) proposed this model to explain the terrace sediments of the central Inn Valley and Horvacki (1982) discussed this model in regards to lacustrine sediments in Tyrol. This model has also been used to explain the post-LGM lacustrine sediments in the Hopfgarten area of Tyrol (Reitner, 2007).

The topic of the lake and dam configuration of the Inn Valley palaeolake, specifically the one giving rise to the Baumkirchen sediments, has been further complicated by the discovery of two geochemically and chronologically distinct lake phases through the recent drilling which date to ca. Marine Isotope Stage (MIS) 4 and ca. mid to late MIS 3, respectively (Barrett et al., 2017). In terms of sediment sources, the inconclusive evidence of Zoeke (1944), Horvacki (1982) and Poscher & Lelkes-Felvári (1999) is further confounded by the considerable compositional heterogeneity of the Baumkirchen sediments noted by Barrett et al. (2017) on the basis of X-ray fluorescence (XRF) data, which suggest individual laminae may have had distinct sediment sources.

1.1 Aims and motivation

We investigated the mineralogy of Würmian and modern sediments in the Inn Valley to provide constraints on the dynamics of the Würmian sediment delivery system. In particular we compare data from the Baumkirchen lacustrine sequence to modern river sediments to investigate sedimentary processes, sediment sources and catchment hydrology, and to shed light on the nature of the two different lake phases identified by Barrett et al. (2017). Very little previous work has been done on the composition of modern sediments in the Inn river system (Mangelsdorf, 1971; Kaschanian, 1980), which provided additional motivation for this study. Although heavy mineral analysis commonly is more diagnostic in terms of determining sediment source (and has been applied to Pleistocene sediments in the Inn Valley – Zoeke, 1944; Poscher & Lelkes-Felvári, 1999; Steinbrener, 2011), we investigated the bulk mineralogy for several reasons:

1. We aimed to explain the bulk composition of the Baumkirchen lacustrine sediments.
2. In order to allow for the interpretation of continuous elemental geochemical data (from XRF core scanning) in terms of sediment bulk mineralogy.
3. We aimed especially at understanding the source of detrital carbonates in the Baumkirchen lacustrine sediments, which are commonly not represented in heavy mineral analysis.
4. Little bulk mineral composition data is available for the modern Inn river system of western Austria.
5. Heavy mineral analysis on clay-rich silt using standard optical microscopy methods is challenging and highly time consuming.

2. Study area

The Baumkirchen sequence is exposed in an abandoned clay pit (47.3066° N, 11.5692° E) between the villages of Baumkirchen and Fritzens near the southern rim of the Gnadenwald terrace on the northern side of the Inn Valley, around 12 km east of Innsbruck (Figs. 1B and C). In addition to the surface outcrops, a composite sequence of ca. 250 m of lacustrine sediments is known from four overlapping scientific drill cores from two nearby sites (Fig. 1C; see Barrett et al., 2017).

2.1 Regional geology

For the purpose of discussing the potential sources of sediment in the modern streams and rivers and to the Baumkirchen site, the catchment of the modern Inn river is considered. The Inn Valley is a major geological boundary between the carbonate-dominated Northern Calcareous Alps (NCA) to the north, and much more diverse mainly crystalline rocks to the south. The NCA are comprised of limestones and dolostones, and local occurrences of shales, carbonate-poor sandstones and evaporites. Although the NCA comprise a large area, most of the major streams and rivers flow north into the Alpine foreland rather than south into the Inn, and therefore the NCA make up only a small proportion of the total catchment area of the Inn. The region between Baumkirchen and Zirl (see Fig. 3), including the catchments of the Weißenbach (Hall Valley) and the Vomperbach (Vomperloch), is dominated by the Wetterstein Limestone with a minority of dolostone (mostly Hauptdolomit). Beyond Zirl, up to the western limit of the NCA, the dolostones of the Hauptdolomit are the dominant lithology in the catchment (in the vicinity of the Arlberg pass).

The majority of the Inn River catchment area lies south of the Inn Valley and the various sub-catchments are shown along with the bedrock geology in Figure 1A. The several relatively small valleys flowing north directly into the Inn Valley near Baumkirchen (termed VWW catchments) mostly drain quartzphyllite bedrock. To the southwest of Innsbruck, the catchments of the rivers Melach, Ötztaler Ache and Pitze drain large areas of gneiss, mica schists and some amphibolite. The Sill catchment south of Innsbruck is diverse: there are areas of quartzphyllite and gneiss, but also two large areas of carbonate-bearing crystalline rocks. To the west of the Sill river are several areas of low-grade metamorphic carbonates known as the Brenner Mesozoic, which are mostly dolostone (e.g. the Kalkkögel range), and to the east is a large area of mostly calc-schists and calc-phyllites. Lastly, the lower part of the upper Inn catchment drains gneisses and calc-schists as well as limestone and dolostone terrains of the NCA.

2.2 The Baumkirchen Palaeolake Sediments

The sequence of lacustrine sediments at the Baumkirchen site is comprised of 250 m of almost uninterrupted monotonous mm- to cm-scale laminated clayey silts. A simplified log (after Barrett et al., 2017) is shown in Figure 2 along with core photographs showing several examples of the sediment. Barrett et al. (2017) classified the laminae which make up the sequence as either "background" laminae comprised of fine silt with a minor clay matrix, and coarser "mS-S" laminae comprised of medium silt to fine sand with no clay matrix. These "mS-S" laminae are interpreted to represent both sub-annual higher-run-off events and less common slope-failure events, and are thus hereafter referred to as "event layers".

Barrett et al. (2017) also identified two lake phases on the basis of chronology corroborated by geochemical data suggesting different sediment compositions (different Ca and thus carbonate content). The lower lake phase (LP1) is constrained by luminescence dating and spans from ca. 77 to 55 ka. The base of the upper phase (LP2) is constrained to ca. 45 ka on the basis of luminescence ages and the top to ca. 33 ka cal BP on the basis of luminescence and radiocarbon ages. On the basis of the Baumkirchen sequence and other nearby drill cores and outcrops, the authors proposed a model of the sedimentary history of the central Inn Valley with the two lake phases representing two separate lake periods with different lake levels and likely different damming mechanisms (Fig. 1C).

3. Methods

3.1 Sample collection

The majority of the samples were taken from the Baumkirchen drill cores. Roughly 1 cm^3 was collected from discrete layers, or other rare and unusual layers. Samples of background and event layers were taken spaced throughout the sequence with several short sections being investigated in greater detail (Fig. 2 and SOM 2).

