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High-altitude erratics in the Bernese Alps (Switzerland)

Christian Gnägi · Christian Schlüchter

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Abstract Little is known about the Early Pleistocene landscape and glacial history of the Swiss Alps, largely because of the scarcity of sediments dating from that period. Here we investigate high-altitude, presumably Early Pleistocene relics of unconsolidated, near-surface sediments that occur at the Stockeseen site (close to the Stockhorn) and at Wagenmoos (close to Sibe Hängste) in the Bernese Alps. We complemented our study by analysing cave gravels from 13 sites. Whereas the underlying bedrocks are part of the purely sedimentary Penninic Prealps and the Helvetic zone, the investigated sediments and cave gravels contain characteristic erratic crystalline clasts (HP-LT-metagabbro, medium-grade metamorphic quartzite, jadeitite, glaucophane-schist, low-grade metamorphic gabbro and peridotite). The erratics originate from Penninic and Austroalpine nappes which are exposed only south of the Bernese High Alps, today's water divide. In combination with partly distinct glacial features of the indicator erratics, this suggests that transfluences existed from the Valais (Rhône valley) to the Bernese Alps. Our findings suggest two transfluence routes, one over a precursor of the Gemmipass to the palaeo-Kander valley, providing crystalline erratics towards Sibe Hängste, and one over precursors of the Sanetschpass and Saanenmöserpass into the palaeo-Simmen valley and towards the Stockhorn. The Wagenmoos erratics must have been deposited before the re-routing of the palaeo-Aare river (from northward to westward) and its subsequent deepening, which indicates an Early Pleistocene timing of the respective transfluence. This is in agreement with published burial ages of ~1.87 Ma ± 0.21 for cave gravels with crystalline components in the cave system Réseau Siebenhengste–Hohgant (beneath the Wagenmoos site).

Keywords Early Pleistocene · Glaciation · Transfluence · Sibe Hängste · Nieder-Simmental · Valais glacier

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C. Gnägi (✉)
Länggasse 7, 3360 Herzogenbuchsee, Switzerland
e-mail: christian.gnaegi@weg-punkt.ch

C. Schlüchter
Institut für Geologie, Universität Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland

1 Introduction

During the middle and late Pleistocene, landscape evolution in the northern Swiss Alps was characterised by strong erosion as a result of increasing glacial impact (Häuselmann et al. 2007; Valla et al. 2011). It has been suggested that while the valleys were incised, high-altitude areas were more preserved from erosion. Hence, Early Pleistocene sediments are scarce and information about former landscape evolution is fragmentary (Schlüchter 2004). There is often a hiatus in sediment deposition between the Sundgau gravel (youngest Pliocene deposits) and the widespread sediments of the last two glacial cycles. Over time, however, several outcrops of high-altitude erratics alongside the northern margin of the Penninic Prealps and the Helvetic nappes have been reported (mostly orally). Already more than 40 years ago, Nussbaum (1946) and Minet (1971) mentioned erratic crystalline clasts near Stockhorn and Sibe Hängste in the Bernese Alps (Fig. 1b), although the outcrops were not investigated in detail. Furthermore, researchers and speleologists have also reported and collected crystalline pebbles from the cave system "Réseau Siebenhengste-Hohgant" (Fig. 1b, see

Jeannin (1991). Similar cave deposits have been documented from other sites in the Bernese Alps (Chilchli-Höhle, Ranggiloch) by Andrist et al. (1964), as well as by speleologists from the Sulzfluh-Höhlen (Wildberger 1996) and the Furgglen-Höhle (Merz 1993), ca. 200 km further east (Fig. 1a). The sedimentary bedrock of these caves implies that cave gravels partly originate from near-surface sediments that are and were washed down into the caves. A recent cave evolution study using cosmogenic nuclides yielded a burial age estimate of 1.87 Ma ± 0.21 for the oldest cave gravel with crystalline pebbles from the Réseau Siebenhengste-Hohgant (cave A201 in Häuselmann et al. 2007). These findings not only suggest that remnants of Early Pleistocene sediments can be preserved in karst areas at high altitudes (1,550–2,300 m a.s.l.), but also that the erratic nature of the crystalline pebbles might also provide valuable information about provenances and former landscape evolution.

Due to the very limited extent and volume of the outcrops, the petrography, lithology and provenance of the erratic sediments have remained controversial. The deposits were considered as either of glacial origin (Nussbaum 1946; Jeannin 1991) or as relicts of flysch or as remnants of eroded nappes (Wildberger 1996). Nussbaum (1946) suggested a transfluence of the Valais glacier from the Swiss Plateau to the Bernese Alps (Figs. 1a, 2). In contrast Jeannin (1991) proposed an Aare glacier advance extending to the Sibe Hängste based upon a granitic clast reminiscent of the Mittagfluh granite (exposed in today's Aare catchment) from the Réseau Siebenhengste-Hohgant. However, the studied outcrops (1,550–1,870 m a.s.l.) are all located above the elevation of the proven maximal extension of the Quaternary Valais and Aare glaciers which is placed at 1,440 m along the southern border of the Swiss Plateau (Tercier 1928; Rutsch 1967).

Here we propose and discuss the scenario that the near-surface erratic sediments from the Nieder-Simmental and Sibe Hängste areas are also of Early Pleistocene age and document transfluences from the Valais glacier over passes

