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Post-depositional impacts on 'Findlinge' (erratic boulders) and their implications for surface-exposure dating

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Abstract Understanding and interpretation of 'numbers' produced about the depositional age of an erratic boulder by cosmogenic nuclide surface-exposure dating is important in the construction of glacial chronology. We have sampled three 'Findlinge' (glacially transported boulders) located on the right-lateral margin of the Aare glacier at Möschberg, Grosshöchstetten, southeast of Bern, with the aim of shedding light on this topic. The boulders have the same depositional, but different post-depositional histories: simple exposure; exhumation; and human impact. This sampling is specially selected for this study, since the boulders showing exhumation and human impact would not have been sampled in a regular surface-exposure dating application. We measured cosmogenic ^{10}Be concentrations and calculated apparent exposure ages that are 13.6 ± 0.5, 18.1 ± 0.8, and 7.5 ± 0.4 ka, respectively. The exposure age of the first boulder reflects exhumation. The apparent exposure age of 18.1 ± 0.8 ka (erosion-corrected exposure age 19.0 ± 0.9 ka) from the second boulder correlates well with the end of the Alpine and global last glacial maximum. The third boulder shows evidence of quarrying as it is surrounded by a rim of excavation material, which is also reflected by the 7.5 ± 0.4 ka apparent exposure age. We modeled the variation of ^{10}Be concentrations with depth down into the sediment in which the first (exhumed) boulder was once buried in, and down into the third (quarried) boulder. According to our modeling, we determined that the exhumed 'Findling' was buried in sediment at a depth of around 0.5 m, and around 2 m of rock was quarried from the third 'Findling'. Our results reveal the importance of sampling for surface-exposure dating within a well defined field context, as post-depositional impacts can easily hinder exposure-dating of surfaces.

Keywords Cosmogenic ^{10}Be · Findling · Inheritance · Exhumation · Human impact · Alpine Foreland

1 Introduction

An erratic boulder, '*Findling*' in German, is an allochthonous piece of rock of variable size whose lithology differs from that of the underlying local bedrock. In 1818, L. von Buch first recognized the occurrence of '*Findlinge*' in Switzerland and tried to correlate them with their analogues in northern Europe (Agassiz 1840). These allochthonous large clasts contributed to the understanding that the Alpine glaciers had once advanced hundreds of kilometers onto the Alpine Foreland and Jura Mountains (Agassiz 1840; Charpentier 1841). '*Findlinge*' delineate the maximum extent of the last glacial maximum (LGM) and the most extensive glaciation (MEG) glaciers (Fig. 1, see, for instance, Ivy-Ochs et al. 2004).

Surface-exposure dating using terrestrial cosmogenic nuclides (e.g. ^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, and ^{36}Cl) produced in situ, has become a widely accepted dating technique in Quaternary geology and geomorphology over

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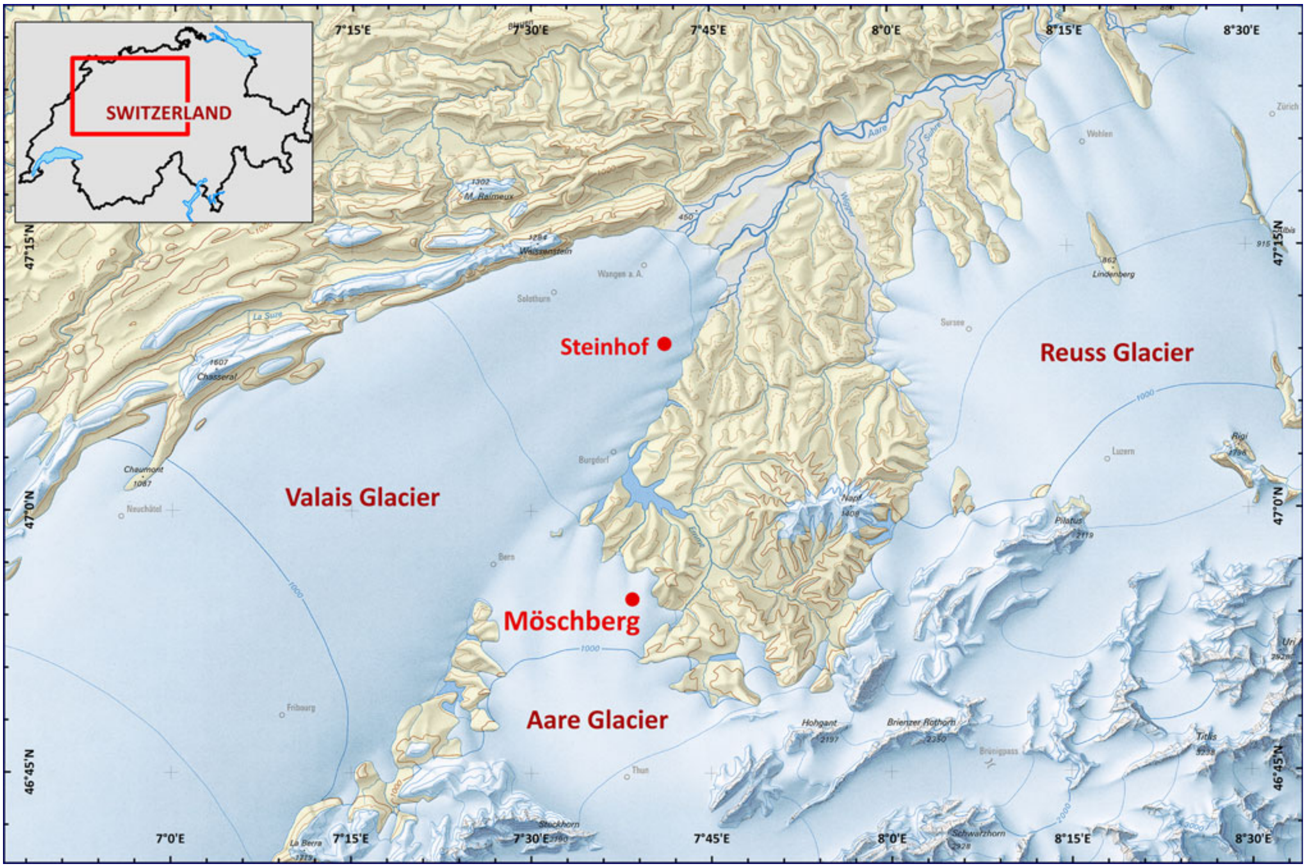