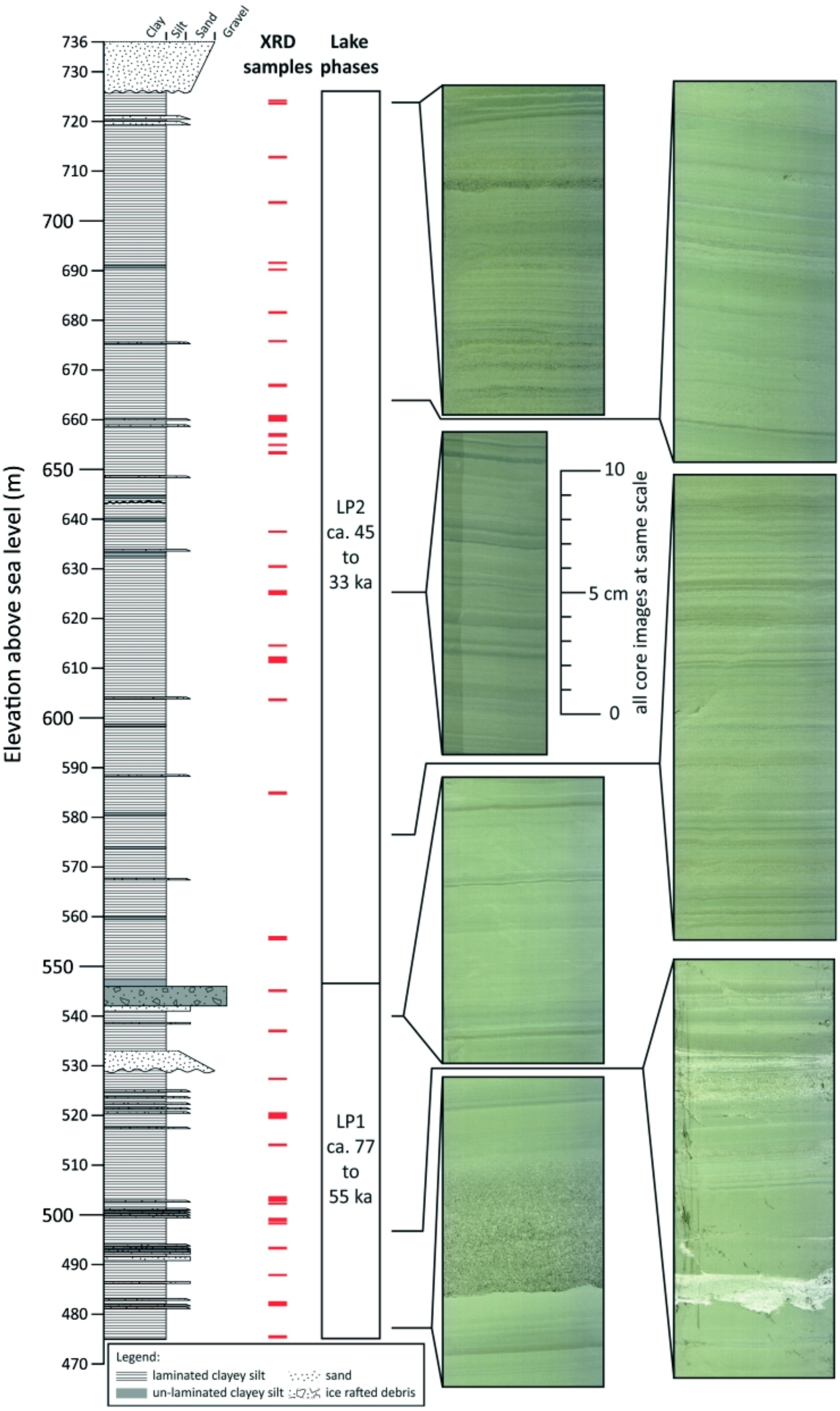

Figure 2: Simplified composite log of the Baumkirchen lacustrine sequence with lake phases indicated after Barrett et al. (2017). XRD sample depths and representative core photographs from throughout the sequence are also shown.

Samples of similar laminated lake sediments of pre-LGM age outcropping at several other locations in the central Inn Valley were also collected (Fig. 1B, SOM 1 & 2). Two locations in the suburbs of Innsbruck on the northern rim of the valley, where there is a subtle terrace of Quaternary deposits (Steinbruchstraße and Arzl), and from Weerberg ca. 7 km east of Baumkirchen in a prominent terrace on the southern rim of the valley (Fig. 1B).

For comparison in terms of potential sediment sources (i.e. modern rivers), sediments from a number of nearby rivers and streams (the Inn, Sill, Wattenbach, Weißenbach and Vomperbach) were sampled (Fig. 1B, SOM 1 & 2). Roughly 1 to 2 kg was collected in plastic bags from shoreline sandbars at the waterline. In several locations, multiple samples were taken in close proximity to assess small-scale heterogeneity.

3.2 Sample preparation and analysis

The mineralogical composition of selected samples from the drill cores, outcrops and modern sediments was investigated by powder X-ray diffraction (XRD). Several grams of air-dried sample material was ground in an agate or ceramic mortar and pestle and the powder mounted with ethanol on 2.2 x 2.2 cm² glass slides. Specimens were measured with a Bruker D8-Discover powder diffractometer. Powder patterns were recorded with Cu-radiation (40 kV, 40 mA) in Bragg-Brentano geometry with θ-2θ-coupling in the range between 2 and 70° 2θ with a step size of 0.01° 2θ and a measuring time of 1 s per step. The diffractometer is equipped with a primary-beam Ge-monochromator and a LYNXEYETM silicon strip detector. Calculation of the quantitative phase composition via Rietveld refinement using the fundamental parameter approach was carried out with the TOPAS software version 4.2 (Bruker-AXS, 2009). For minerals with very low abundances (e.g. actinolite) refinement was not carried out unless a corresponding peak could be seen in the diffraction spectra. Several slides prepared from the same ground samples were measured to determine the combined preparation, measurement and refinement uncertainty. Four modern samples were repeated (prepared, measured and quantified) three times each (INN3-1, INN2-3, INN3-3, SILL1-C2) and two samples from the Baumkirchen cores were repeated five times each (BK3-19-82cm-BG-A an BK3-19-86cm-C).

4. Results

4.1 Uncertainties

Table 1 shows the uncertainties calculated from the replicate samples. The Baumkirchen samples have a systematically higher precision than the modern samples, and the finer samples

