LGM and Late Glacial glacier advances in the Cordillera Real and Cochabamba (Bolivia) deduced from 10Be surface exposure dating

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LGM and Late Glacial glacier advances in the Cordillera Real and Cochabamba (Bolivia) deduced from ^{10}Be surface exposure dating

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Abstract

Surface exposure dating (SED) is an innovative tool being already widely applied for moraine dating and for Late Quaternary glacier and climate reconstruction. Here we present exposure ages of 28 boulders from the Cordillera Real and the Cordillera
5 Cochabamba, Bolivia. Our results indicate that the local Last Glacial Maximum (LGM) in the Eastern Cordilleras occurred at ∼22–25 ka and thus synchronous to the global temperature minimum. We were also able to date several Late Glacial moraines to ∼11–13 ka, which likely document lower temperatures and increased precipitation ("Coipasa" humid phase). Additionally, we recognize the existence of older Late Glacial
10 moraines re-calculated to ∼15 ka from published cosmogenic nuclide data. Those may coincide with the cold Heinrich 1 event in the North Atlantic region and the pronounced "Tauca" humid phase. We conclude that (i) exposure ages in the tropical Andes may have been substantially overestimated so far due to methodological uncertainties, and (ii) although precipitation plays an important role for glacier mass balances in the trop-
15 ical Andes, it becomes the dominant forcing for glaciation only in the drier and thus more precipitation-sensitive regions further west and south.

1 Introduction

Reconstruction of past climatic conditions is important to identify relevant forcings and mechanisms of climate change ("the past is the key to the future", http://www.pages.
20 unibe.ch). Long high-resolution records are available at high latitudes (ice-cores from Greenland and Antarctica) and from marine sediments. Comparable tropical and subtropical terrestrial records, however, are more scarce. Here, glacial deposits may provide valuable information about temperature and precipitation changes, the two dominant controls on glacier extent (Kaser, 2001; Kull et al., 2003, 2007). So far, the lack of
25 organic material for radiocarbon dating has been a major limiting factor for the establishment of reliable glacial chronologies, especially in dry mountain regions, like e.g.

EGU

the Central Andes (Harrison, 2004; Heine, 2004; Mark et al., 2004). Surface Exposure Dating (SED) is an innovative new method that may provide the means to date glacial deposits more accurately (Gosse and Phillips, 2001).

The Central Andes are part of the PEP I transect (Markgraf et al., 2000, Pole-Equator-Pole American Transect: http://www.pages.unibe.ch) and are a key area for global climate reconstruction because they lie at the transition zone between the mid-latitude and the tropical atmospheric circulation (the westerlies in the south: Vuille and Ammann, 1997; and the South American Summer Monsoon (SASM) in the north: Zhou and Lau, 1998; Vuille and Keimig, 2004, see also Fig. 1). Intensity changes and shifts of the two circulation systems should therefore be recorded in suitable archives, for example glacial chronologies. Extensive SED was recently conducted in the Eastern Cordillera of Bolivia and Peru by Smith et al. (2005a, b). They concluded that glaciers reached their greatest extent at ∼34 ka and were retreating by ∼21 ka. This would imply that tropical controls on ice volumes were asynchronous with those in the northern hemisphere, which would have far-reaching consequences concerning the inter-hemispheric linkages. It has already been speculated that the Andean tropics and the mid-latitude southern hemisphere may lead the polar regions (Shulmeister et al., 2006). On the other hand, Schaefer et al. (2006) interpreted this very dataset of Smith et al. as evidence for a near-synchronous interhemispheric termination of the LGM (Last Glacial Maximum) in mid-latitudes.

With this study, we hope to further illustrate the high potential of SED, while increasing awareness of the method's current limitations. We

  (i) present results of our [10]Be (beryllium) SED in the Cordillera Cochabamba and the Cordillera Real, Bolivia,

 (ii) derive a "relative" glacial chronology addressing potential causes for the observed scatter in ages,

(iii) highlight the systematic uncertainties of the exposure ages and, finally,

(iv) discuss the paleoclimatic context and the possible implications of our results.

EGU

2 Regional setting

The Cordillera Cochabamba and the Cordillera Real form the north-eastern boundary of the Altiplano plateau (~3800 m) towards the Amazon Basin (Fig. 1). Some summits reach altitudes of more than 6000 m. The steep altitude gradient causes a pronounced climatic gradient. Precipitation decreases from >1500 mm/a in the lowlands to ~1000 mm/a in the Cordilleras and to less than 500 mm/a on the Altiplano. Further south, where the so-called "Arid Diagonal" crosses the Central Andes (25–27° S), no glaciers exist even at altitudes above 6000 m (Ammann et al., 2001; Kull et al., 2002).