Fig. 1 Extension of the Valais, Aare and Reuss Glaciers during the last glacial maximum (LGM) and locations of Steinhof and Möschberg (from Bini et al. 2009). © Federal Office of Topography, swisstopo, CH-3084 Wabern

the last two decades (Gosse and Phillips 2001 and references therein). This dating technique can essentially be applied over timescales of approximately 100 a to 5 Ma depending on the surface preservation and exposure history (Akçar et al. 2008; Ivy-Ochs and Kober 2008).

The best-known application of this tool is the dating of Quaternary ice volume fluctuations from mainly glacially transported boulders (e.g. '*Findlinge*') and glacially abraded bedrock surfaces (Ivy-Ochs et al. 2008 among others). In the Alps, the extent of LGM Piedmont glaciers (the Valais, Aare, Reuss, Linth-Rhein and Rhein glaciers) onto the Alpine Foreland is relatively well delineated; however, the timing has been quantitatively constrained only for the Valais Glacier (Ivy-Ochs et al. 2004). During the LGM, the Valais Glacier advanced across the Alpine Foreland to the Jura Mountains, where the northward extension of the Piedmont glacier was blocked; the glacier was split into two lobes: the Geneva Lobe to the southwest and the Solothurn Lobe to the northeast (Ivy-Ochs et al. 2004; Bini et al. 2009). This advance is exposure-dated by four large '*Findlinge*' in Wangen a.d. Aare from the Solothurn Lobe (ER1, ER2, ER7 and ER8 in Ivy-Ochs et al. 2004), which was fed by the combined Aare and Valais glaciers, and by eleven '*Findlinge*' in the Jura Mountains (Graf 2008). The reconstruction for the pre-LGM advances is controversial, especially with regard to the timing of MEG, although ten available 'Findlinge' were from the Jura Mountains surface-exposure dated (Ivy-Ochs et al. 2004; Graf et al. 2007; Graf 2008).

The actual number of surface-exposure dated '*Findlinge*' in the Alps is <20, some of which were mentioned above. Considering the modern analogues of the Piedmont glaciers and the glacial landscape in the Arctic regions, however, landscape in the Alpine Foreland and the Jura Mountains must have been covered with thousands of erratic boulders in the past. The surprising lack of erratic boulders in the landscape leads to the question as to what happened to the '*Findlinge*' following the final retreat of LGM glaciers.

The first contact of man with the '*Findlinge*' dates back to the Stone Age when the Paleolithic cultures built menhirs (large, upright standing stone; Krüger 2008). Since then, the '*Findlinge*' were subjected to intensive anthropogenic activity, i.e. most of them have been quarried and used as construction material and/or building stone since Roman or even earlier times. For instance, the landscape of the area between the Alps and the Jura Mountains (Schweizerischer Mittelland) was covered with numerous ‘*Findlinge*’ until eighteenth century (Maurer 2005). Just as these erratic boulders were easily accessible, so also were they used as construction material and/or building stone. Many of the buildings from the Middle Ages contain pieces of quarried erratic boulders and several boulders were quarried to construct fountains (e.g. Graf 2008). Later, erratic boulders were also used in the railway and road constructions. The modernization of agriculture during the second half of the eighteenth century resulted in a systematic “cleaning up” of the farmlands, which dramatically changed the picture (Maurer 2005; Krüger 2008). This systematic “cleaning up” continued until the nineteenth century when Swiss natural scientists realized the importance of protection, e.g. Canton Bern legislated the protection and identification of all ‘*Findlinge*’ on May 14, 1868 (Maurer 2005). Although protected by law, they have also been destroyed by dynamite in order to ‘clean up’ farmland in modern times. The 10-m high ‘*Findling*’ (Sample ER-1) in Steinhof in Wangen a.d. Aare, for instance, bears scars of attempts to destroy it with dynamite (Ivy-Ochs et al. 2004). Most of the surviving ‘*Findlinge*’ are now located either in forests, or along property boundaries, or are of poor stone quality.

The anthropogenic impact on erratic boulders such as quarrying, displacement, or turning over will result in the modification of cosmogenic isotope concentration, i.e. the calculated age will be younger than the time of deposition by the glacier. Thus, such numbers will hinder the determination of the real age of exposure/deposition of the ‘*Findling*’. We think that every single erratic boulder is unique and has its own exposure history. This uniqueness can be particularly critical in the calculation of mean ages of a given geomorphological structure, such as a terminal moraine. An erratic boulder on a terminal moraine ridge, which bears a post-depositional impact, can easily influence the calculation of the mean exposure age of the moraine ridge (e.g. Akçar et al. 2007). The aim of this study is, therefore, to shed light on the understanding and interpretation of ‘numbers’ produced from the surface-exposure dating of boulders, by determining the apparent exposure ages of three ‘*Findlinge*’ on the same moraine ridge with the same glacial, but obviously different post-depositional histories. This will help non-cosmogenic experts to interpret surface-exposure ages produced in the studies on Quaternary glaciations. With this aim in mind, we are: (1) focusing on three erratic boulders on Möschberg in Grosshöchstetten, Bern (Fig. 1); (2) showing how divergent the exposure ages from the same glaciomorphological unit can be; and (3) explaining the causes of this divergence.