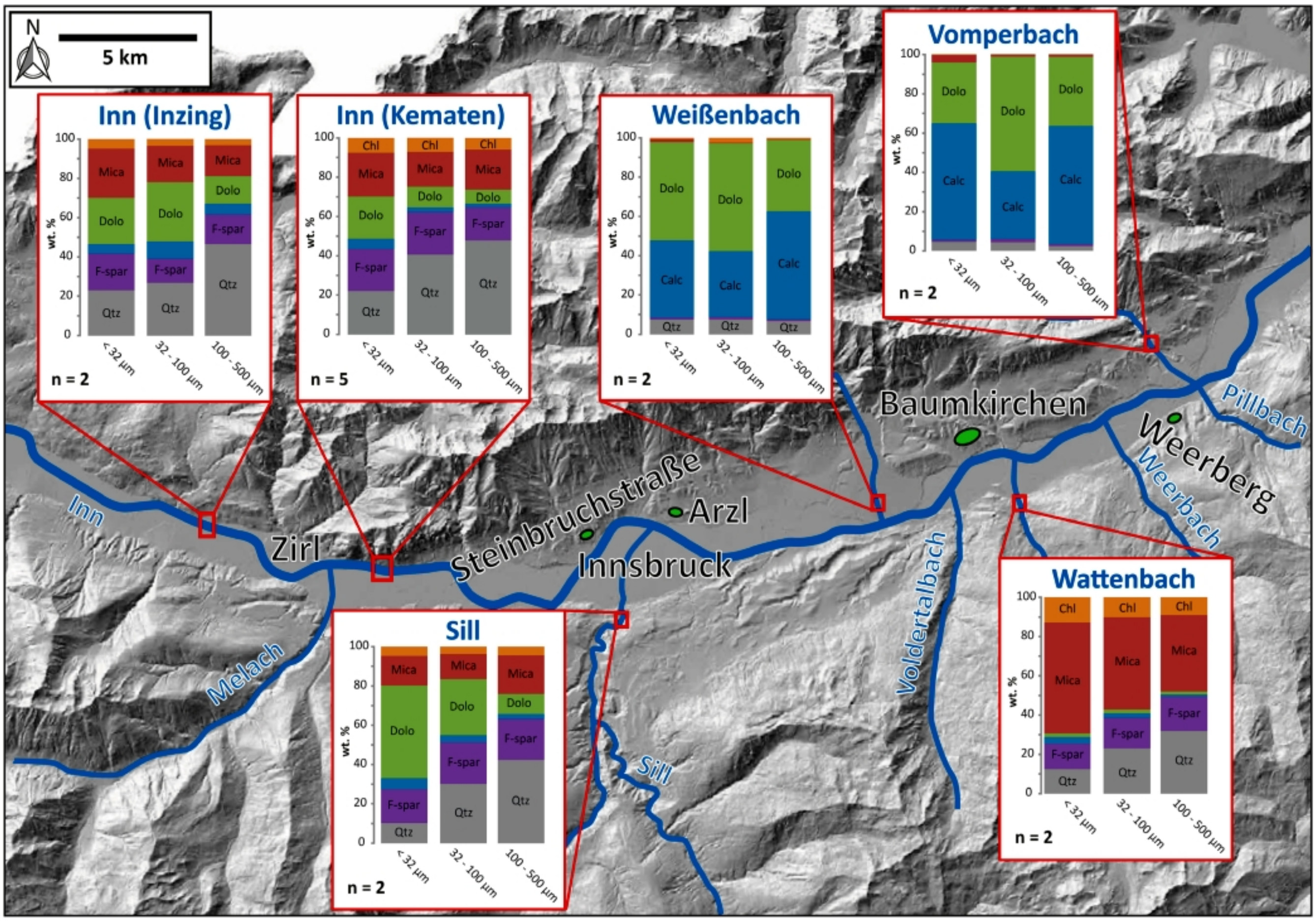

Figure 3: Mineralogical composition of modern stream and river sediments by grain-size fraction. Chl = chlorite, Dolo = dolomite, Calc = calcite, F-spar = feldspars (albite + orthoclase), Qtz = quartz. Base map: TIRIS hillshade.

(both modern sieved to <32 µm and the unsieved background samples from the Baumkirchen cores) have a systematically higher precision than the coarser samples. The effect of grain size on precision may be analogous to the effect of grain size on the precision of grain-size measurements, where larger coarse-grained samples are required to attain the same precision as finer-grained samples due to the reduced number of grains being sampled (e.g. Rawle, 2015).

4.2 Modern samples

Figure 3 shows the average mineralogy of the modern sediment samples by site and grain-size fraction. The results from the Inn at both Kematen and Inzing are mineralogically diverse, and there is a little less carbonate (dolomite in particular) in the intermediate and coarse fractions at Kematen. The Sill sediments are similar to those from the Inn except with a strong grain-size dependent change in dolomite vs quartz with around 50 % dolomite in the <32 µm fraction. Calcite is found in both the Sill and Inn sediments, however, is always less than 10 % and mostly around only a few percent; the dolomite/calcite ratio is always strongly in favour of dolomite (2.5 – 5 in the Inn and 3.5 to 8.5 in the Sill).

The local streams closer to the Baumkirchen site, with much smaller catchment areas, have distinct and less diverse compositions. Unsurprisingly, the Weißenbach and Vomperbach (both draining only the NCA) sediments are comprised almost entirely of carbonates with a minor quartz fraction. There is no clear grain-size dependent change in the mineral distributions in either stream. In contrast to the dolomite/calcite ratio from the Sill and Inn, they are close to parity being between 0.5 and 1.7. In contrast, the Wattenbach draining the Tux Alps to the south contains almost no carbonate (despite some metamorphic carbonate rocks being present near the head of this valley) and is dominated by mica. There is a strong grain-size dependence in the mica and quartz components with quartz increasing with increasing grain size.

Figure 4 shows the degree of uncertainty due to local heterogeneity. At the Kematen site, the variance is lowest for quartz, while for dolomite and micas there is a much higher variance in the fine-grain-size fraction between nearby sites. The uncertainty also shows that some differences between the two sites are significant (e.g. 32 – 100 µm fraction for both quartz and dolomite), while others are not (e.g. <32 µm for mica). For example, the difference in the average dolomite content of the finest (<32 µm) fraction between the two sites is much smaller than the internal variance (represented by the standard devination) at Kematen. In contrast, the differences in the intermediate (32 - 100 µm) and coarse (100 - 500 µm) fractions are significantly higher than the uncertainty from local heterogeneity.

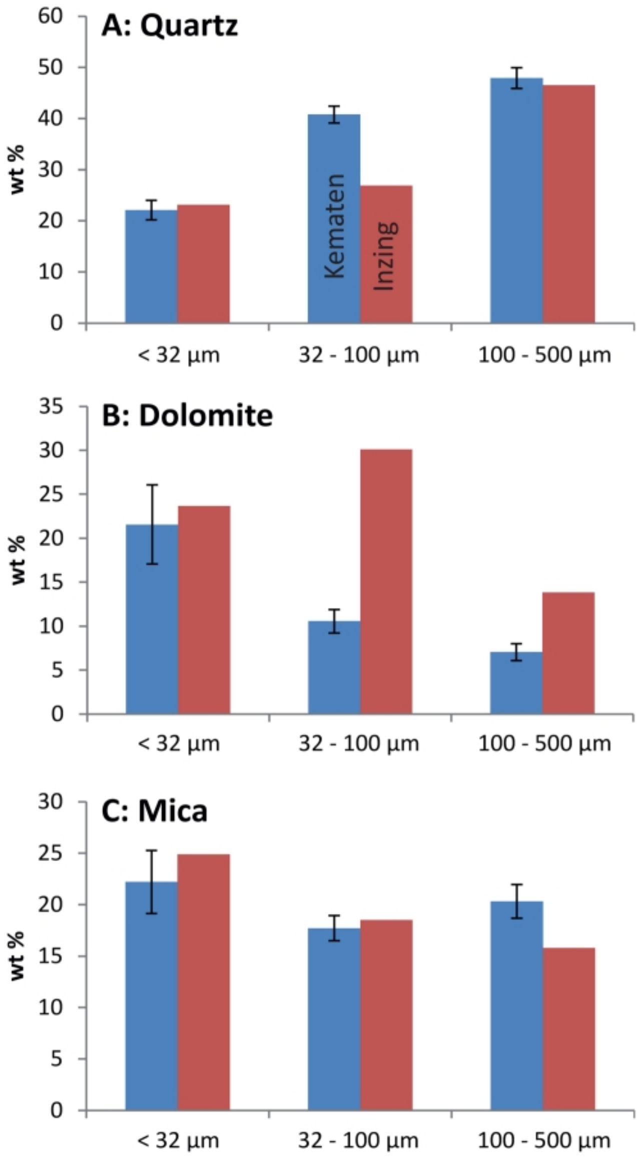

Figure 4: Average mineralogical composition of modern Inn river sediments at two sites with standard deviation of Kematen samples (n=5) to show local heterogeneity and ability to determine significant differences.