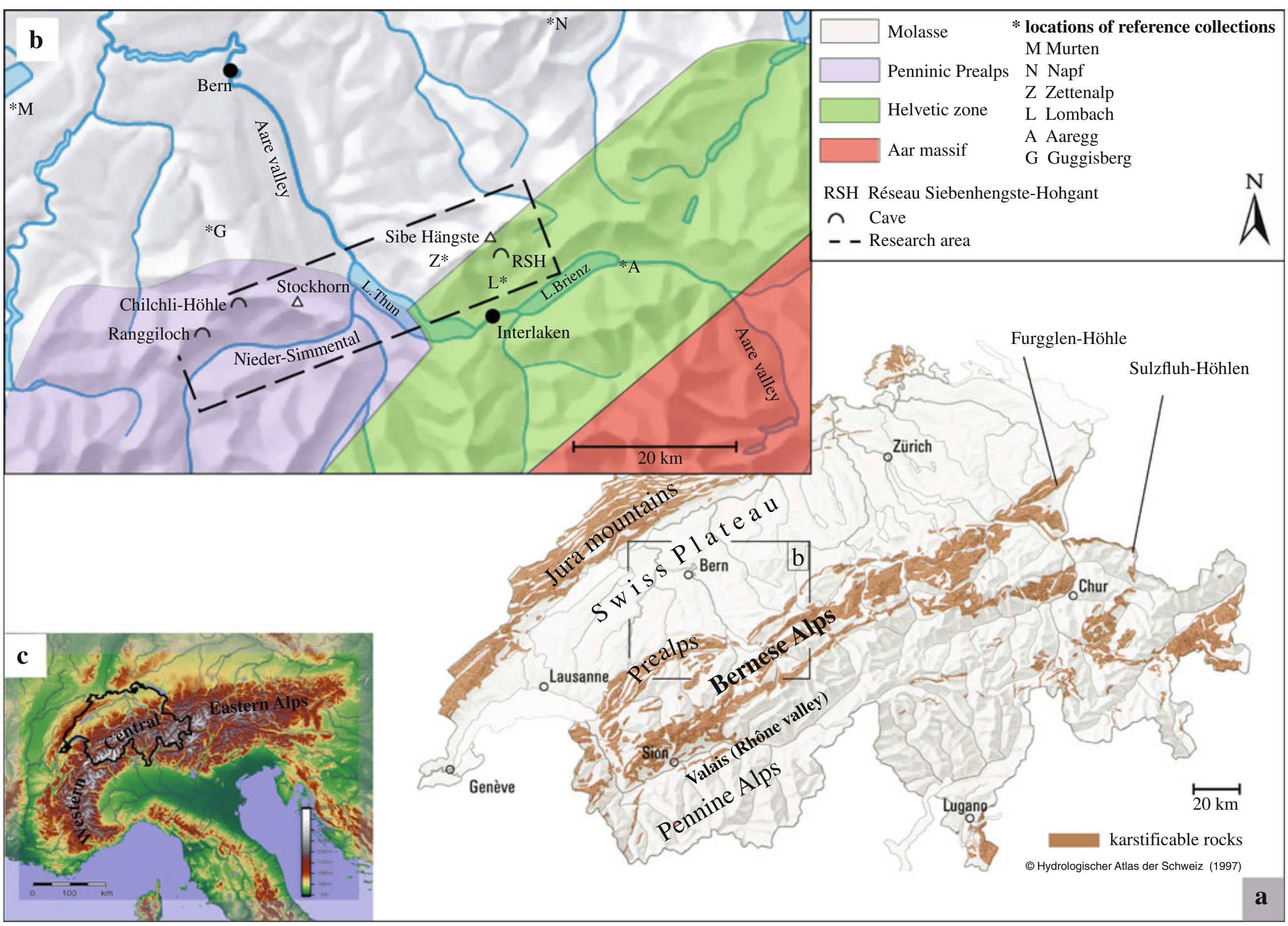

Fig. 1 **a** Extension of karstificable rocks in Switzerland and outcrops of high-altitude deposits containing clasts of crystalline rock (karst map from Dematteis et al. 1997). **b** Research area and sample localities of the reference collections. **c** Location of Switzerland within the Alpine arc (*map source*: http://de.wikipedia.org/wiki/Alpen)

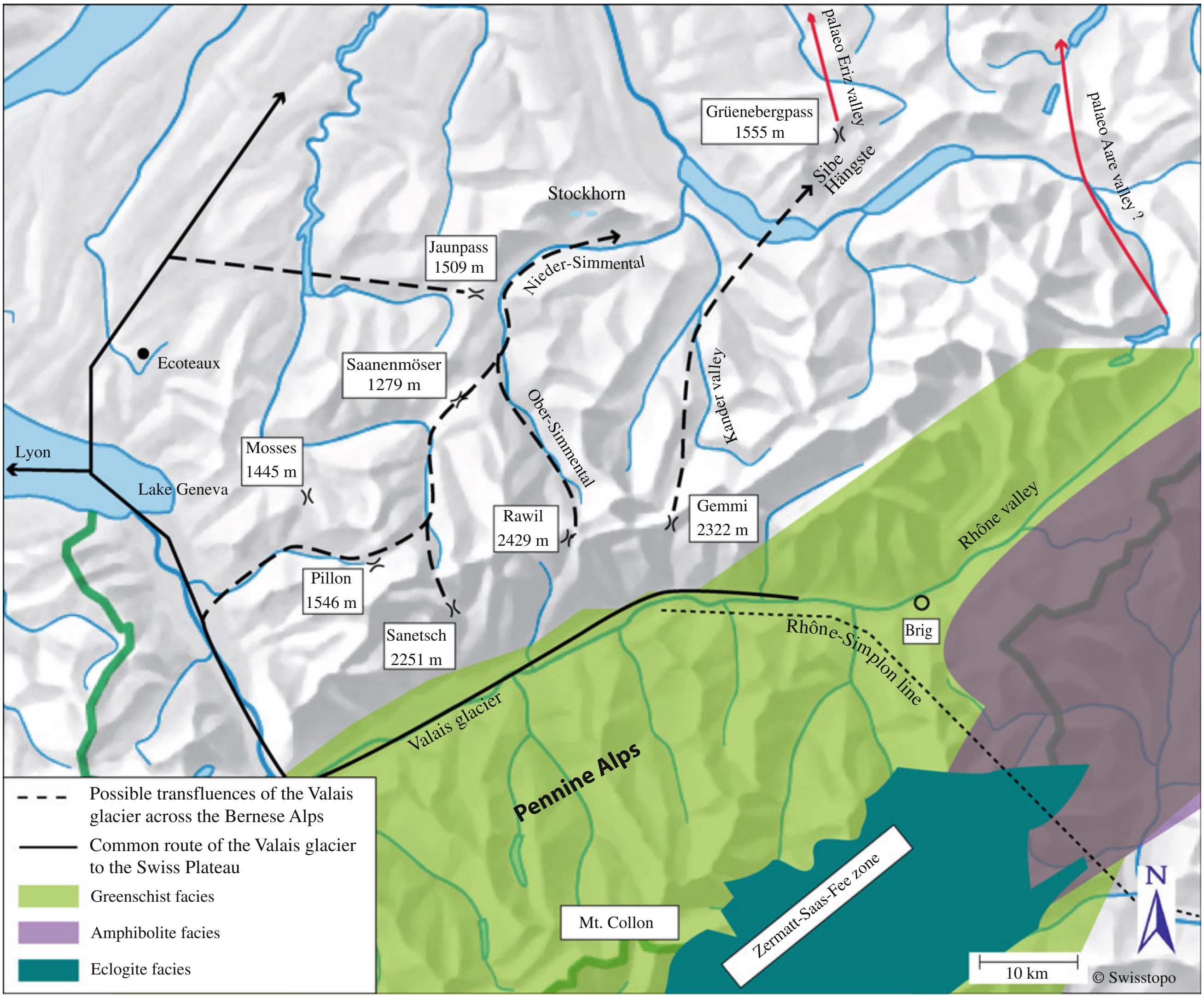

Fig. 2 Main route of the Valais glacier and possible transfluence passes across the Bernese Alps. Facies zones of Alpine metamorphism in the western Swiss Alps are coloured (facies zones according to Stampfli 2001): *no colour* indicates the area of very low-grade Alpine metamorphism. The facies zones evidence an increase in temperature from north to south. In the nappes north of the greenschist facies zone metamorphism reached uppermost anchizonal conditions (less than 300 °C). Only rocks in the catchment area of the Rhône river and its southern tributaries experienced more than 300 °C

across the Bernese Alps (Fig. 2). We present the results of new mapping and rock identification, and an analysis of facies and provenance.

2 Geological setting, sampling and methods

2.1 Geological setting

The northern Swiss Alps consist mainly of sedimentary units of the Helvetic and Pennine zones (Pfiffner 2009). Some of the Flysch deposits and mélanges in these zones contain crystalline clasts, as do some of the Molasse conglomerates along the front of the Alps. Only the basement of the external massifs (e.g. Aar massif) is build up by crystalline units. Beyond the extension of the Alpine glaciers, unconsolidated sediments with crystalline clasts are usually limited to recent fluvial deposits.

During Alpine metamorphism, the nappes exposed in the northwestern Swiss Alps experienced from anchizonal conditions in the border ranges of the Penninic Prealps and the Helvetic zone to 300 °C along the northern margin of the Aar massif (Frey and Ferreiro Mählmann 1999; Bill et al. 2001, see Fig. 2). Only the southern Aar massif, the western Gotthard massif and parts of the Pennine Alps were affected by temperatures of more than 300 °C (Stampfli 2001). This implies a now eroded overburden of 2–3 km on the border ranges and up to 10 km on the northern margin of the Aar massif (Soom 1990). The eroded parts consisted of Pennine and Austroalpine nappes, overthrust on to the Helvetic nappes (Pfiffner 2009) and included metamorphic rocks of greenschist facies in some parts. The eroded rocks are reflected in the composition of the Molasse conglomerates along the northern front of the Alps (localities Guggisberg and Napf, see Fig. 1b). The conglomerates of the Guggisberg fan north of the Prealps contain almost no crystalline clasts, apart from a few volcanites and pebbles provided by the interfingering with the Napf alluvial fan (Schmid 1970). In contrast, the Napf alluvial fan in front of the eastern Bernese Alps includes a high percentage of crystalline components (Matter 1964).

2.2 Research sites and sampling

The research area encompasses the northernmost Bernese ranges of the Penninic Prealps and the Helvetic zone and extends over 120 km^2 (Fig. 1b). The relictic character of the studied deposits necessitated the investigation of as many outcrops as possible but none had been exactly located before. We limited the extensive preparatory searching to sediment traps between 1,400 and 1,900 m a.s.l., including the area between the topographically highest erratics of the last glaciations along the southern border of the Swiss Plateau and the highest finds of crystalline clasts resulting from cave research.