2 Study area

The study area is Möschberg, located approximately 20 km southeast of Bern and 2 km northeast of Grosshöchstetten (Figs. 1, 2). Möschberg is a glacially formed molasse ridge with LGM glacial deposits draped on it and with an altitude of 900–1,000 m above sea level (Fig. 2). Here, the mapped glacial deposits mark the right-lateral margin of the Aare glacier during the LGM, although morphological mapping suggests an outer glacial margin (Fig. 1). In that sense, locations of Möschberg and Steinhof (Ivy-Ochs et al. 2004) with regard to the LGM ice margin are identical (Fig. 1).

3 Surface-exposure dating

3.1 How to select a sample?

Within a surface-exposure dating application, especially with ^{10}Be and ^{26}Al, the saying that numerical ages are only as good as the samples upon which they are based holds very true, especially when the time and costs required from sampling to accelerator mass spectrometry (AMS) measurements are considered. Fewer local production rate adjustments and geometrical measurements will be necessary, when strict sampling strategies are quoted. Thus, the resulting reduction in random errors will significantly improve the total quality of the calculated ages. The aim of sampling is to collect and describe the characteristics of a sample that precisely represents the exposure history of a given landform (Gosse and Phillips 2001).

For instance, selection of an erratic boulder for sampling to determine the exposure history of a terminal moraine would be as follows: (1) the boulder lithology should be appropriate; (2) the boulder should be located on the crest-line of the terminal moraine; (3) its size should be large enough to avoid any post-depositional instabilities such as displacement, tilting, and rolling over; (4) the boulder should be flat topped; (5) physical and chemical weathering of the surface boulder should be considered. The best sample location on such a boulder is the middle of the flat top surface. After the selection of the sample, the guideline given in Table 1 is applied during the sampling (modified after Akçar 2006).

As well as the proper sampling strategy, it is rare, in the field, to afford an endless supply of ideal samples characterized by suitable lithology and ideal geometry. Collection of extra samples in the field would seem useful for replicating analyses or for sharing with other investigators, however time, availability of appropriate samples, and restrictions on transport of samples usually limit such collection. The aim is, therefore, to collect enough sample mass so that sufficient nuclides can be extracted or released

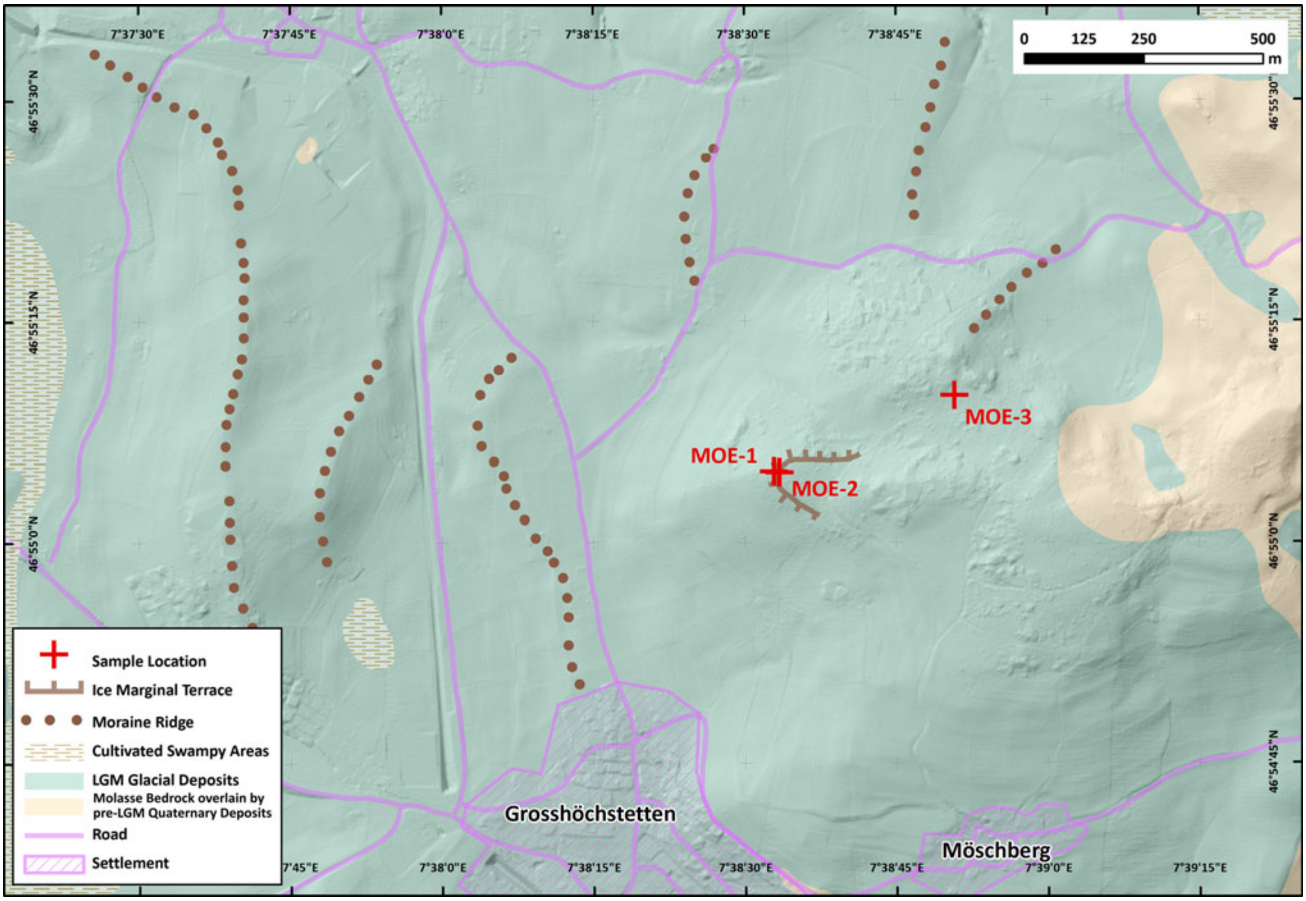

Fig. 2 Geological map of the study area and locations of the sampled boulders. Simplified from Kellerhals et al. (1999). © Federal Office of Topography, swisstopo, CH-3084 Wabern