	Standard Deviation (wt.-%)								
	Quartz	Muscovite	Calcite	Dolomite	Albite	Orthoclase	Chlorite	Actinolite	Annite
Baumkirchen samples	1.40	1.20	0.21	0.72	0.92	0.99	0.44	0.69	1.11
Modern samples	2.59	1.29	0.58	1.25	1.35	1.17	0.79	0.82	0.99
Background or < 32µm	0.60	1.06	0.35	0.76	0.92	0.95	0.49	0.63	0.60
Event or > 32 µm	2.62	1.34	0.50	1.17	1.29	1.16	0.73	0.83	1.22
All	**2.09**	**1.22**	**0.44**	**1.02**	**1.15**	**1.07**	**0.64**	**0.74**	**1.02**

Table 1: Precision of XRD mineral phase analysis for each mineral, and sediment and sample type.

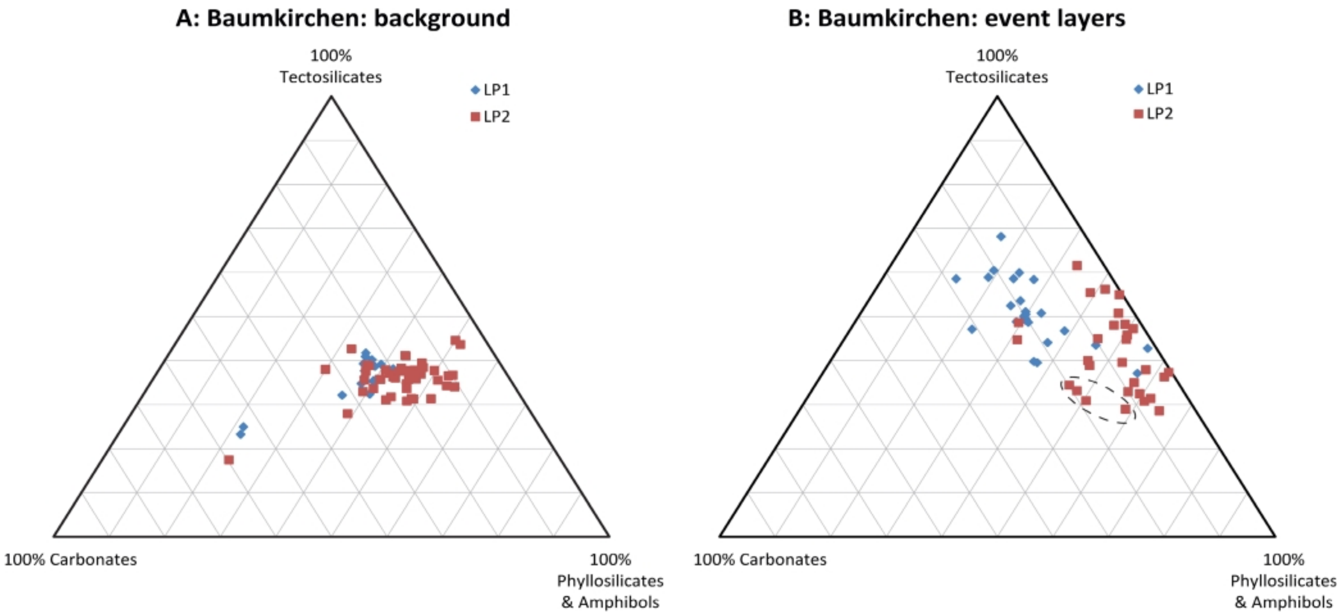

Figure 5: Mineralogical composition of lake phases 1 and 2 from background (A) and event (B) layers from the Baumkirchen sequence. The dashed circle in B indicates the four highest samples in LP2 (from within the top 50 m).

4.3 Baumkirchen samples

The Baumkirchen data set for both the background and event layer samples is split into LP 1 and LP 2 after Barrett et al. (2017). The majority of the background samples from both lake phases form a tight cluster around 40 - 50 % phyllosilicates, 10 - 30 % carbonates and 30 - 40 % tectosilicates (Fig. 5A). The LP1 samples are slightly offset towards higher carbonate proportions, but still overlap with the LP2 samples. The three outliers with 50 - 60 % carbonate are a distinct type of layer, similar in grain-size to the background laminae, but being of beige or cream (rather than grey) colour.

The event layer results are much more scattered and there are significant differences between the clusters of the two lake phases (Fig. 5B). LP2 clusters mostly below 10 % carbonates with variations in the phyllosilicate content mostly between 40 and 60 %. The LP1 cluster is offset from LP2, mostly in having more carbonate (generally 15 - 25 %), and slightly more tectosilicates. However, there are outliers of LP1 lying in the LP2 cluster, and vice versa. While there is generally no observed pattern with depth within the lake phases, the four highest samples from the top 50 m of the sequence (labelled in Fig. 5B) show slightly higher carbonate contents than the