As there were no natural outcrops, we opened 2 m deep pits, one in each of the two largest areas of near-surface sediment, at the Wagenmoos and the Stockesee sites (see below). All indicator rock clasts on the surface and in the pits were analyzed (ca. 500 p. per locality). We also had access to samples from the Ranggiloch and Chilchli-Höhle excavations, deposited by Andrist in the Museum of Natural History in Berne (Andrist et al. 1964), as well as the reference collections of Jeannin (1991), Häuselmann et al. (2007) and other speleologists of the cave system "Réseau Siebenhengste-Hohgant". We compared the rock spectrum of the studied sediments not only with exposed crystalline bedrock units but with crystalline clast-bearing sediments in the northwestern part and in front of the Alps. For that purpose, we collected pebbles for reference collections (ca. 1,000 p. per locality) at several localities (see Fig. 1b): in the Napf area (as reference for the youngest Molasse conglomerates of the Napf alluvial fan), near Murten (for Valais glacier deposits outside the confluence area with the Aare glacier), at Aaregg (for recent Aar massif gravel), in the Lombach (for Sörenberg flysch-mélange) and at Zettenalp (for Subalpine flysch-mélange). In the Prealpine flysch and mélange deposits, crystalline clasts are scarce and sampling for a reference collection was not possible. The youngest Molasse conglomerates in the Guggisberg alluvial fan were not sampled, because they are known to contain almost no crystalline clasts (Schmid 1970).

2.3 Facies analysis

Depending on weathering, facies analysis can reveal depositional constraints because depositional and weathering processes control the lithological properties of unconsolidated sediment. The focus is on fluvial and glacial transport processes; including local displacements by mass movement and slope processes. As all studied sites are located in karst areas their particular conditions have to be taken into account. Remnants of formerly superposed units, as well as fluvial and glacial deposits, are washed down into caves and may be prevented from erosion for millions of years (Audra et al. 2006). When erosion unroofs caves, cave deposits look like near-surface sediments (Sebela 1999; Knez and Slabe 1999). All kinds of till and till flows come into question as glacial sediments, as well as glaciofluvial and fluvial gravel for fluvial deposition. Fissility, till fabric, glacigenically scratched and shaped clasts, balanced granulometric composition and over-consolidation are the main features of basal lodgement till (Schlüchter 1989). In a weathered layer these features may disappear with the exception to the non-calcerous glacigenic scratched and shaped clasts. Erratic boulders are an additional evidence of former glaciation. The cave gravel features are well-rounded, often broken, clasts mainly from the host rock, mixed with flowstone clasts (or cemented by flowstone) and enriched in shining, polished quartz grains (Gnägi 2008). Fluvial gravel is often imbricated and well-layered, with a bimodal grain-size composition, and the clasts are well-rounded (depending on the flow patterns and the particular rock type). In contrast, glacifluvial gravel is not well-graded, partly unlayered or deposited in fining-upwards cycles. Clasts are often broken, largely subangular shaped and still show glacigenic scratching (Gnägi 2008). These properties differ from fluvial gravel but decrease with increasing transport distance from the feeding glacier, which is also reflected by the ratio of flattening to rounding of micritic limestone pebbles (Schlüchter 1989). We measured this ratio in a population of pebbles from gravels in the Stockesee sediment.

2.4 Indicator rocks and provenance analysis

Thin sections, heavy mineral analysis, X-ray diffractometer and Raman spectroscopy provided rock identification data. Due to the mainly sedimentary units of the northwestern Swiss Alps, sedimentary rocks are too widespread to serve as indicator rocks for provenance analysis, apart from a few specific ones like the Niesen breccia, the Taveyannaz sandstone and siliceous concretions (Gnägi 2008).

Granites and micaschists are ubiquitous rocks in all investigated crystalline clast-bearing units as well as in the Aar massif and in the Pennine Alps. Only specific varieties like glaucophane-schist or Dent Blanche granite are suitable as indicator rocks. Many metamorphic rocks, especially quartzites (originating from metamorphosed sandstones and quartz veins), take a key position in provenance analysis. As stated above, during Alpine metamorphism quartzitic layers in the northwestern Swiss Alps (e.g. within Triassic and Liassic series of the Helvetic nappes, the base of the Niesen nappe and the Breccia nappe) experienced not more than 300 °C, in contrast to many quartzitic layers exposed in the Pennine Alps (Fig. 2). Quartzite is a common rock in many types of conglomerates and gravels due to its hardness. The granular structure of quartzite changes with progressive metamorphism temperature and the individual grains increasingly begin to recrystallize. We determined the temperature according to Stipp et al. (2002) using the structural changes and the average size of the recrystallized quartz grains. They demonstrated that the structure of quartzite is changing from bulging recrystallization (280–400 °C) to subgrain-rotation recrystallization (400–500 °C) and grain-boundary-migration recrystallization (>500 °C). The method of Stipp et al. (2002) was developed with quartz veins in a contact metamorphic setting and was successfully tested in our project for application to provenance analysis (Fig. 3). Concerning the provenance of high-grade metamorphic rocks, series with pre-Variscan metamorphism in the basement of the northwestern Aar massif also have to be taken into consideration (Abrecht 1994).

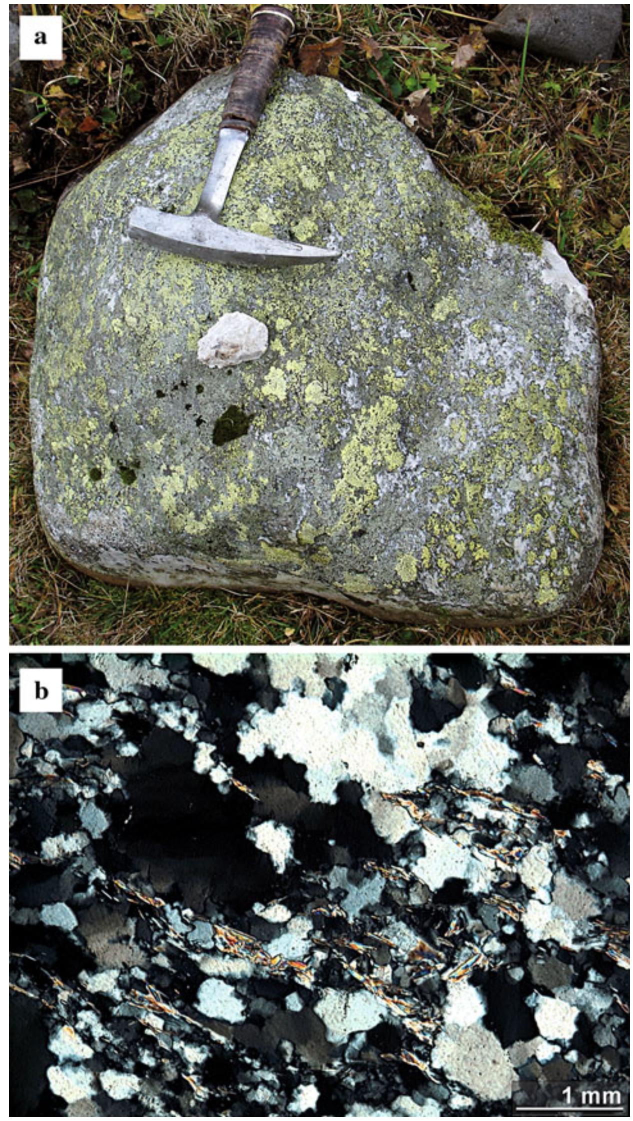

Fig. 3 **a** Medium-grade metamorphic quartzite boulder (0.7 m) from the Stockesee sediment. **b** Thin section of the same boulder: quartz grains appear as *black*, *grey* and *white* patches, the *coloured ones* are mica lamellae. The recrystallized quartz grains have been partly aggregated by grain-boundary-migration marked additionally by the lobate shape of the grain boundaries. The structure and the average size of the recrystallized grains (ca. 83 μ) resulted from a metamorphic temperature of 500–600 °C, according to the method of Stipp et al. (2002)