Table 1 Guideline for sampling for ^{10}Be and ^{26}Al

Step (after the selection of sample)
Determine the geographical position and altitude
Take photographs of the boulder
Measure the dimension of the boulder
Measure the strike and dip of the top surface
Measure topographical shielding
Measure local shielding
Describe vegetation
Describe the potential sample with its surrounding (e.g. lithology, weathering, and differential movements)
Take photographs of the potential surface
Take the sample (up to the required weight)
Take the pictures of the sample and boulder after sampling

to get satisfactory results during the AMS measurements at the desired level of confidence. The minimum amount of sample varies depending on the exposure, the duration, the local production rate and the nature of the analysis (Gosse and Phillips 2001).

3.2 Theory

For successful exposure-dating of a '*Findling*', three conditions must be met. *First* and *foremost*, the cosmogenic isotope concentration at the beginning of exposure (inheritance) must be known or zero (e.g. Abbühl et al. 2009). *Second*, the correct production rate must be known and must have been constant during exposure. *Third*, the system must have been closed with respect to either gain or loss of the cosmogenic isotope. With regard to these conditions, inheritance and variable local production rates during the time of exposure are particularly crucial.

Inheritance results either from exposure at the source of the '*Findling*' prior to glacial plucking, or supraglacial transport, or englacial transport (close to the ice surface), or by reworking of previously deposited and exposed material (e.g. Ivy-Ochs et al. 2007; Porter and Swanson 2008). Accumulation of cosmogenic isotopes at the source occurs both at the surface and depth, accordingly, long exposure time at the origin leads to the accumulation of more isotopes that can easily be detected by surface-exposure dating. For instance, Akçar et al. (2011) detected inherited cosmogenic ^{10}Be concentrations in boulders of a historical rock avalanche that occurred in the upper Ferret valley in the Mont-Blanc region (Italy) in 1717. These concentrations are equivalent to several hundred years of exposure at the surface at the source of boulders. As sediments deposited onto the glacier by slope instabilities would be exposed during the transport, the accumulation would start prior to deposition. Similarly, englacial transport close to the glacier surface would result in inheritance (Porter and Swanson 2008). Reworking is the result of re-mobilization and re-deposition of formerly deposited materials. A '*Findling*', for example, eroded from its source, transported to the Alpine Foreland, and deposited by MEG glaciers, could have been reworked and re-deposited during LGM. Cosmogenic exposure dating of surfaces with inheritance will result in older exposure ages, if the inherited concentration is measurable with AMS. Otherwise, inheritance will be restricted to the limits of errors, i.e. it will not be detected.

The ratio of inheritance to regular exposure (concentration of isotopes) is relatively low for glacial chronological studies (Putkonen and Swanson 2003; Putkonen and O'Neal 2006), compared to applications such as exposure dating of large mass movements (e.g. Ivy-Ochs et al. 2009) or archaeological structures (e.g. Akçar et al. 2009). The reason for this is relatively simple: in the repeatedly glaciated areas such the Alps, advancing glaciers erode the bedrock more than 2–3 m deep and erase the existing cosmogenic isotope concentrations in the bedrock (e.g. Ivy-Ochs and Schaller 2010 and references therein). Such continuous and deep glacial erosion activity will hamper the accumulation of inherited isotope concentrations. Although not common, inheritance is evident in exposure dating of glacially transported boulders and glacially abraded bedrock surfaces due to the statistical outliers, as reported in several studies (e.g. Briner and Swanson 1998; Bierman et al. 1999; Fabel et al. 2002, 2004; Briner et al. 2005).

In contrast to inheritance, variable local production rates will yield younger exposure ages. This can occur due to anthropogenic impact such as quarrying or turning over. These kinds of post-depositional displacement activities will directly affect the production rate and thus result in younger exposure ages.

Due to post-depositional surface processes, exhumation of a '*Findling*' through the degrading of moraine material will gradually change the local-production-rate at the boulder surface due to the thinning of the overburden. Thus, exposure-dating of such a boulder will result in an age younger than the depositional age. Although the thinning of the overburden is, in general, a natural surface process, it can also be caused by human activity. Good examples of unnatural exhumation are the erratic blocks which are exhibited along highways and in parks all around Switzerland. All these blocks were excavated during the construction. As a consequence, these boulders are not appropriate for surface-exposure dating.

Inheritance cannot be detected in the field, whereas anthropogenic impact and/or exhumation can be identified when physical evidence is present and observable. The identification of anthropogenic impact seems to be easier than inheritance, since traces of human activity (e.g. quarrying) may be recognized in the field. In the case of displacement or turning over, however, recognition can be more difficult. The ambiguity created by exhumation can sometimes be avoided by careful observation within a well structured field context, but it often remains a challenge.

3.3 Methodology

In this study, three samples from erratic boulders were collected with a hammer and chisel following the strategies defined in previous studies (e.g. Akçar 2006). Three erratic boulders were chosen carefully for sampling with respect to the aim of the study, geomorphic setting, lithology and size in the study area.