Large moraines in the Eastern Cordillera document Late Quaternary periods much more favourable for glaciation than today, i.e. lower temperatures and/or increased precipitation. However, considerable uncertainties concerning the glacial chronology exist. Based on soil development on moraines, bedded slope deposits and basal radiocarbon ages, various authors have suggested a local LGM either before, synchronous or after the global LGM (recently reviewed by Heine, 2004; and Mark et al., 2004). In addition, there is no consensus concerning the exact timing of Late Glacial readvances such as the Younger Dryas (YD) or the Antarctic Cold Reversal (ACR). The reviews of the region's glacial history by Heine (2004) and Mark et al. (2004) both highlight the need for improved age control.

In order to provide some dating control on the glacial chronology in the Eastern Cordillera, we selected three research areas for ^{10}Be SED based on the occurrence of well-defined moraine stratigraphy and the availability of suitable, i.e. large and quartz-bearing, boulders (Fig. 1):

- Valle San Francisco (south-western side of the Illampu massif, 16.00° S, 68.54° W), ~80 km northwest of La Paz

- Valle de Rio Suturi (17.23° S, 66.45° W), ~30 km northwest of Cochabamba

- Valle Huara Loma (17.21° S, 66.26° W), ~15 km north of Cochabamba

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

3   Materials and methods

Fieldwork included mapping of the moraines, sampling of suitable boulders ($\sim$0.5 kg from the flat top of preferentially large, stable and uneroded boulders), and documentation of the samples (geographic location (GPS), topographic shielding, sample geometry, and photographs: see supplementary material A.1 (http://www.clim-past-discuss.net/3/839/2007/cpd-3-839-2007-supplement.pdf) for the sample photos). Laboratory preparation and analysis followed standard procedures (e.g. Ivy-Ochs, 1996). In brief, this involved (i) separation of quartz, (ii) dissolution of the quartz in HF after addition of ^{9}Be carrier, (iii) chromatographical purification of beryllium (Be), (iv) precipitation and oxidation, and (v) AMS measurement of the ^{10}Be over ^{9}Be ratio.

Surface exposure dating is based on the production and accumulation of cosmogenic nuclides (e.g. ^{10}Be) in the upper few decimetres of an exposed rock surface (Gosse and Phillips, 2001). In order to calculate the exposure age of a sample from its ^{10}Be concentration, the local ^{10}Be production rate must be estimated. This is accomplished by scaling a reference production rate (typically at sea level and high latitude, SLHL) to the sampling location, using scaling models that describe the latitude and altitude dependence of the cosmic radiation. Several scaling models have been proposed (Lal, 1991; Dunai, 2000; Stone, 2000; Desilets and Zreda, 2001, 2003; Dunai, 2001; Lifton et al., 2005; Desilets et al., 2006), but currently there is debate as to which is most appropriate. Uncertainties in the predictions of these various models are variable, but are typically quoted as on the order of 10–15% (Gosse and Phillips, 2001). Major international efforts currently aim at the development of an internationally accepted protocol to calculate exposure ages with accuracy of at least 5% (CRONUS-Earth and CRONUS-EU projects: www.physics.purdue.edu/cronus and http://www.cronus-eu.net, respectively). Therefore, while we calculated the exposure ages below using the scaling model of Lifton et al. (2005), we also examined the sensitivity of our calculated exposure ages to various calculations schemes and assumptions. All presented ages are corrected for topographic shielding (Dunne et al., 1999) and sample thickness, whereas snow and

EGU

vegetation cover can likely be neglected due to the relatively dry conditions and the scarce vegetation cover.

4 Results and discussion

Exposure ages and the relevant sample data are given in Table 1. We will first present the exposure ages in their stratigraphic context (Figs. 2–4). Then, we will address the age scatter due to sample-specific effects, i.e. possible over- or underestimation of the deposition age of the respective moraine (all ages plotted in Fig. 5). Subsequently, we will discuss the systematic uncertainties (Fig. 6). Finally, the paleoclimatic context and the paleoclimatic implications of our results will be addressed.