3 Results

3.1 Occurrence of crystalline erratics

In the research area west of the Aare valley, high-altitude crystalline erratics seem to be limited to the left side of Nieder-Simmental in the elevation range 1,720–1,860 m. East of the Aare valley, crystalline erratics occurred only on the karstic plateau of Sibe Hängste at elevations of 1,550–1,870 m. Concerning cave gravels, the altitude of the cave entrance is relevant for reconstructing former sediment deposition. An intensive search provided crystalline erratics from four outcrops, including the previously reported sites at the Stockeseen and the Wagenmoos (see below). Three of the outcrops are located in the Sibe Hängste and one in the Stockeseen area. The two largest ones are named Stockesee sediment (in Nieder-Simmental) and Wagenmoos sediment (in Sibe Hängste). Finally, data was available also from 13 caves. In the Nieder-Simmental, we found four caves providing a few crystalline clasts, in addition to the two (Ranggiloch and Chilchli-Höhle) formerly excavated for archaeological purposes (Andrist et al. 1964). In the Sibe Hängste, all seven caves providing crystalline clasts are part of the Réseau Siebenhengste-Hohgant, one of the largest cave systems in Switzerland.

3.2 Sibe Hängste, site details

The Sibe Hängste encompasses a mountain area located to the east of the Aare valley in the Helvetic Drusberg nappe

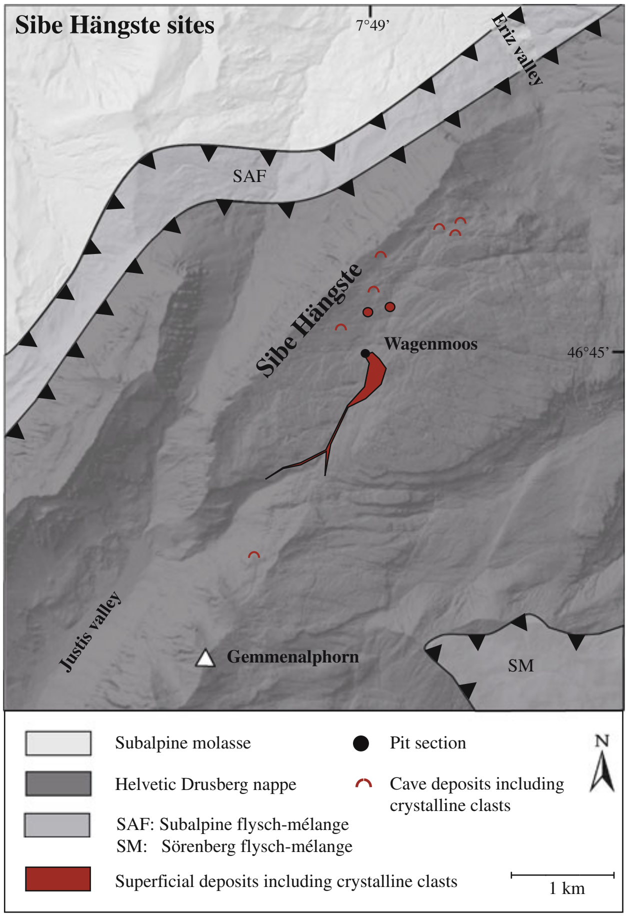

Fig. 4 Simplified tectonic map of the Sibe Hängste area, showing the location of the investigated sites. All caves are part of the cave system which is known as "Réseau Siebenhengste-Hohgant" (relief background taken from http://map.geo.admin.ch)

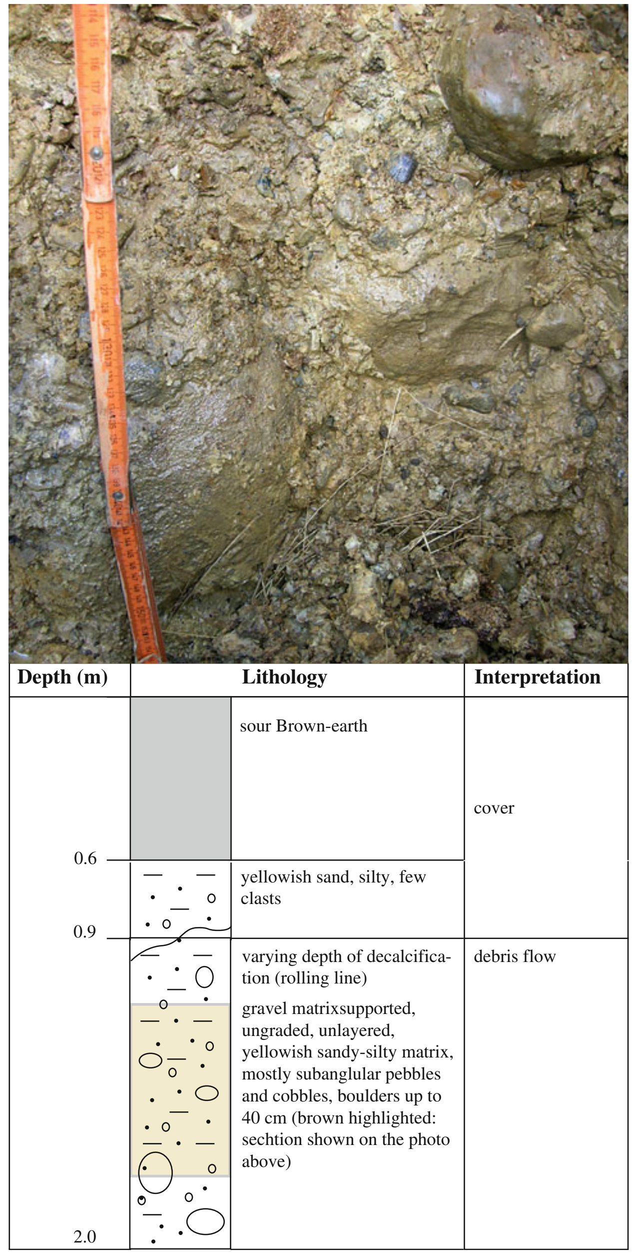

Fig. 5 Pit profile of the Wagenmoos sediment. The photo shows part of the debris flow section

(Figs. 1b, 4). The bedrock consists of thick-layered, sometimes siliceous limestone beds intercalated with marls and covered by mostly sandy cap-rocks. The near-surface outcrops are embedded in sediment traps like hollows, dolines and dry valleys. The Wagenmoos sediment area, a small part of the Sibe Hängste in which the pit (Swiss grid coordinates 629.310/177.880) was cut, is about 1 km in length and covers the bottom of a 200 m wide depression and the bed of an adjacent coomb. A small stream excavating a natural outcrop vanishes in a doline, illustrating the process of washing pebbles down into caves.

The pit face revealed a sediment featuring a weak depositional influence of water: ungraded and unlayered pebbles with few cobbles and boulders up to 35 cm in size, largely supported by yellowish silty-sandy matrix, with no clay (Fig. 5). Properties of cave gravel (from an unroofed cave), such as well rounded, often broken limestone pebbles, mixed with flowstone clasts and shining polished quartz grains, are absent. The pebbles are chaotically deposited within the matrix, not aligned (no till-fabric) and the sediment is not over-consolidated (no characteristics of basal lodgement till). The petrographic spectrum includes sandstones, limestones and 5 % erratic rocks (Table 1). The majority of the sandstone (88 %) and limestone (75 %) clasts are just subangular in shape. Due to acid moor water affecting the surface of the calcareous clasts only a few black siliceous concretions exhibit short glacigenic scratches and only a few limestone clasts show traces of etched scratches.