The first sample (MOE-1) shows clear evidence of exhumation, since it is standing on a steep slope of the LGM ice marginal terrace, close to the second sample (Figs. 2, 3). The second sample (MOE-2) is taken from the top of the ice marginal terrace in the right-lateral margin of the Aare glacier, close to the edge (Figs. 2, 3) and it constitutes an almost perfect sample according to our sampling strategies, since there is no post-depositional effect on the boulder. The third sample (MOE-3) bears clear evidence of quarrying with a flat boulder-top, chisel marks and a rim of waste material around

Fig. 3 'Findlinge' MOE-1 and MOE-2 in Möschberg. Although the exhumation of MOE-1 is not clear in this image, it is obvious in the field

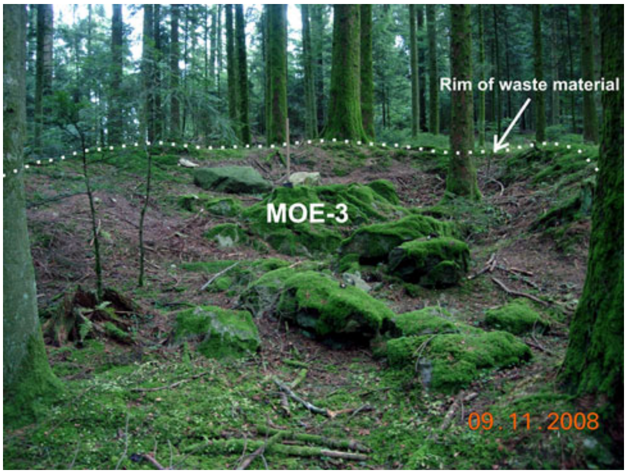

Fig. 4 Quarried 'Findling' MOE-3. Note the rim of waste material delineated with *dashed-line* and the trees grown on the rim. This indicates that the trees are younger than the rim. Quarried pieces are still around the 'Findling'. Sledge hammer handle is 80 cm

it (Fig. 4). We assume quarrying since Roman times, possibly Middle Ages based on Krüger (2008), recent evidence on the third boulder are dynamite drill marks. One should remember that this sampling strategy is different than a regular surface-exposure dating application, since the boulders showing exhumation and human impact would not normally have been sampled. The height of the boulders vary from 0.85 to 1.00 m. A description of the samples is given in Table 2.

Using a modified version of the technique introduced by Kohl and Nishiizumi (1992), Ivy-Ochs (1996) and Akçar (2006), these samples were prepared at the University of Bern for the AMS measurements of $^{10}Be/^{9}Be$ at the ETH tandem facility in Zurich (Kubik and Christl 2010). The measured ratios had been normalized to the ETH in-house standard S555 (Kubik and Christl 2010). All ^{10}Be results have been renormalized to the 07KNSTD standard by applying a conversion factor of 0.9124 (Balco et al. 2008; Kubik and Christl 2010). Samples were processed in two batches: the first batch contained two samples (MOE-1 and MOE-2) and one full process blank; and the second batch contained sample MOE-3 with one full process blank. Two different carrier materials were used for each batch. The long-term laboratory average (over 100 blank measurements in 6 years) $^{10}Be/^{9}Be$ ratio of the carrier used in the first batch is $(2.20 \pm 0.17) \times 10^{-14}$. The average of the second carrier is $(0.30 \pm 0.05) \times 10^{-14}$. The carrier contributes <5% to the ^{10}Be concentrations measured.

For the ^{10}Be exposure age calculations, we used the CRONUS-Earth online calculator of Balco et al. (2008; http://hess.ess.washington.edu/math/) using wrapper script 2.2, main calculator 2.1, constants 2.2.1 and muons 1.1. We calculated the local production rates according to the time-dependent Lal (1991)/Stone (2000) altitude/latitude scaling scheme using a production rate due to spallation (at sea level, high latitude), of 4.39 ± 0.37 atoms/gSiO_2.a (CRONUS calculator update from v. 2.1 to v. 2.2 published by Balco in October 2009). Topographic shielding was calculated following Dunne et al. (1999). Depth correction was made using an exponential attenuation length of 160 g/cm^2. Rock density was taken as 2.65 g/cm^3. No correction was applied for shielding by vegetation and snow cover. The cosmogenic nuclide data for the samples are given in Table 3.

4 Results

In Table 3, measured ratios, full process blank ratios, ^{10}Be concentrations and the calculated exposure ages are given as well as the cosmogenic nuclide data of the samples. The calculated exposure ages are presented without (apparent) and with correction for erosion (3 mm/ka from Ivy-Ochs et al. 2004). The corrections to account for thickness, dip of rock surface, and shielding of the surrounding topography were included in the calculation of apparent ages, but erosion correction was excluded. The erosion-corrected exposure age for samples MOE-1 and MOE-3 was not calculated due to exhumation (MOE-1) and quarrying (MOE-3) of the boulders after their deposition (Table 3).

For our samples MOE-1, MOE-2 and MOE-3, the ^{10}Be concentrations are $(11.90 \pm 0.40) \times 10^4$, $(17.29 \pm 0.76) \times 10^4$, and $(7.21 \pm 0.35) \times 10^4$ atoms/g, respectively. We calculated apparent exposure ages of 18.1 ± 0.8 ka from the regular erratic boulder without any post-depositional

Table 2 Description of samples from Möschberg, Grosshöchstetten

Sample name	Altitude (m)	Latitude, °N (DD.DD) WGS84	Longitude, °E (DD.DD) WGS84	Boulder height (cm)	Sample thickness (cm)	Thickness correction factor[a]	Shielding correction factor[b]
MOE-1	898	46.91669	7.64149	85	5.0	0.9597	0.9207
MOE-2	900	46.91667	7.63165	90	5.0	0.9597	0.9999
MOE-3	918	46.91811	7.64647	100	4.0	0.9676	0.9985

[a] Correction for sample thickness was done after Gosse and Phillips (2001), with mean attenuation length of 160 g/cm^2 and rock density of 2.65 g/cm^3

[b] Calculated for topographic shielding and dip of the surface after Dunne et al. (1999)