4.1 Stratigraphy and exposure ages in the Valle San Francisco, Rio Suturi and Huara Loma

Our stratigraphic field work in the Valle San Francisco corroborates previous detailed work by e.g. Jordan et al. (1993). A large number of (recessional) stages is documented by numerous lateral and terminal moraines. Only the major stages could be sampled, however, due to the need for large boulders, which were not present on moraines associated with minor stages (see Fig. 2 for the sampling locations). The oldest dated glacial deposit is an outer lateral moraine at ∼4670 m altitude, where three boulders yielded exposure ages of 18.5±0.8, 22.6±0.8 and 24.1±0.9 ka (samples SF41-3). The dominant inner lateral moraine yields boulder ages of 17.2±0.7 and 19.3±0.6 ka (SF32 and 33) and probably correlates with a lateral moraine on the other side of the valley, where two boulders date to 15.3±0.7 and 20.3±0.8 ka (SF12 and 13). Three boulders from a recessional terminal moraine in the valley bottom yield exposure ages of 9.4±0.6, 12.9±0.6 and 11.5±0.5 ka (SF51-3), and the youngest dated recessional terminal moraine, which dams the Laguna San Francisco, yielded boulder ages of 10.4±0.5 and 10.0±0.5 ka (SF21 and 22).

EGU

EGU

In the Valle de Rio Suturi, two boulders from the prominent latero-frontal moraine date to 13.0±0.8 and 11.6±0.6 ka (RM31 and 33, see Fig. 3). A boulder from an adjacent, stratigraphically older lateral moraine remnant has an exposure age of 10.1±0.8 ka (RM22). The oldest age in the Valle de Rio Suturi was obtained from the
5 remnants of a middle moraine preserved between Valle de Rio Suturi and the northern neighbouring valley: Boulder RM41 has an exposure age of 22.0±1.2 ka. Another boulder (RM42) from that location is 12.2±0.9 ka old. The most prominent of a number of recessional moraines was sampled as well. Boulder ages there are 12.2±0.7 and 10.3±0.7 ka (RM13 and 14). The youngest age was obtained from a terminal moraine
10 up-valley (boulder RM51: 7.0±0.5 ka).

The stratigraphic situation in the Valle Huara Loma may be more complicated than initially thought (Fig. 4). The oldest exposure ages that we obtained are from boulders on an outer lateral moraine (16.9±0.6 and 14.6±0.5 ka, HH51 and 52). Just inside, another lateral moraine yields two boulder ages of 11.8±0.5 and 11.4±0.5 ka (HH41
15 and HH43). Up-valley, boulders on the large prominent lateral moraine yield exposure ages of 13.3±0.6 and 11.5±0.4 ka (HH11 and 22). Two boulders from a recessional moraine are dated to 10.4±0.5 and 11.0±0.4 ka (HH31 and 32).

4.2 Exposure age scatter: inheritance versus degradation

Interpretation of exposure ages is principally limited by two possible sources of errors:
20 "Inheritance" and "degradation". Inherited nuclide concentration due to exposure before moraine deposition can lead to an overestimation of the deposition age. Although it is difficult to determine whether and to what extent a boulder was "pre-exposed", probability for inheritance is generally assumed to be very low (Shanahan and Zreda, 2000; Putkonen and Swanson, 2003). On the other hand, exposure ages may underestimate
25 the deposition age, when formerly covered boulders were exposed after deposition, e.g. due to denudation of the moraine matrix, frost-induced upheaval, toppling of boulders, melting of buried glacier ice etc. (Briner et al., 2005; Zech et al., 2005; Putkonen and O'neal, 2006). Furthermore, rock surface erosion has the same effect, as it results

in loss of accumulated cosmogenic nuclides. The "oldest age model" suggests that, generally, the oldest exposure age from a landform feature yields the best, although possibly still a too low estimate for its deposition age, unless, of course, it is identified as an old outlier due to inheritance based on the age distribution of a large dataset or
5   based on the stratigraphic context.