Table 1 Allochthonous rocks of the Nieder-Simmental and Sieben Hengste sites and their possible provenance

	Sites				Reference collections and exposed units					
	WS	RS	SS	CS	SF	NB	AM	VE	P/H	Possible origin of indicator rocks
Metamorphic rocks										
Quartz-epidote-schist	×	×				×	×	×		
Micaschist	×	×	×	×	×		×	×	×	
Greenschist		×	×		×	×		×	×	
Gneiss	×	×	×		×	×	×	×	×	
Low-grade metamorphic quartzite	×	×	×		×		×	×	×	
Low-grade metamorphic calcite-quartzite	×	×	×	×				×	×	
Middle-grade metamorphic quartzite	×	×	×			×		×		Pennine Alps (in particular)
Glauconite-sandstone				×	×	×				
Calcite-quartz-vein clasts	×	×	×	×		×		×	×	
HP-LT-metagabbro	×					×	×	×		
HP-LT-metagabbro with Mg-chloritoide	×							×		Zermatt-Saas-Fee zone
Garnet-amphibolite	×	×				×	×	×		AM/Pennine Alps
Amphibolite		×	×				×	×	×	
Metaultrabasite	×					×	×	×		
Jadeitite	×							×		Pennine Alps
Metaharzburgite	×						×	×		Southern AM/Gotthard massif/Pennine Alps
Glaucophane-schist	×							×		Pennine Alps
Serpentinite	×	×					×	×		
Wehrlite			×							Mont Collon mafic complex
Plutonic rocks										
Gabbro/diorite		×	×		×	×	×	×	×	Mont Collon mafic complex (only for SS)
Granite	×	×	×		×	×	×	×	×	
Habkern granite					×				×	
Leucogranite	×	×	×		×	×	×	×	×	
Specific sedimentary rocks										
Niesen breccia	×							×	×	
Black siliceous concretions	×	×	×					×	×	

Investigated sediments: *WS* Wagenmoos sediment, *RS* Réseau Siebenhengste-Hohgant, *SS* Stockesee sediment, *CS* Caves Nieder-Simmental

Reference collections: *SF* Schlieren flysch-mélange/Subalpine flysch-mélange, *NB* Napf beds, *AM* Aar massif, *VE* Valais glacier erratics in the Swiss Plateau

Exposed units: *P* Préalpes romandes, *H* Helvetic nappes in the catchment area of the Aare river

References: Ackermann 1986; Bayer 1982; Beck 1911; Elter et al. 1966; Flück 1973; Reber 1964; Stuijvenberg 1979; Winkler 1983

3.3 Nieder-Simmental, site details

The Nieder-Simmental (the lower part of the Simme valley) is incised in the Penninic Prealps and enters the Aare valley from the west (Fig. 1b). The Prealpine nappes consist of marine sedimentary rocks, such as limestones, marls, flysch deposits, dolomites and low-grade metamorphic quartzite (Baud and Septfontaine 1980). The Stockesee sediment area (pit location: Swiss grid coordinates 606.800/170.700) is a small part of the Nieder-Simmental and extends over 15,000 m^2 between 1,720–1,760 m a.s.l. It covers the bottom of the karstified northern slope of the Cheibehorn (Fig. 6). The surface is littered with erratic boulders up to 1 m in size (Niesen sandstone, silicious Liassic limestone, low-grade metamorphic gabbro, granites, glacifluvial conglomerates and medium-grade metamorphic quartzite) and run-of-hill scree (Malm limestone). The face of the pit showed two distinctly separated layers: diamictic, strongly weathered cover above ungraded, slightly layered and rock-like cemented gravel (Fig. 7). Due to weathering in the diamicton no depositional structures are preserved and particularly calcareous clasts potentially featuring glacigenic scratches have been dissolved. The majority of the sandstone clasts are dispersed. The petrographic spectrum includes 5 % crystalline clasts, such as granites, gneisses, quartz-hornblende-gabbro, micaschists, greenschist, medium-grade

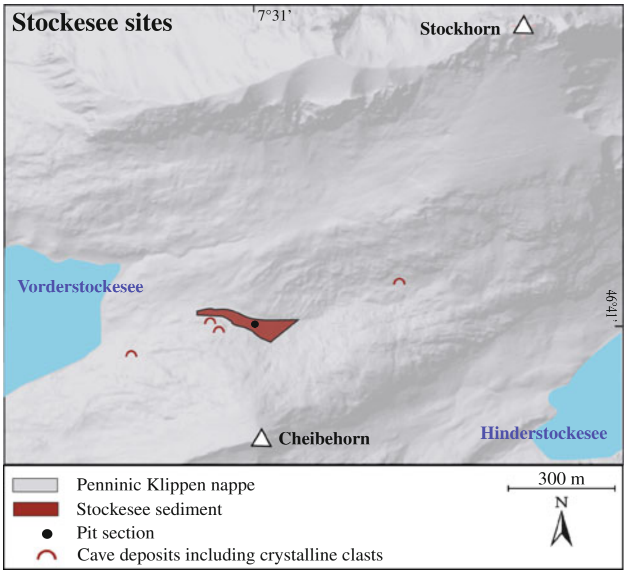

Fig. 6 Simplified map of the Stockesee area, showing the location of the investigated sites (relief background taken from http://map.geo.admin.ch). The sites lie completely within the Penninic Prealps

Depth (m)	Lithology	Interpretation
	many erratic boulders on the surface up to 1 m yellowish sandy-silty diamict, decalcified, few weathered pebbles and cobbles (sandstone and crystalline)	cover (most likely weathered till)
1.2	gravel, rocklike calcitified, ungraded, slighltly layered, boulders up to 30 cm, pebbles mostly subangular and partly flattened	glaciofluvial gravel, proximal facies
1.7		

Fig. 7 Pit profile of the Stockesee sediment. The photo is taken looking down into the pit and shows the weathered till, at the top, and the underlying glacifluvial gravel, with the contact at about 1.2 m depth

metamorphic quartzite, amphibolite and wehrlite (Table 1). The gravel layer only contains a few crystalline clasts. The rounding index of the limestone clasts features a first peak (23 % of the clasts) between 200 and 250 (Fig. 8). The ratio of Md(Fi):Md(Ri) = 200:250 (median flattening index to median rounding index) reflects glaciofluvial deposition in the proximal area of a glacier (according to Schlüchter 1989). Reworked, well-rounded fluvial pebbles generate the second peak at 500–550. The application of U/Th-dating to the calcite cement failed due to excessive silt concentration. For methods based on organic material, the amount of TOC (Total Organic Carbon) was too low.

Excavating the Chilchli-Höhle (Swiss grid coordinates 606.535/170.555) and the Ranggiloch (Swiss grid coordinates 592.375/164.925), Andrist et al. (1964) analyzed the lithology of the erratic clasts. Beneath cave loam they found in the Ranggiloch balm relictic till with many allochthonous, partly glacigenic scratched clasts (Fig. 9). Our systematic searching in the environments of the Stockesee sediment provided four other caves with single crystalline clasts spread on the cave floor (Fig. 6).

3.4 Petrology

3.4.1 Erratics at the studied sites

At the Sibe Hängste sites, some sedimentary rocks, such as the frequent black siliceous concretions and Niesen breccia, are indicator rocks, as well as medium-grade metamorphic quartzite, metaharzburgite, and high-grade metamorphic rocks, such as jadeitite, garnet-glaucophane-schist and HP-LT-metagabbro (Table 1). The siliceous concretions with characteristic orange ferrite discolouration originate from black shale, which is confirmed by the cleavage and included fossils. One of the gabbro clasts turned out to be Mg-chloritoid-bearing HP-LT-metagabbro proved by Raman-spectroscopy. At the Nieder-Simmental sites low-grade metamorphic quartz-hornblende-gabbro

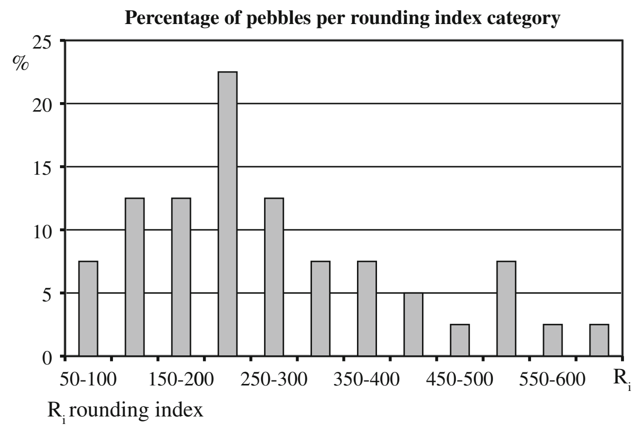

Fig. 8 Rounding index of the Stockesee gravel (Fraction 20–100 mm; $n = 40$). The first peak between 200 and 250 is characteristic for glaciofluvial deposition in the proximal area of a glacier (for details see in the text)

Fig. 9 Glacigenic scratched limestone pebble from the Ranggiloch (Nieder-Simmental)

and wehrlite are indicator rocks, as well as medium-grade metamorphic quartzite and amphibolite.