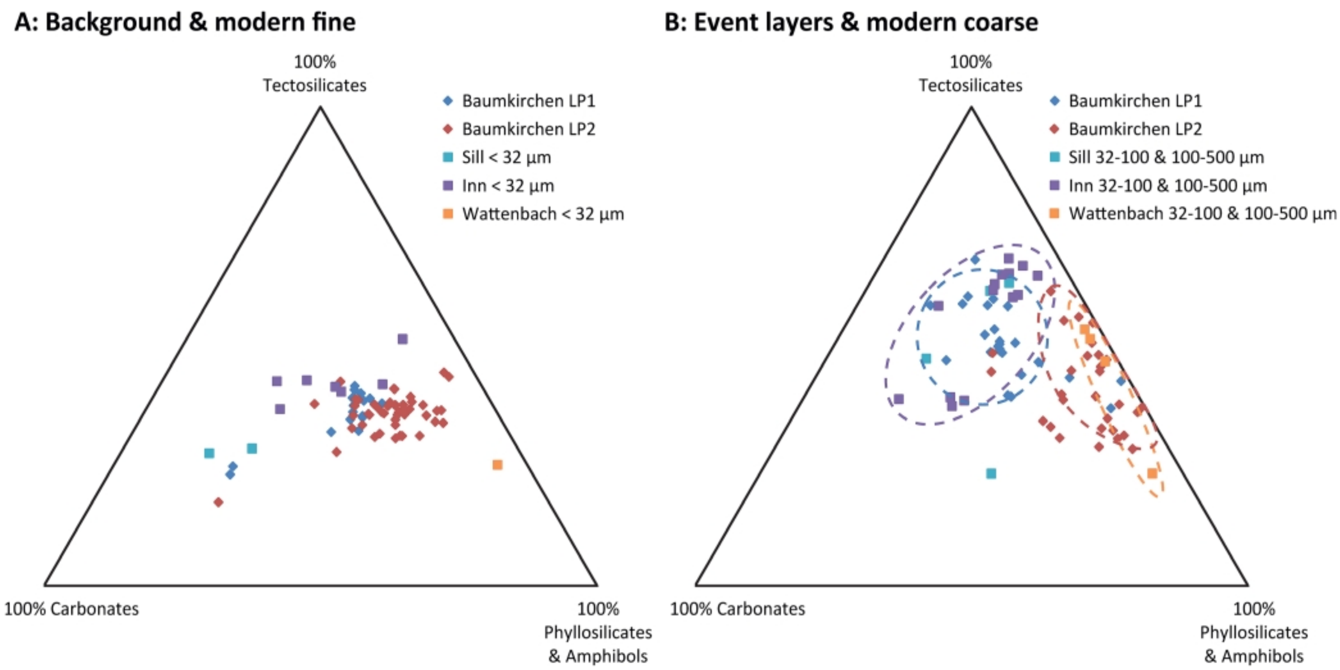

Figure 6: Mineralogical composition of Baumkirchen samples by sediment type and lake phase compared to modern river samples by grain-size. Dotted ellipses indicate clusters of data points.

main LP2 cluster.

These data are compared with the modern stream data in Figure 6. The main cluster of background compositions (Fig. 6A) is intermediate between the Inn and Wattenbach fine sediment (< 32 µm) values, although much closer to those from the Inn. The event layers from LP1 cluster in the same range as the medium to coarse (32 - 100 and 100 - 500 µm) samples from the Inn and Sill, while the LP2 cluster mostly overlaps with the Wattenbach cluster.

The proportion of calcite and dolomite in the samples from each lake phase is shown in Figure 7. With the exception of four outliers (excluded from plot), there is a positive correlation between calcite and dolomite. The LP2 data mainly has a dolomite/calcite ratio of between 1 and 2 while the LP1 data is almost all above 2. Figure 7B shows the entire Baumkirchen data set compared with the modern data from the Sill, Inn and NCA stream sediments. The Inn and Sill data has a positive correlation between calcite and dolomite; however, the ratio is extremely high compared to the Baumkirchen data, being greater than 3. The NCA samples show a negative correlation, because carbonates dominate the mineralogical composition of these; however, the proportion of calcite in both absolute and relative terms is significantly greater than in the Baumkirchen samples or other modern river samples.

4.4 Other sites

The majority of the samples from the three sites of Arzl, Steinbruchstraße and Weerberg all cluster closely around the same range as the background data from Baumkirchen: around 25 % carbonate and 40 % phyllosilicates (Fig. 8). The group of outliers (mostly from Weerberg) above 50 % tectosilicates are all sandy layers, and the only other outlier, which is very rich in carbonate (55 %), is from a distinctively white/cream layer at the locality Steinbruchstraße, probably of the same nature as the similar layers from the Baumkirchen sequence (see above).

5. Discussion

5.1 Comparison with previous work at Baumkirchen

The samples analysed by Horvacki (1982) roughly correspond to those from the drilled Baumkirchen sequence between ca. 660 and 676 m a.s.l. However, while there is a similar degree of scatter (excluding the outlying rare carbonate rich layers (see above)) between Horvacki's Baumkirchen data and that from the present study (SOM 3), there is an offset: Horvacki's data is systematically around 20 to 30 % higher in phyllosilicates. This offset is likely due to the now obsolete methods used by Horvacki, i.e. semi-quantitative comparison of isolated peaks of a narrow portion of the XRD spectrum

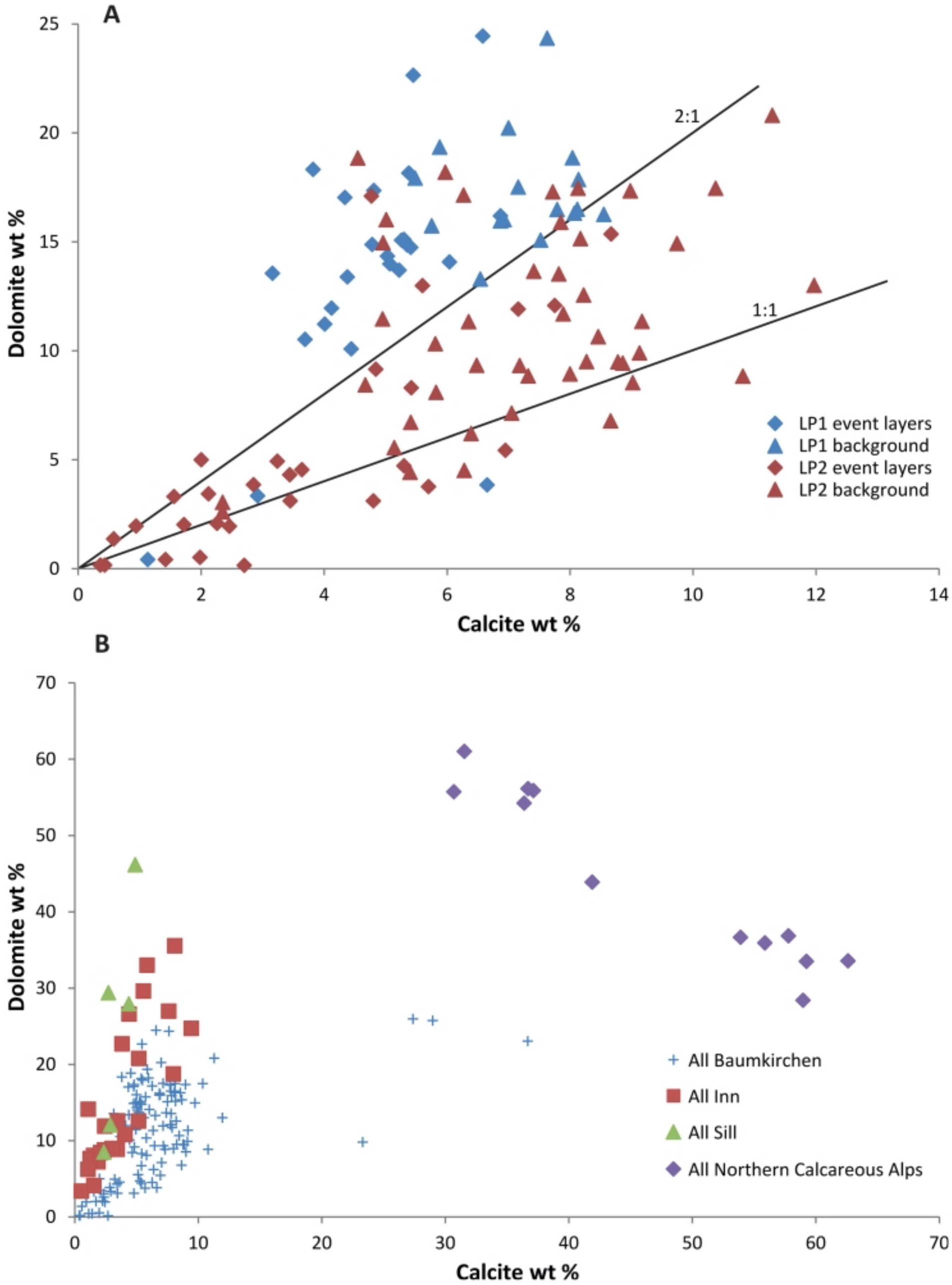

Figure 7: Dolomite and calcite data for A: Baumkirchen samples split by lake phase and sediment type. Lines indicating dolomite to calcite ratios of 1:1 and 2:1 are shown for reference. B: Baumkirchen samples compared with modern river sediment samples.

rather than the analysis of the entire, broader spectrum by Rietveld refinement (Bish and Howard, 1988). The relationships within the Horvacki data set may, however, still be significant. For example, the Arzl data is offset towards less phyllosilicates in both the Horvacki data and the data in this study (SOM 3 & Fig. 8).