In order to illustrate the scatter in our data and to identify possible outliers, we plot all exposure ages in stratigraphic order (Fig. 5). Our data set is admittedly too limited to identify with certainty all boulders, which may have problems with prior exposure. Applying the "oldest age model" allows us to establish the following tentative
10   chronology. In the Valle San Francisco the outer lateral moraine documents a glacial advance at ∼24.1±0.9 ka (SF43). The subsequent prominent glacial advance is dated to ∼20.3±0.8 ka (SF13), and the recessional stages also yield stratigraphically consistent ages of 12.9±0.6 (SF52) and 10.4±0.5 ka (SF21), respectively. The age of the oldest deposit in the Valle de Rio Suturi clearly requires verification; it may be as
15   old as 22.0±1.2 ka (RM41), but this conclusion is based only on a single age. The prominent latero-frontal moraine is more confidently dated to ∼13.0±0.8 ka (RM31), although a younger exposure age of 10.1±0.8 ka (RM22) is obtained from the adjacent, stratigraphically older moraine remnant. The assumption that this 10.1 age is a "degradation" age is corroborated by the recessional moraine up-valley dated to
20   ∼12.2±0.7 ka (RM13). Finally, a much younger age (7.0±0.5 ka, RM51) is obtained from another recessional stage, but it awaits corroboration. In the Valle Huara Loma, a minimum age of 16.9±0.6 ka (HH51) characterizes the outer lateral moraine. We can only speculate about its correlation with the older moraines in the other two valleys, since both boulders clearly had signs of erosion and are not perfectly suited for SED
25   (see photos in the supplementary material). The inner lateral moraine yields an age of 11.8±0.5 ka (HH41). This seems to contradict the minimum age inferred for the upper lateral moraine, which is tentatively dated to 13.3±0.6 ka (HH11). We note, however, that the complicated stratigraphic situation does not rule out that the lower, inner lateral moraine actually documents a glacial advance inside the older, high lateral moraine.

EGU

Finally, the innermost recessional moraine is dated to 11.0±0.4 ka (HH32).

The above discussion shows that interpreting our dataset using the "oldest age model" leads to a generally consistent picture of glaciation: The oldest deposits are roughly dated to 22–25 ka (>17 ka in the Valle Huara Loma), and substantial read-
5 vances – especially in the Cordillera Cochabamba – occurred between ~11–13 ka. Undoubtedly, more exposure ages would help to corroborate and refine the glacial chronologies in the research areas.

4.3   Systematic uncertainties of the exposure ages

Interpretation of exposure age chronologies in the paleoclimatic context requires
10 awareness about the systematic uncertainties. These are uncertainties due to scal-
ing and the reference production rate. As already mentioned, there is no internation-
ally accepted way to calculate exposure ages so far. The exposure ages presented above have been calculated according to Lifton et al. (2005). Their model takes into account past changes of the geomagnetic field intensity (composite model based on
15 Guyodo and Valet, 1999; (Sint800); and Yang et al., 2000), the dipole wobble for the Holocene (composite model based on Merrill and Mcelhinny, 1983; and Ohno and Hamano, 1993), and solar modulation (based on Solanki et al., 2004). Additionally, fast and slow muons are scaled independently of the neutron flux. We used a total ref-
erence production rate of 5.87 atoms a^{-1} g^{-1} SiO_2. This value has been derived from
20 calibration of the cosmogenic nuclide data that were used by Stone (2000) to derive a production rate of 5.1 atoms a^{-1} g^{-1} SiO_2. Respective data were accessed in May 2007 from the website of the "Cosmogenic Isotope Laboratory, University of Washing-
ton" (http://depts.washington.edu/cosmolab).Note that significantly younger exposure ages are obtained when using the scaling system of Lifton et al. (2005) instead of
25 Stone (2000) (open squares in Fig. 6). Due to its simplicity, the scaling system of Stone is still widely used, but major potential error sources are (i) that it is based on a relatively small neutron flux dataset, (ii) it neglects the altitude dependence of the energy spectrum of the cosmic radiation, and (iii) it does not take into account past

EGU

changes of the geomagnetic field.

The 10% error bars for the "Lifton ages" in Fig. 6 illustrate the estimated total systematic uncertainty of exposure dating according to Gosse and Phillips (2001). It includes mainly uncertainties related to the reference production rate and to scaling. Given that
5 uncertainty the exposure ages calculated according to Pigati and Lifton (2004) (orange squares in Fig. 6) are in very good agreement with the "Lifton ages". Note that we up-dated the Pigati and Lifton spreadsheet, which is based on the scaling system of Desilets and Zreda (2003), with the new scaling coefficients published in Desilets et al. (2006). The reference production rate to use is 5.41 a^{-1} g^{-1} SiO_2 – based on the
10 same calibration sites as outlined above. Calculations according to Dunai (2001) are also in very good agreement, but results are not shown here because the application of that latter calculation scheme would ideally require local inclination data of the geomagnetic field.