An important feature in all outcrops and cave deposits is the occurrence of metamorphic rocks, particularly medium-grade metamorphic quartzite. Overall, the extended outcrops include ≥80 % of the crystalline rocks found in the caves. Due to their smaller extent, the cave deposits contain not all of the rocks types found in the outcrops, particularly in the Nieder-Simmental. There is an evident difference in the indicator rock spectrum of the Stockesee sediment compared to the Wagenmoos sediment. At the Stockeseen site high-grade metamorphic rocks are absent and at Wagenmoos low-grade metamorphic gabbro and wehrlite are absent (Table 1).

3.4.2 Reference collections

Many Prealpine flysch and mélange deposits, such as the Zone Submédiane and the Niesen, Klippen, Breccia, Hundsrück and Gurnigel flysch units, contain crystalline clasts and polygenic conglomerates (Table 1), although these clasts are scarce. Common lithologies are granites, gneisses, micaschists and, rarely, volcanites (Ackermann 1986; Elter et al. 1966; Flück 1973; Stuijvenberg 1979). The same applies to the Subalpine flysch-mélange and the Sörenberg flysch-mélange in the eastern Bernese Alps where our samples from Zettenalp and Lombach (Fig. 1b) confirmed the results of Beck (1911), Reber (1964), Bayer (1982) and Winkler (1983). Indicator rocks of these eastern mélanges are polymictic breccia with volcanic, granitic and reddish feldspar components, Habkern granite with reddish K-feldspar, green quartz-sandstone (called "Ölquarzit") and, in the Subalpine flysch-mélange, also Taveyannaz sandstone.

The main crystalline lithologies of the northwestern Aar massif represented in the Aare gravel at Aaregg (Fig. 1b) are granites, granodiorites, gneisses, crystalline schists, migmatites and amphibolites. In addition there are small amounts of acid volcanic rocks, a unit of amphibolite-facies to anatectic overprint with mafic–ultramafic inclusions (e.g. with serpentinite, metaperidotite) and dykes of subvolcanic-volcanic composition (Labhart 1977; Abrecht 1994; Schaltegger et al. 2003).

The youngest preserved units in the Molasse of the western Swiss Alps are the Guggershorn formation of the Guggisberg alluvial fan in the west and the Napf beds of the Napf alluvial fan in the east, both of Miocene age (Kälin 1997; Strunk and Matter 2002; see Fig. 1b for the location of Guggisberg and Napf). In contrast to the Guggershorn formation, the Napf beds include many crystalline rocks of various types, such as granites, gneisses, quartzites, gabbro, amphibolites and volcanites (Matter 1964). In our samples from the top of the Napf (Fig. 1b) green and red granites, spilite breccia and other volcanites turned out to be indicator rocks.

4 Discussion

4.1 Provenances of the erratics

In addition to quartzites and metaharzburgite, rocks from high pressure (HP) zones, such as high pressure-low temperature (HP-LT) metagabbro, jadeitite and garnet-glaucophane-schist, are characteristic at the Sibe Hängste sites. In western Switzerland, HP-zones only occur in the Pennine nappes of the Pennine Alps, but the Aar massif contains also high-grade metamorphic lenses from pre-Alpine orogeny. Mg-chloritoid-bearing HP-LT-metagabbro from the Wagenmoos sediment (Fig. 10a) is mineralogically an equivalent of the Allalin gabbro exposed uniquely in the Penninic HP-zone of Zermatt-Saas-Fee (Meyer 1983, see Fig. 2). Metaharzburgite (Fig. 10b) is exposed in small

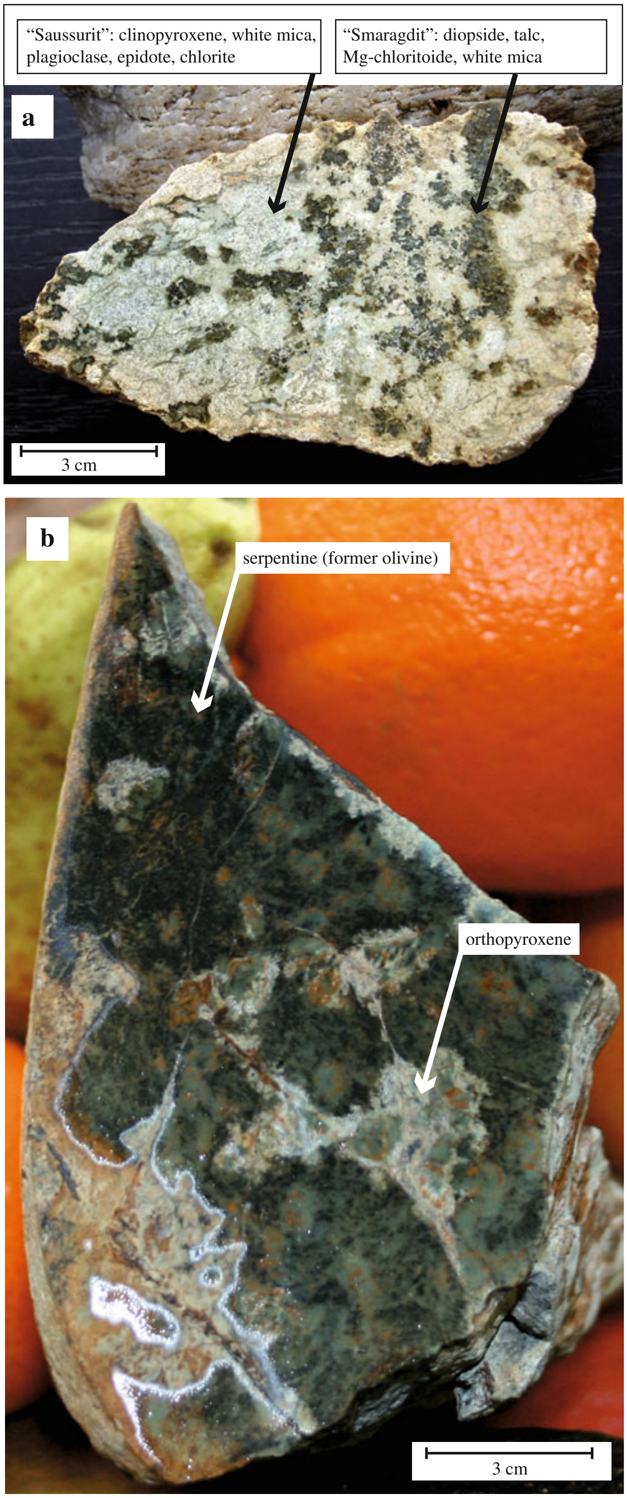

Fig. 10 Metamorphic rocks from the Sibe Hängste sites. **a** HP-LT-metagabbro bearing Mg-chloritoid, mineralogically identical with Allalin gabbro (called formerly saussurite-smaragdite-gabbro) from the Zermatt-Saas-Fee zone in the Pennine Alps. **b** Metaharzburgite originating probably from the upper Rhône valley and metamorphosed under greenschist facies conditions

outcrops in the southern Aar massif, the western Gotthard massif and the Pennine Alps, but this low-grade metamorphic type originated most likely from the Pennine Alps. Neither Allalin gabbro nor jadeitite, nor garnet-glaucophane-schist nor metaharzburgite were found in any of the referenced sites except in the Valais glacier deposits (Table 1). They are exposed (in western Switzerland) only in the Pennine Alps south of the Bernese Alps and the Rhone valley.