Table 3 Cosmogenic nuclide data and ^{10}Be exposure ages

Sample name	Quartz dissolved (g)	^{9}Be spike (mg)	Measured $^{10}Be/^{9}Be \times 10^{-14}$	Full process blank ratio ($^{10}Be/^{9}Be$) $\times 10^{-14}$	^{10}Be (10^4 atoms/g)	Apparent exposure age (ka)	Exposure age (ka) erosion corrected ($\varepsilon = 3.0$ mm/ka)
MOE-1	35.5032	0.2035	33.27 ± 1.03	2.20 ± 0.17	11.90 ± 0.40	13.6 ± 0.5 (1.2)	–
MOE-2	35.9433	0.2033	47.95 ± 2.01	2.20 ± 0.17	17.29 ± 0.76	18.1 ± 0.8 (1.7)	19.0 ± 0.9 (1.9)
MOE-3	100.6804	0.2547	42.96 ± 2.06	0.30 ± 0.05	7.21 ± 0.35	7.5 ± 0.4 (0.7)	–

Reported ratios and concentrations are referenced to 07KNSTD (Kubik and Christl 2010). AMS measurement errors are at 1σ level, including the statistical (counting) error and the error due to normalization of standards and blanks. Exposure ages are calculated with the CRONUS-Earth exposure age calculator (http://hess.ess.washington.edu/math/; v. 2.2; Balco et al. 2008 and update from v. 2.1 to v. 2.2 published by Balco in October 2009) and time dependent Lal (1991)/Stone (2000) scaling model. Exposure ages are corrected for dip of rock surface, shielding of surrounding topography, and sample thickness, as explained in the text; the uncertainties reported in parentheses also include the production rate error. A half-live of 1.39 Ma for ^{10}Be (Korschinek et al. 2010; Chmeleff et al. 2010) is used for the age calculations

impact (MOE-2); 13.6 ± 0.5 ka from the exhumed boulder (MOE-1); and 7.5 ± 0.4 ka from the quarried boulder (MOE-3). The erosion corrected (3.0 mm/ka) exposure age for MOE-2 is 19.0 ± 0.9 ka (Table 3).

5 Implications for surface-exposure dating

According to our results, only one ^{10}Be cosmogenic exposure age (erosion corrected) of 19.0 ± 0.9 ka correlates with the timing of the end of LGM in the Alps (Ivy-Ochs et al. 2006) and the global LGM (21.0 ± 2.0 ka, Mix et al. 2001) during MIS-2 (Thompson and Goldstein 2006 among others). Although the post-depositional impacts on two '*Findlinge*' (MOE-1 and MOE-3) hinders direct exposure-dating of the retreat of the Aare glacier, we may obtain fundamental information for our understanding of post-depositional impacts on cosmogenic nuclide concentrations. The calculated apparent exposure age of around 7 ka from the quarried boulder (MOE-3) is not a real exposure age, i.e. it cannot be interpreted that the boulder has been quarried at least 7 ka before. It is only an age equivalent of the concentration at depth. For a better understanding of this case, we modeled the variation of ^{10}Be concentration with depth for MOE-3 considering an exposure time of 21.0 ± 2.0 ka without inheritance (Fig. 5). From the results of this depth profile, we can estimate how much rock was removed from the top of the boulder. The measured ^{10}Be concentration from sample MOE-3 indicates that around 2 m of rock was quarried from top of the '*Findling*' (Fig. 5). Mining/quarrying certainly occurred on the largest boulder. The possibility of any inherited concentration cannot be excluded, and in the case of inheritance the thickness of the removed rock would decrease depending on the inherited concentration. A complex post-depositional impact, e.g. the combination of human impact with exhumation of the boulder, is unlikely for MOE-3 when we consider today's topography and field context. However, this possibility cannot be

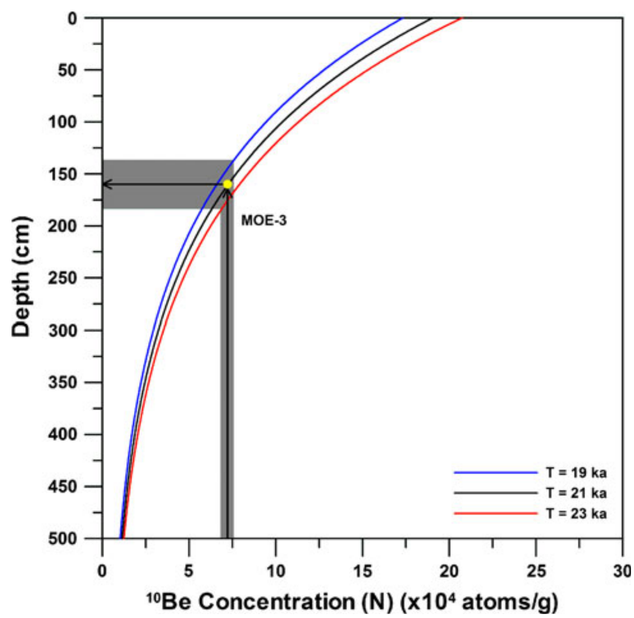

Fig. 5 Variation of ^{10}Be concentration with depth for sample MOE-3 based on an exposure of 21.0 ± 2.0 ka (*shaded area*) without inheritance with constant erosion at a rate of 3 mm/ka and rock density of 2.65 g/cm^3. Around 2 m of rock is quarried above MOE-3

completely ruled out for other '*Findlinge*' and it can only be recognized by the analysis of multiple cosmogenic radionuclides. Additional analysis of ^{14}C in quartz (e.g. ^{10}Be and ^{14}C), for instance, can help to determine complex exposure histories (e.g. Goehring et al. 2011).