Apart from the selection of the applied scaling system, three more factors contributing
15 to the exposure age uncertainties shall briefly be discussed here: the use the Standard Atmosphere, neo-tectonics and the eustatic sea level change: (i) Altitude scaling requires the calculation of the atmospheric depth and the pressure, respectively, for the sampling locations. The application of the Standard Atmosphere, as used in the calculations above, is only a rough estimate for the real atmospheric conditions (Stone,
20 2000). Parameterisation of the pressure-altitude relationship in the Central Andes according to Farber et al. (2005: sea level pressure 1012.8 instead of 1013.15 mbar, and sea-level temperature 301.73 instead of 288.15 K) would result in ages slightly older than the ones presented above (blue diamonds in Fig. 6). However, neither the temperature nor the lapse rate can be assumed to have been constant over time and reliable
25 reconstructions of these parameters are not available. (ii) Concerning neo-tectonics, they would also affect altitude scaling. Whereas Holocene exposure ages would hardly change, an uplift rate of 5 mm/a would already increase the calculated age of a "20 ka-boulder" by ∼2.5% (i.e. 0.5 ka). Although the main Andean orogenesis is generally assumed to have ceased several million years ago, there is geomorphologic evidence

EGU

for very active regions today, e.g. faulted moraines, so that exposure age errors due to neo-tectonics cannot be excluded. (iii) Finally, the lowering of the eustatic sea level during the LGM (e.g. Fleming et al., 1998) increases the "apparent" altitude of the samples. A correction of ∼2.5% towards younger ages would, for example, seem to be
5 necessary for a 20 ka-boulder. However, according to Osmaston (2006), air pressure and thus altitude scaling at a given location do not change because of replacement of air by the growing ice sheet masses during the LGM.

Summarizing, we emphasize that although we currently favour the application of the calculation scheme according to Lifton et al. (2005) as outlined above, there is an
10 urgent need for local calibration studies in the Andes in order to better constrain the systematic uncertainties. This is not only important with regards to the scaling system, but also with regards to the reference production rate, which will be addressed later on in more detail.

4.4 Paleoclimatic context and implications

15 In the following, we will first compare our results with the surface exposure age chronologies of Smith et al. (2005a, b) and Farber et al. (2005), then with independent age controls on the glacial history in the research area. Thereafter, we will discuss the role of temperature and precipitation on the glaciation in the Central Andes.

4.4.1 Comparison with published surface exposure ages

20 Our exposure age dataset from Bolivia is admittedly small. In order to derive meaningful paleoclimatic interpretations we can, however, refer to the large dataset of Smith et al. (2005a, 5b) and Farber et al. (2005). Based on more than hundred ^{10}Be surface exposure ages Smith et al. had suggested that glaciers reached their greatest extent at ∼34 ka and were retreating by ∼21 ka (Ages published in Smith et al., 2005a; are
25 slightly younger than the ones published in Smith et al., 2005b, because geomagnetic correction has been included in the calculations, see Fig. 7). Farber et al. (2005) dated

EGU

glacial advances to ~29 and 16.5 ka (geomagnetically corrected), respectively. These results seem to disagree with our chronology (glacial advances at ~22–25 and 11–13 ka), but re-calculation of the exposure ages of Smith et al. and Farber et al. using Lifton et al. (2005) instead of Stone (2000) yields considerably lower ages. Figure 7 illustrates this for the samples from Valle Antacocha in Peru. The recalculated exposure ages are in much better agreement with our results, indicating that the maximum glaciation during the last glacial cycle occurred at ~22–25 ka, i.e. much later than previously assumed and roughly synchronous with the global temperature minimum. A recessional moraine in the Valle Antacocha is recalculated to ~15 ka. This advance is clearly older than the Late Glacial advances that we dated. Younger Late Glacial moraines (recalculated ages ~12 ka) are described, however, for example in the Calcalcocha Valley (Smith et al.) or at the "Breque" site in Peru (also shown in Fig. 7) (Farber et al., 2005). Note that for illustration in Fig. 7 we intentionally chose moraines with a low scatter in ages only. Larger scatter indicates that the glacial morphologies may be more complicated or that dating those moraines is more challenging due to rock surface erosion or landscape instability.