In addition to medium-grade metamorphic quartzite (Fig. 3), low-grade metamorphic wehrlite and quartz-hornblende-gabbro are characteristic rocks at the Nieder-Simmental sites. Similar rocks do not occur in the Swiss Prealpine Flysch nappes nor in the northwestern Aar massif (Table 1). While medium-grade metamorphic quartzite is exposed in many Penninic nappes, low-grade metamorphic wehrlite and quartz-hornblende-gabbro are only known from the Mont Collon mafic complex (Fig. 2) of the Austroalpine Dent Blanche nappe (Monjoie 2004). The Zermatt-Saas-Fee zone and the Mont Collon mafic complex are located in the middle part of the Rhône valley. Interestingly, rocks of the lower Rhône valley are completely absent at the Sibe Hängste and the Nieder-Simmental sites.

It needs to be discussed, whether the metamorphic rocks of the studied sites could originate from (today eroded) crystalline Penninic and Austroalpine nappes thrusted over the Helvetic nappes to the northern slope of the Alps. While their sedimentary cover was partly detached from its crystalline basement and transported upon the Helvetic nappes and beyond, the crystalline parts remained more in the south (Pfiffner 2009). The Prealps and several Klippen alongside the northern margin of the Helvetic nappes are remnants of this detachment. In the Iberger Klippen (Central Switzerland), containing unique remnants of Austroalpine units north of the Aar massif, Upper Austroalpine sedimentary layers are superimposed Penninic sediments. There is no crystalline unit (Trümpy 2006). In addition, the rock spectrum of the Miocene Molasse conglomerates or the Pliocene Sundgau gravel (palaeo-Aare river deposit in the north of the Jura Mountains, Fig. 1a) should reflect eroded crystalline nappes at the northern slope of the Bernese Alps. In contrast, as stated above, Molasse conglomerates of the Guggisberg fan only contain sedimentary rock clasts, and the clast supply to the Napf fan coming from nappes to the west of the Rhône–Simplon line (Fig. 2), e.g. today's Austroalpine Dent Blanche nappe and Penninic HP-zones, ceased 20 Ma ago (Eynatten 1999). The Alpine component of Sundgau gravel consists primary of displaced Molasse clasts (Liniger and Hofmann 1967). Therefore, it is unlikely that the metamorphic rocks of the studied sites originate from eventually eroded crystalline nappes at the northern slope of the Alps.

Could the clasts have been deposited millions of years ago in caves and had been eroded and displaced by unroofing of the caves later on? Indeed, caves with glacial or fluvial infilling are known from several places in the Alps, testifying of ancient topography (Audra et al. 2006). A prominent example is the Augenstein formation in the Northern Limestone Alps (Eastern Alps) deposited upon a karstic plateau before uplift (Frisch et al. 2002). Pebbles washed to the caves beneath (called Augensteine) were partly preserved to this day. However, this situation is not comparable to the Central Alps. In Switzerland, the conglomerates had been deposited in front of the Alpine nappes in the Molasse basin and not on the nappes—at least there is no geologic support for this. In contrast, the Alpine nappes were overthrust progressively on to the prograding alluvial fans (e.g. Pfiffner 2009).

4.2 Deposition and transport

As stated above, the characteristics of fluvial gravel, cave gravel and basal lodgement till are absent in the Wagenmoos sediment. The chaotic deposition, the mainly subangular shape of the clasts and the silty-sandy matrix with no clay indicate a weak depositional influence of water, and certainly not enough to transport boulders. Otherwise, a diamict with subangular, rarely scratched, pebbles and boulders up to 35 cm is consistent with a deposition not far from a glacier, e.g. a basal-lodgement till, washed for a short distance, or a melt-out till (Schlüchter 1989). The distribution of the Sibe Hängste sites over 3 km^2 and an altitude range of 300 m, as well as cave sediments in the same range of altitude representing washed unweathered till (Jeannin 1991) are additional supports for a glacial deposition.

The diamictic layer of the Stockesee sediment is neither a pure solifluction cover nor a slope wash or residuum of limestone solution due to the completely karstified slope above, the included allochthonous crystalline and sandstone clasts and the little clay content. If it is a till, the weathering destroyed many of the characteristic glacial features like fissility, till fabric, scratched clasts and overconsolidation. However, the diamictic character with partly angular erratic clasts, the boulders on its top and many clasts of Niesen sandstone (exposed in the Ober-Simmental, Fig. 2) suggest a glacial deposition by the Simmen glacier. This is supported by the till and washed till with few glacigenic scratched pebbles of the Ranggiloch cave some kilometres upstream the Stockesee sediment (Andrist et al. 1964), as well as crystalline clasts washed into other caves in the same range of altitude. The basal gravel layer of the Stockesee sediment features the morphometric properties of proximal glaciofluvial gravel, but an associated deposition is not constrained due to the missing transition between the two layers.

In summary, the properties of the Wagenmoos sediment and Stockesee sediment suggest deposition in a glacial environment, supported by coeval crystalline rock spectra of glacial sediments in nearby caves.

4.3 Implications: transfluences of the Valais glacier to the Bernese Alps

In the western Swiss Plateau, only the conglomerates of the Napf Molasse and the Valais glacier deposits contain clasts of medium-grade metamorphic quartzite and other metamorphic rocks from Pennine and Austroalpine nappes (Table 1). In contrast to the Napf conglomerates, the Valais glacier deposits include all the indicator rocks occurring at the Stockesee and Sibe Hängste sites. In the course of extended glaciations the Valais glacier was flowing downstream in the Rhône valley to the present-day Lake Geneva (Fig. 2). There, it divided into two substreams, one continuing in the direction of Lyon (France) and the other one alongside the Jura Mountains in a northeastern direction. A transfluence from the Rhône valley to the Saane valley over Col des Mosses is proven by erratics so far (Twerenbold 1954). In contrast, a transfluence to the Bernese Alps has not been indicated neither directly from the Rhône valley nor from the Swiss Plateau. Valais erratics at the southern border of the Swiss Plateau occur up to only 1,440 m a.s.l. (Tercier 1928; Rutsch 1967).

A transfluence from the Swiss Plateau over passes in the Alpine border ranges such as Jaunpass or Grüenebergpass (Fig. 2) is doubtful for two reasons. Firstly, the studied sites are located up to 1,860 m a.s.l. and would require a huge ice volume in the Swiss Plateau for a transfluence under present-day conditions. Secondly, this transfluence would carry the rock spectra found in the studied outcrops and in the Valais glacier deposits of the Swiss Plateau. However, we found no rocks from the lower Rhône valley in the investigated outcrops (e.g. Vallorcine conglomerate, Dent-Blanche hornblende granite, rhyolite from the Aguilles Rouges, Arolla gneiss, Fully gabbro or Verrucano).

The rock spectra of the Nieder-Simmental and Sibe Hängste sites diverge implying a transfluence of Valais ice along different routes and before reaching the lower Rhône valley. Gastern granite-like pebbles contained in the Wagenmoos sediment but missing in the Stockesee sediment could be an additional support for a transfluence across the Bernese Alps (Gastern granite outcrops in the Gastern valley near Gemmipass up to 3,000 m a.s.l., Fig. 2). Rocks of the Mont Collon mafic complex could have arrived at the Simmen valley directly over Rawilpass or via the Sanetschpass–Saane valley–Saanenmöser route.