Based on the depth model described above, we use the ^{10}Be concentration of the exhumed '*Findling*' (MOE-1) to estimate the thickness of the sediment covering the boulder at the time of its deposition. With the modified model (shielding correction factor of 0.9207, scaling factor of 1.97, sediment density of 2.1 g/cm^3 and no erosion) as used for MOE-3, we estimate maximum 0.5 m sediment that was once shielding the erratic boulder from the cosmic ray cascade. Our model assumes zero erosion in the sediment cover (i.e. recent instant removal), therefore we report maximum thickness of sediment. Gradual removal of the sediment cover at a linear rate would result in a thinner overburden. The modeled maximum amount of overburden material fits wells with today's topography. Inheritance would reduce the calculated thickness of the sediment cover.

6 Conclusions

We analyzed three samples from 'Findlinge' from the right-lateral margin of Aare glacier in Möschberg (Grosshöchstetten, southeast of Bern), for cosmogenic ^{10}Be. Calculated apparent exposure ages are 13.6 ± 0.5 ka (MOE-1), 18.1 ± 0.8 ka (MOE-2), 7.5 ± 0.4 ka (MOE-3), respectively. These ages are significantly different from each other due to different post-depositional histories. The apparent and erosion-corrected exposure ages of 18.1 ± 0.8 and 19.0 ± 0.9 ka from MOE-2 fit well with the timing of local (Ivy-Ochs et al. 2004), regional (Ivy-Ochs et al. 2008) and global LGM (e.g. Thompson and Goldstein 2006). The apparent exposure age of 13.6 ± 0.5 ka for MOE-1, which is younger than an expected exposure age of around 19 ka, is explained by exhumation that is also evidenced in the field. The 7.5 ± 0.4 ka apparent exposure age is interpreted as resulting from human impact, i.e. quarrying, as is evidenced by traces on and around the boulder. Nevertheless from our measured ^{10}Be concentrations from MOE-1 and MOE-3, we modeled the ^{10}Be concentrations with depth into the sediment. We were able to glean information about the thickness of the sediment covering MOE-1 at the time of deposition, and the thickness of the quarried rock for MOE-3. We determined that the '*Findling*' MOE-1 was buried in sediment at a depth of around 0.5 m, and that around 2 m of rock was quarried from '*Findling*' MOE-3. This is at least important information for sampling practice in the application of cosmogenic nuclides to problems in earth sciences and archaeology. We need to remember that the 'numbers' gathered from an analysis are related to what is sampled in the field. Thus, we would suggest non-experts have an expert on their team while sampling or, at least, consult an expert before sampling.

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References

Abbühl, M. L., Akçar, N., Strasky, S., Graf, A., Ivy-Ochs, S., & Schlüchter, C. (2009). A zero-exposure time experiment on an erratic boulder: Evaluating the problem of pre-exposure in Surface Exposure Dating. *Quaternary Science Journal (Eiszeitalter und Gegenwart), 58*, 1–11.

Agassiz, L. (1840). *Etudes sur les glaciers*. Soleure: En commission chez Jent & Gassmann.

Akçar, N. (2006). Paleoglacial records from the black sea area of Turkey field and dating evidence. Ph.D. dissertation, Bern University, Bern, Switzerland.

Akçar, N., Deline, P., Ivy-Ochs, S., Alfimov, V., Hajdas, I., Kubik, P. W., Christl, M., & Schlüchter, C. (2011). The 1717 AD rock avalanche deposits in the upper Ferret Valley (Italy): A dating approach with cosmogenic ^{10}Be. *Journal of Quaternary Science* (in press).

Akçar, N., Ivy Ochs, S., Alfimov, V., Yilmaz, I. O., Schachner, A., Altiner, D., et al. (2009). First results on determination of cosmogenic ^{36}Cl in limestone from the Yenicekale Complex in the Hittite capital of Hattusha (Turkey). *Quaternary Geochronology, 4*, 533–540.

Akçar, N., Ivy-Ochs, S., & Schlüchter, C. (2008). Application of in situ produced terrestrial cosmogenic nuclides to archaeology: A schematic review. *Quaternary Science Journal (Eiszeitalter und Gegenwart), 57*, 226–238.

Akçar, N., Yavuz, V., Ivy-Ochs, S., Kubik, P. W., Vardar, M., & Schlüchter, C. (2007). Paleoglacial records from Kavron Valley, NE Turkey: Field and cosmogenic exposure dating evidence. *Quaternary International, 164–165*, 170–183.

Balco, G., Stone, J. O., Lifton, N. A., & Dunai, T. J. (2008). A complete and easily accessible means of calculating surface exposure ages or erosion rates from Be-10 and Al-26 measurements. *Quaternary Geochronology, 3*, 174–195.

Bierman, P. R., Marsella, K. A., Patterson, C., Davis, P. T., & Caffee, M. (1999). Mid-Pleistocene cosmogenic minimum-age limits for pre-Wisconsinan glacial surfaces in southwestern Minnesota and southern Baffin Island: A multiple nuclide approach. *Geomorphology, 27*, 25–39.

Bini, A., Buoncristiani, J.-F., Couterrand, S., Ellwanger, D., Felber, M., Florineth, D., et al. (2009). *Die Schweiz während des letzteiszeitlichen Maximums (LGM) 1:500 000*. Bern: Federal Office of Topography, swisstopo.

Briner, J. P., Kaufman, D. S., Manley, W. E., Finkel, R. C., & Caffee, M. W. (2005). Cosmogenic exposure dating of late Pleistocene moraine stabilization in Alaska. *Geological Society of America Bulletin, 117*, 1108–1120.

Briner, J. P., & Swanson, T. W. (1998). Using inherited cosmogenic Cl-36 to constrain glacial erosion rates of the Cordilleran ice sheet. *Geology, 26*, 3–6.

Charpentier, J. de (1841). *Essai sur les glaciers et sur le terrain erratique du bassin du Rhône*. Lausanne.

Chmeleff, J., von Blanckenburg, F., Kossert, K., & Jakob, D. (2010). Determination of the Be-10 half-life by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B-Beam Interactions with Materials and Atoms, 268*, 192–199.