5.2 Modern samples

The diversity of the Inn sediments is expected on the basis of the diverse geology of the catchment of this large river. The very high dolomite/calcite ratio is expected as the NCA in the upper Inn catchment (west of Zirl) is mostly dolostone of the Haupdolomit Formation (e.g., Brandner, 1980; Schubert et al., 2003; Schuster et al., 2013). The reduced proportion of carbonates, especially dolomite, in the Inn sediments at Kematen compared to Inzing may be due to dilution of the Inn sediment by input from the Melach. This is likely as the dilution appears to be due to an increased proportion of quartz which is to be expected from the entirely non-carbonate crystalline Melach catchment.

Despite the much smaller catchment of the Sill compared to the upper Inn, the similar diversity of the mineralogical composition of the Sill sediments is also expected based on the diverse geology of the catchment. The high proportion of quartz in the coarse fraction likely comes from the nearby Innsbruck Quartzphyllite and the more distant but significantly more extensive gneisses. The extremely large proportion of dolomite in the finest fraction, along with the lack of calcite, is harder to explain. Carbonate bedrock makes up only ca. 31 % of the total catchment area with over half (ca. 18 % of the total catchment) being calc-schists (containing calcite rather than dolomite) and the remainder (ca. 13 % of the total catchment) being the mostly dolomitic metamorphic carbonates of the Brenner Mesozoic. Thus there appears to be a significant overrepresentation of dolomite and underrepresentation of calcite in the finest sediment fraction compared to the catchment geology. Much of the research on the relationship between stream sediments and catchment geology has focused on the sand fraction of river sediments, and is thus not directly applicable to the production of finer sediment by different lithologies. However, two general conclusions concerning the so-called "sand generation index" (Palomares and Arribas, 1993) are likely also applicable to other grain-size fractions: (1) that stream sediment composition is highly dependent on a number of properties of the rocks themselves including texture and grain size (e.g. the sand generation potentials of sparry vs micritic carbonates (Arribas and Tortosa, 2003) or granites vs schists (Vezzoli et al., 2004 and Palomares and Arribas) are quite different), and (2) that the composition is affected by catchment geography (e.g. relief and glacier extent - Vezzoli et al., 2004). Specifically concerning carbonates, Picard and McBride (2007) found that dolomite was overrepresented in the sand fraction compared to outcrop area in rivers draining the Italian Dolomites (although no explanation was offered). Thus, in this case, it is likely that the Brenner Mesozoic has a particularly high "silt generation index" compared to the rest of the catchment, particularly compared to the extensive gneisses which are likely to mainly produce quartz sand rather than silt (as seen in the higher proportion of quartz than dolomite in the sand fraction in the Sill). The particularly low calcite content is likely partially explained by it not being the dominant component in the calc-schists in contrast to the Brenner Mesozoic dolostones which are comprised almost entirely by dolomite. Furthermore, a significant proportion of material is removed from the Alps as dissolved rather than suspended river load (ca. 30 % for the Inn at Oberaudorf – Bavaria, Germany – Hinderer et al., 2013). Thus it is also possible that the higher dissolution rate of calcite compared to dolomite further contributes to the greater representation of dolomite than calcite.

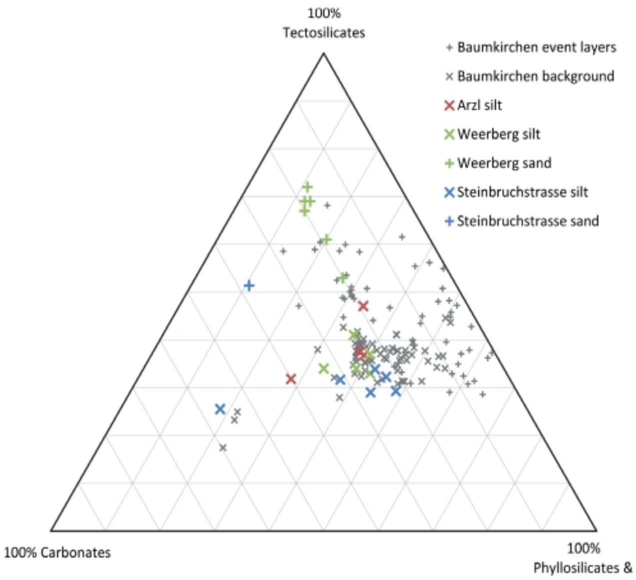

Figure 8: Mineralogical composition of Baumkirchen samples compared to those from other investigated sites.

The results from the Wattenbach confirm that while metamorphic carbonates constitute part of the upper catchment, the contribution from this to the total sediment delivered to the Inn Valley is negligible. The dominance of quartz and mica fit with the vast majority of the catchment being comprised of the Innsbruck Quartzphyllite. The grain-size dependent anti-correlation between these minerals is likely due to either transport processes (i.e. micas are more easily broken down than quartz), or a larger proportion of clay minerals included in the mica fraction which are small to begin with. As the geology of the nearby Voldertalbach and Weerbach catchments is essentially identical to that of the Wattenbach (although without metamorphic carbonates), it can be assumed that these other streams would provide sediments of a very similar composition (and thus the collective referencing of them as a single sediment source (VWW) is valid in this context).

The small amounts of quartz in the local NCA sediments, especially in the Weißenbach, are attributable to the sandstones which occur locally in the area as well as the non-carbonate component of the Hauptdolomit (Fruth and Scherreiks, 1982, report non-carbonate components of the Hauptdolomit in the nearby Seefeld area as ranging from 1 to 4 wt.-%). Considering the geology of both catchments, the relatively large proportion of dolomite is surprising. While the dolomite/calcite ratio in the stream sediments varies between 0.5 and 1.7 (depending on the stream and grain-size fraction), the Hauptdolomit/Wetterstein Limestone ratio in both catchments is less than 0.5 (data based on Moser, 2008a, 2008b). Dolomite is thus apparently being systematically overrepresented. This phenomenon has also been observed on a larger scale in the sand fraction (i.e. considering larger rivers and catchment areas) in the Italian Dolomites by Picard and McBride (2007). In contrast, Arribas and Tortosa (2003) found an underrepresentation of dolomite in the sand fraction compared to outcrop area in a dominantly sedimentary area of Spain, although they noted that the potential of source rocks to produce sediment (sand in particular) was highly dependent on source rock petrography (specifically in this context, as stated above, regarding spary vs micritic carbonates). Furthermore, dolomitisation reduces rock strength and resistance to abrasion relative to limestone (Thiel and Lathram, 1946). Thus, it is likely that this overrepresentation of dolomite is largely caused by the petrographic properties of the source rocks in the catchment and their potential for producing sediment of different grain sizes. It is also possible on the small scale of our study that local differences in the geography of the catchments (e.g. more scree slopes in dolostone areas) contribute to this discrepancy.