A transfluence Saane valley–Saanenmöser–Nieder-Simmental is documented even for the last glaciation (Nussbaum 1906). As all outcrops with crystalline clasts are located on the left side of the Nieder-Simmental (Saanenmöser side) with none in the Ober-Simmental, a transfluence Sanetschpass-Saanenmöser is more probable than directly across Rawilpass (Ober-Simmental). Rocks from the Zermatt-Saas-Fee zone could have arrived at the Sibe Hängste from the Valais across Gemmipass–Kander valley. An ice-flow from the west of today's Aare valley to the Sibe Hängste is supported by rock clasts from South-Helvetic and Prealpine nappes (Niesen breccia, low-grade metamorphic calcite-quartzite, black siliceous concretions and of calcite-quartz-veins) which are only exposed in this part of the Bernese Alps (Gnägi 2008).

4.4 Implications for the drainage evolution since the Early Pleistocene

Knowledge about the evolution of Alpine topography since the Early Pleistocene is limited and assuming present-day valley and drainage patterns may be flawed. Nevertheless, transfluences over several passes between the Rhône valley and the Bernese Alps—maybe precursors of the present-day Gemmi- and Sanetschpass—best explain the petrographic spectra of the investigated high-altitude deposits. Valais glacier indicator rocks, possible Gastern granite clasts and missing Aare glacier indicator rocks in the Wagenmoos sediment raise the question of post-depositional changes in drainage organisation. A glacier advance from the Kander valley to the Sibe Hängste area crossing the Aare valley, the actual main valley of the Bernese Alps, is unlikely. Häuselmann et al. (2007) inferred from cave evolution analysis that the Early Pleistocene drainage of the Sibe Hängste area took course to the north and not in direction to the today's Aare valley, implying that the (palaeo)-Eriz valley (Fig. 2) was the main drainage direction. Increased deepening of the Aare valley and associated drainage reorganisation started at the Middle Pleistocene Transition. Our rock identification data is coincident with the proposal of Beck (1954) based on valley morphology analysis, that the Aare-valley took course more radially to the Aar massif prior to the glaciations (Fig. 2).

4.5 Chronological aspects

There are sparse clues with regard to the age of the studied deposits. An indirect estimate for the Wagenmoos sediments is possible through comparison with dated cave gravels. Crystalline pebbles were washed down into the Réseau Siebenhengste-Hohgant repeatedly since 1.87 ± 0.21 Ma (Häuselmann et al. 2007). The oldest cave gravels (2.32 Ma ± 0.33 and 4.35 Ma ± 0.6) prove an earlier existence of the Réseau Siebenhengste-Hohgant, but as they do not include erratics (oral communication P. Häuselmann), the burial age of 1.87 Ma is probably the best estimate for the first deposition of crystalline clasts. The infill of unweathered erratic components in caves of different ages (Jeannin 1991) suggests repeated deposition of fresh material in the Sieben Hengste, and it could be possible that the near surface sediments at Wagenmoos were deposited after 1.87 Ma. In fact, compared to the deeply weathered Deckenschotter deposits of Early Pleistocene age in Northern Switzerland (Graf 1993; Bolliger et al. 1996), the near-surface Wagenmoos sediments look rather fresh and unweathered. However, although the coincident rock spectra of the near-surface sediments and the cave gravel could be explained by one single deposition event as well as repeated depositions, the erratic sediments would still very likely date to the Early Pleistocene, because the major drainage re-organisation occurred before the Middle Pleistocene Transition.

There are no age estimates available concerning the Stockesee sediment. Furthermore, the diverging rock spectra of the Stockesee and the Sibe Hängste sites allow no correlation, despite the noticeable but perhaps coincidental similarity in the range of altitude. Nevertheless, as the Nieder-Simmental sites are located above the LGM-extension (Last Glacial Maximum) of the Simmen glacier (Genge 1955), the deposits originate at least from the penultimate glaciation, which was of major extent (Graf et al. 2007) but without distinct margins in the Bernese Alps.

Our results are in agreement with results from the Deckenschotter deposits in northern Switzerland (Graf 1993; Bolliger et al. 1996; Graf 2009) and glacial sediments in the basin of Ecoteaux (Fig. 2) in western Switzerland (Pugin et al. 1993), which are interpreted as evidence for Early Pleistocene glaciations in the Swiss Alps. It is difficult to determine the extension of these glaciations, because their remnants were mostly removed by later, more extensive advances. So a final issue that needs to be discussed is whether the Early Pleistocene glaciation(s) was (were) large enough to produce the suggested transfluences.

A transfluence of the Valais glacier across the Bernese Alps would require a huge ice volume under present conditions. Such conditions were probably met during the last two glacial cycles, when major glacier advances occurred in Switzerland. The Valais glacier repeatedly reached to the Swiss Plateau and at least once even reached the altitude of the Jura Mountains (Ivy-Ochs et al. 2004; Graf et al. 2007). Kelly et al. (2004) suggested an ice altitude at 2,300 m a.s.l. south of Gemmi Pass for the last glaciation, which would have enabled a transfluence across the Bernese Alps. Ices thicknesses may not have been that large during the Early Pleistocene, but one needs to keep in mind that valley deepening strongly increased only with the beginning of the Mid Pleistocene Transition (Soom 1990; Häuselmann et al. 2007). Valla et al. (2011) recently estimated a deepening of the Rhône valley of 1–1.5 km over the past one million years, while high-altitude areas were preserved from erosion. Hence, glacier transfluences needed less ice volume during the Early Pleistocene than the Late Pleistocene, and it is reasonable to assume that they occurred.

5 Conclusions

We analyzed the lithologic properties and the provenance of high-altitude erratic deposits on the northern rim of the Bernese Alps at 4 outcrops and in 13 caves. The outcrops are limited to karst areas, probably because embedded sediments are protected from erosion for a long time due to subsurface-drainage. We agree with Audra et al. (2006) that the potential of karst areas and their caves to serve as archives for landscape evolution has been underestimated.

The lithologic properties and the erratic spectrum of the Stockesee sediment and the Wagenmoos sediment are distinctly different from the local flysch deposits and Molasse conglomerates of the Guggisberg and the Napf fans in front of the western Swiss Alps. Many of the erratics originate from Penninic and Austroalpine nappes, but no indicator rocks from the northwestern Aar massif were found. The Stockesee and Wagenmoos erratics were therefore probably transported from south of the Aar massif, mainly from the Pennine Alps. In the western Swiss Plateau, only Valais glacier deposits and the conglomerates of the Napf fan contain clasts from Penninic and Austroalpine crystalline units. However, clast supply from nappes of the western Pennine Alps to the Napf Molasse ceased 20 Ma ago. Hence, we suppose that transfluences of the Valais glacier provided the crystalline clasts to the high altitude deposits in the Bernese Alps. The lithologic properties of the Wagenmoos sediment and Stockesee sediment support a final glacial deposition, particularly by few scratched and largely subangular pebbles and boulders up to one metre in size. A transfluence of Valais ice to the Simmen valley was assumed for a long time but now it is supported for the first time by analysis of indicator erratics. The diverging rock spectra of the Wagenmoos sediment and Stockesee sediment imply separate transfluence pathways. Moreover, the high reaches and the missing rocks from the lower Rhone valley are a strong indication for inner Alpine transfluences, for example, across precursors of Gemmipass and Sanetschpass, instead of a transfluence from the Swiss Plateau. Compared to the Stockesee sediment, where no deposition age is available, it is likely that the first transfluence to the Sibe Hängste area coincides with the burial-age estimate of 1.87 Ma for the oldest crystalline clasts from the Réseau Siebenhengste-Hohgant. The weak weathering of the Wagenmoos sediment might indicate later transfluences and deposition, but the required drainage organisation for an ice-flow from the Gemmipass across the palaeo-Kander valley to the Sibe Hängste suggests an Early Pleistocene age. Like the Deckenschotter of northern Switzerland and the glacial deposits from the basin of Ecoteaux in western Switzerland, the crystalline clasts from the Sibe Hängste thus seem to provide evidence for Early Pleistocene glaciations in the Swiss Alps. This is of particular interest, because remnants of these glaciations are scarce. The diverging rock spectra of the Nieder-Simmental and Sibe Hängste sites requires a detailed consideration of individual high-altitude erratic deposits and do not suggest a prior correlation.

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