Dunne, J., Elmore, D., & Muzikar, P. (1999). Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth on sloped surfaces. *Geomorphology, 27*, 3–11.

Fabel, D., Harbor, J., Dahms, D., James, A., Elmore, D., Horn, L., et al. (2004). Spatial patterns of glacial erosion at a valley scale derived from terrestrial cosmogenic Be-10 and Al-26 concentrations in rock. *Annals of the Association of American Geographers, 94*, 241–255.

Fabel, D., Stroeven, A. P., Harbor, J., Kleman, J., Elmore, D., & Fink, D. (2002). Landscape preservation under Fennoscandian ice sheets determined from in situ produced Be-10 and Al-26. *Earth and Planetary Science Letters, 201*, 397–406.

Goehring, B. M., Schaefer, J. M., Schluechter, C., Lifton, N. A., Finkel, R. C., Jull, A. J. T., et al. (2011). The Rhone Glacier was smaller than today for most of the Holocene. *Geology, 39*, 679–682.

Gosse, J. C., & Phillips, F. M. (2001). Terrestrial in situ cosmogenic nuclides: Theory and application. *Quaternary Science Reviews, 20*, 1475–1560.

Graf, A. (2008). Surface exposure dating of LGM and pre-LGM Erratic Boulders: A comparison of paleoclimate records from both hemispheres. Ph.D. dissertation, Bern University, Bern, Switzerland.

Graf, A. A., Strasky, S., Ivy-Ochs, S., Akçar, N., Kubik, P. W., Burkhard, M., et al. (2007). First results of cosmogenic dated pre-last glaciation erratics from the Montoz area, Jura Mountains, Switzerland. *Quaternary International, 164–65*, 43–52.

Ivy-Ochs, S. (1996). Dating of rock surfaces using in situ produced ^{10}Be, ^{26}Al and ^{36}Cl, with examples from Antarctica and the Swiss Alps. Ph.D. dissertation, ETH Zurich, Zurich, Switzerland.

Ivy-Ochs, S., Kerschner, H., Kubik, P. W., & Schlüchter, C. (2006). Glacier response in the European Alps to Heinrich Event 1 cooling: The Gschnitz stadial. *Journal of Quaternary Science, 21*, 115–130.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., et al. (2008). Chronology of the last glacial cycle in the European Alps. *Journal of Quaternary Science, 23*, 559–573.

Ivy-Ochs, S., Kerschner, H., & Schlüchter, C. (2007). Cosmogenic nuclides and the dating of Lateglacial and Early Holocene glacier variations: The Alpine perspective. *Quaternary International, 164–65*, 53–63.

Ivy-Ochs, S., & Kober, F. (2008). Surface exposure dating with cosmogenic nuclides. *Quaternary Science Journal (Eiszeitalter und Gegenwart), 57*, 179–209.

Ivy-Ochs, S., Poschinger, A. V., Synal, H. A., & Maisch, M. (2009). Surface exposure dating of the Flims landslide, Graubunden, Switzerland. *Geomorphology, 103*, 104–112.

Ivy-Ochs, S., Schafer, J., Kubik, P. W., Synal, H. A., & Schlüchter, C. (2004). Timing of deglaciation on the northern Alpine Foreland (Switzerland). *Eclogae Geologicae Helvetiae, 97*, 47–55.

Ivy-Ochs, S., & Schaller, M. (2010). Examining processes and rates of landscape change with cosmogenic radionuclides. *Radioactivity in the Environment, 16*, 231–294.

Kellerhals, P., Haefeli, C., & Rutsch, R. F. (1999). *Geological atlas of Switzerland 1:25.000 sheet: 104 (1167 Worb)*. Bern: Federal Office of Topography, swisstopo.

Kohl, C. P., & Nishiizumi, K. (1992). Chemical isolation of quartz for measurement of in situ-produced cosmogenic nuclides. *Geochimica et Cosmochimica Acta, 56*, 3583–3587.

Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U. C., Knie, K., Rugel, G., et al. (2010). A new value for the half-life of Be-10 by Heavy-Ion Elastic Recoil Detection and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B-Beam Interactions with Materials and Atoms, 268*, 187–191.

Krüger, T. (2008). *Die Entdeckung der Eiszeiten: Internationale Rezeption und Konsequenzen für das Verständnis der Klimageschichte*. Basel: Schwabe.

Kubik, P. W., & Christl, M. (2010). ^{10}Be and ^{26}Al measurements at the Zurich 6 MV tandem AMS facility. *Nuclear Instruments and Methods in Physics Research B, 268*, 880–883.

Lal, D. (1991). Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters, 104*, 424–439.

Maurer, E. (2005). Der Schutz der Findlinge im Kanton Bern. *Mitteilungen der Naturforschenden Gesellschaft in Bern, 62*, 135–159.

Mix, A. C., Bard, E., & Schneider, R. (2001). Environmental processes of the ice age: Land, oceans, glaciers (EPILOG). *Quaternary Science Reviews, 20*, 627–657.

Porter, S. C., & Swanson, T. W. (2008). Cl-36 dating of the classic Pleistocene glacial record in the northeastern Cascade Range, Washington. *American Journal of Science, 308*, 130–166.

Putkonen, J., & O'Neal, M. (2006). Degradation of unconsolidated Quaternary landforms in the western North America. *Geomorphology, 75*, 408–419.

Putkonen, J., & Swanson, T. (2003). Accuracy of cosmogenic ages for moraines. *Quaternary Research, 59*, 255–261.

Stone, J. O. (2000). Air pressure and cosmogenic isotope production. *Journal of Geophysical Research—Solid Earth, 105*, 23753–23759.

Thompson, W. G., & Goldstein, S. L. (2006). A radiometric calibration of the SPECMAP timescale. *Quaternary Science Reviews, 25*, 3207–3215.