5.3 Sediment provenance

The wide spread of the results as a whole, and between the event and background laminae in particular, confirm the findings of Barrett et al. (2017) that the Baumkirchen sediment is rather heterogeneous on the scale of individual laminae. Furthermore, the spread and clustered pattern of the event layer data in particular (Fig. 6) suggests that the differences may be attributable to different sediment sources. As these clusters overlap well with the Inn/Sill and Wattenbach sediment data, it appears that most of the event layers in the Baumkirchen sequence can be described in terms of coming from either of these sources. The distribution of event layer composition, and thus source, also gives an insight into the relative importance of sediment sources in the different lake phases. LP1 appears to be strongly dominated by event layers derived from the Inn/Sill, while the lower LP2 is dominated by those originating largely from the Wattenbach (and thus any of the VWW catchments). The occurrence of several outliers in each lake phase which cluster amongst those from the other phase indicates that the sediment source from these event layers are not exclusively from one source or another during each lake phase and rather, that the situation is one of relative dominance. The composition of the uppermost LP2 event layer samples (spanning the top ca. 50 m of the sequence) is similar but not identical to that of the majority of the LP2 cluster, and so these may either simply be attributable to the local VWW sediment source, but the slightly higher carbonate content indicating a degree of mixing with sediment from the Inn or possibly local NCA sources.

While the event layers of LP2 may largely be coming from

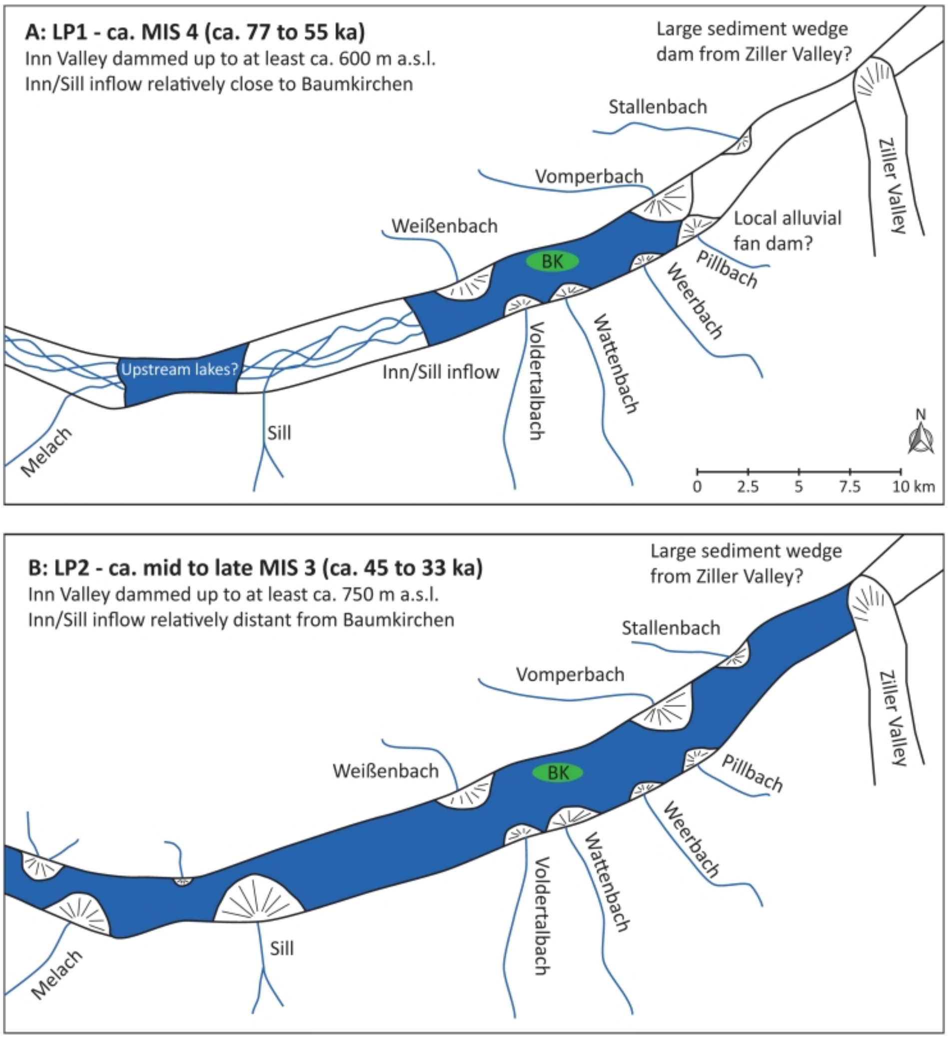

Figure 9: Palaeogeographical sketch of possible situations during lake phases 1 and 2 to explain the observed patterns in sediment composition.

the VWW catchments, the presence of a significant carbonate component in the background sediment indicates that the sediment cannot be derived from the VWW area alone. As the Baumkirchen record is so long and located in the axial zone of the Inn Valley (when considering also the terrace of Gnadenwald), it is unlikely that the palaeo-Inn (including the Sill) could by-pass the lake and not flow into it. Thus, the Inn was almost certainly a major contributor to the background sediment. While the local NCA catchments would also have drained into the lake, they are relatively small, and the lack of coarse (event layer) material from the North suggests that these streams were not significant sediment sources. Also, in LP2, the extremely high sedimentation rate of at least several cm per year (Barrett et al., (2017) and references therein) would be extraordinary from such a small catchment area. The composition of the background sediments from all lake phases are similar to those of the modern Inn sediments. The small offset towards phyllosilicates may be explained by a minor component coming from the VWW catchments. The slight shift away from phyllosilicates and towards carbonates in the LP1 may be explained as a minor shift in the dominant sediment source from the VWW to the Inn.

A major challenge to this explanation for the source of the background sediments is the difference in the calcite content of the Baumkirchen sequence vs the modern Inn and Sill sediments. The significantly lower dolomite/calcite ratio (i.e. more calcite) in the Baumkirchen sequence, and in LP2 in particular, is difficult to explain. A significant sediment input from the NCA is unlikely for the reasons outlined above, although the lower dolomite/calcite ratio could explain the difference, at least in part. One tempting possibility is that the additional calcite is endogenic, i.e. formed in the lake. However, the strong positive correlation between dolomite and calcite strongly suggests that there is no significant endogenic calcite component, and investigation of thin sections (S. Barrett, unpublished data) has not revealed any evidence of endogenic calcite. Likewise, bulk stable isotope analysis of Baumkirchen sediments failed to provide evidence for a significant proportion of non-detrital calcite (S. Barrett and C. Spötl, unpublished data). Also, as the majority of the sediment is clastic, if a major portion of the calcite was endogenic, one might expect a negative correlation with sedimentation rate (after Barrett et al., 2017). Samples from LP1, however, which has a much lower sedimentation rate than LP2, have a higher dolomite component but a similar calcite component compared to LP2. A final possibility is that the grain-size distribution of calcite and dolomite within the fine (<32 µm) fraction of the modern Inn sediments is not identical to that in the Baumkirchen samples. If the dolomite was concentrated in the medium to coarse silt fractions, and the calcite in the fine silt and finer fractions, the background, which is mainly comprised of fine silt and finer, may contain a greater proportion of calcite than the entire <32 µm fraction. In other words, the modern sample <32 µm fraction may then not be directly comparable to the Baumkirchen background sediment.

The majority of the sediments from the other sites (Arzl, Steinbruchstraße and Weerberg) are background rather than event-layers sediments, and their similarity (Fig. 8) to the background samples from Baumkirchen further suggests that the background sediment in general is derived from the Inn rather than any local sediment source.

The significance of the small shift in event layer composition in the uppermost ca. 50 m of LP2 is unclear. Barrett et al. (2017) also noted a gradual increase in Ca concentration in the sediment in general (i.e. heavily weighted towards background composition) in this upper section. In this way, there appears to be a similarity to LP1. However, while the carbonate composition of the event layers is similar to that in LP1, there is a significant difference in the tecto- and phyllosilicate fractions (LP1 event layers have more tectosilicates at the expense of phyllosilicates). Thus, the situation is not simply a repeat of that existing during LP1. Furthermore, Barrett et al. (2017) report significantly higher sedimentation rates during LP2 than LP1, especially in the uppermost section, dissuading any direct comparison. As the transition appears to be gradual on the basis of the Ca data , the changes seen in the uppermost part of LP2 are a gradual variation on the theme of LP2 in general, rather than a distinctly different situation like between LP1 and LP2. The gradual change in sediment composition therefore was more likely caused by changes in sediment transport due to basin filling, or some climatic effect. For example, a less humid climate may shift the balance of sediment delivery away from small local catchments to the larger Inn/Sill catchments.

5.4 Palaeogeography

The above observations and conclusions about the sediment sources allow some information about the palaeogeography of the Inn Valley prior to the LGM to be deduced.

The fine-grained carbonate component in the background sediment of all lake phases at Baumkirchen appears to be derived from the Inn. Thus, the Inn drained into the lake during all lake phases. The apparently Inn and Sill-derived event layers in LP1 indicate that the distance between Baumkirchen and the inflow of the Inn/Sill was relatively short during this period. The low abundance of such event layers during LP2 implies that the inflow of the Inn/Sill was much further away. However, the occasional occurrence of Inn and Sill-derived event layers indicates that there was no major barrier to coarse (silt to sand) sediment delivery such as trapping in separate up-stream lakes. A representation of the possible situation is shown in Figure 9.

Although their precise age is not known, the sediments from Steinbruchstraße and Arzl provide an opportunity to test an aspect of this model. As the phyllosilicate-rich event layers at Baumkirchen are assumed to largely originate from the VWW catchements, such event layers would not be expected at the upstream sites near Innsbruck today. Unfortunately, few of the samples were targeted at the event layers at these sites, but several sandy layers were included. As all of these plot as relatively tectosilicate- or carbonate-rich compared to the background sediment, and thus lacking any significant fraction of VWW derived phyllosilicates, the prediction is fulfilled. The origin of the tectosilicate-rich sands from Weerberg is unclear. The quartz could easily originate from the Innsbruck Quartzphyllite (from the VWW catchments). However, one would also expect some phyllosilicates, and very little carbonate, but to the contrary they all contain > 15 % carbonate.

The relatively distant inflow from the Inn/Sill during LP2 implies a large lake. While age control is lacking, lake sediments are known from various sites upstream of Innsbruck (Horvacki, 1982) and there are pre-LGM delta complexes from the palaeo-Melach indicating the presence of a lake (Poscher & Lelkes-Felvári, 1999). As separate up-stream lakes seem unlikely as they would to some extent block Inn sediment from reaching the Baumkirchen lake, this evidence of the presence of a lake upstream of suggests a rather large, fjord-like lake.

The question of damming remains elusive. Along with the above evidence, the large distance from the Inn inflow to Baumkirchen during LP2 implies the fjord-like lake scenario, which would require a single large dam downstream of Baumkirchen. The most likely candidate is a sediment body (e.g. alluvial fan) at the confluence of the Inn and Ziller Valleys. The clastic sediments damming the Achensee against the Inn Valley, although currently undated, are derived from the south (Poscher, 1994) and may have been part of a much larger sediment body crossing the Inn Valley prior to the LGM. The shorter distance during LP1 suggests something closer to the local alluvial fan model, and therefore, it is possible that the damming mechanism is different than in LP2. The alluvial fans of Pillbach and Vomperloch are possible candidates, the latter containing pre-LGM delta gravels (Scholz and Köhler, 2006). Alternatively, the LP1 lake may have largely existed due to glacial overdeepening, although this explanation does not account for LP2.

6. Conclusions

The modern stream data corresponds well to expectations based on catchment geology, with a correlation between quartz fraction and grain size in all the non-NCA catchments. The only major discrepancies are the apparent overrepresentation of dolomite in the NCA stream sediments and in the finer fractions of the Sill sediments (with respect to the catchment geology), both of which are likely partially or completely explained by differences in the sediment generation potential of the source rocks. Together there are three mineralogically distinct sources: (i) the compositionally diverse Sill and Inn, (ii) the mica and quartz-rich and carbonate-poor southern catchments (Wattenbach), and (iii) the NCA catchments composed almost entirely of carbonates.

The data shows significant heterogeneity in the Baumkirchen sediment on the lamina scale. However, there is a distinct pattern for the event layers which form two compositional clusters closely overlapping with the Inn/Sill and Wattenbach/VWW modern stream data. The background laminae correspond to an Inn/Sill source throughout the sequence. The event layers corresponding to an Inn/Sill source are significantly more common in LP1, while those corresponding to a local Wattenbach source are dominant in LP2. The composition of the background sediments appears to suggest a major source of fine material from the Sill/Inn during both lake phases. Together, these observations indicate a change in the lake/ catchment configuration between LP1 and 2. This further confirms that the two lake phases, which are known to be separate in time, are also distinct in terms of their catchment and lake configuration. In the proposed model, the Inn/Sill flows into the lake during both lake phases, but the inflow from the Inn/Sill is significantly closer to Baumkirchen during LP1 compared to LP2. The question of lake damming remains to be conclusively answered, but these new data and interpretations support the suggestion of Barrett et al. (2017) regarding the possibility of different damming mechanisms in each lake phase.

The subtle and gradual changes in sediment geochemistry and mineralogy in the uppermost part of LP2 compared to LP2 in general point to a gradual process as the cause. A change in sediment delivery due to basin filling or climate change is plausible.

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