The Breque moraine deserves further emphasis, because it may actually serve as a local calibration site, independently dated to ~13.1 cal. ka BP (Rodbell and Seltzer, 2000; Farber et al., 2005) (blue box in Fig. 7). Although the "Lifton ages" seem to be too young, we argue that his scaling system is nevertheless preferable over the one of Stone (2000) based on the reasons outlined above. Including atmospheric correction (blue diamonds) increases the exposure ages, but still the mean of all boulders seems to result in a significant age underestimation. Because the Breque site yields a reference production rate of only 4.66 atoms a^{-1} g^{-1} SiO_2 and appears to be an outlier compared to all other calibration sites, we currently hesitate to include it in the calculation of the mean reference production rate (5.87 atoms a^{-1} g^{-1} SiO_2). On the other hand, we cannot totally exclude the possibility that using Breque as local calibration site yields the best estimates for the real exposure ages in the tropical Andes. Corresponding results are therefore also shown in Fig. 6. The need for further research

to reduce the exposure age uncertainties, particularly the need for more high-altitude calibration sites, is obvious.

4.4.2   Independent age control

There is not much independent dating control on the glacial advances in the Central
5   Andes with which to evaluate our exposure age chronology. Most previous work is based on morphology, soil development and bedded slope deposits (e.g. Lauer and Rafiqpoor, 1986; Lauer and Rafiqpoor, 1989; Jordan et al., 1993; Reuter et al., 1995; Heine, 1996). Numerous minimum radiocarbon ages for moraines have been reported from basal peat and lake sediments (summarized in Smith et al., 2005c: minimum
10   ages range from 9 to 12 ^{14}C ka BP. Note that calibrated ages are older than ^{14}C ages. Use e.g. http://www.calpal-online.de if necessary). In Peru, maximum-limiting ^{14}C ages suggest that substantial glacial stillstands or readvances there occurred between ~16-13 cal ka BP (Rodbell, 1993; Seltzer et al., 1995; Rodbell and Seltzer, 2000). Maximum-limiting ^{14}C ages in Bolivia are available for the Valle San Francisco
15   (~33 ^{14}C ka BP: Argollo, 1980) and bracketing ages exist for the Rio Kollpaña (Servant et al., 1981: 16.6 and 27 ^{14}C ka BP, respectively). All these data are in agreement with our results of a maximum glaciation at ~22–25 ka and deglaciation after ~11 ka.

There are, however, also findings that have been interpreted to corroborate an early local LGM: First, a minimum age for a glacial advance of ~20 ^{14}C ka BP has
20   been reported from the Laguna Kollpa Khota (Seltzer, 1994). We argue that this age (~24 cal ka BP) does not necessarily contradict our proposed chronology, because it is just a minimum age for a potentially much older, and more extensive glaciation than the last one. Secondly, the sudden drops of magnetic susceptibility (MS, a proxy for glacial flour) in the sediments of Lake Titicaca and Lake Junin at ~20 ka BP have led Seltzer
25   et al. (2002) to conclude that deglaciation occurred much earlier than in the Northern Hemisphere. Glacial flour may be trapped very effectively as soon as the most extensive glacial stage is abandoned and a sediment trap is created behind the terminal moraines. Subsequent, although still significant, glacier fluctuations may therefore not

EGU

be recorded in the MS signal. In fact, the MS signal in core NE985PC in Lake Titi-caca (close to the Cordillera Real) reaches high values only between 25 and 20 ka BP (Seltzer et al., 2002), indicating that the glaciers there (e.g. in the Valle San Francisco) advanced during and not before that time. Our chronology is also in good agreement

5 with a maximum ^{14}C age of 24.4 ka BP (~27.4 cal ka BP) obtained from a soil inter-calated between two moraines in the Cordillera Tunari near Cochabamba (J.-H. May, 2007, personal communication). The last glacial ice advance thus did not reach that site before that time. The basal moraine is much more weathered and older; it prob-ably correlates with glacial advances from earlier glacial cycles (see e.g. Smith et al.,

10 2005a).

4.4.3 Glaciation – the role of temperature

Modelling studies in the humid parts of the Eastern Cordillera show the high sensi-tivity of the glacier mass balance to temperature changes (Klein et al., 1999; Kull et al., 2003; Imhof et al., 2006; Kull et al., 2007). Provided that moisture availability did

15 not become a limiting factor in the past, glacial advances should therefore have co-incided with temperature minima, i.e. particularly the LGM at ~20–25 ka. During the Late Glacial and the general warming trend, a sudden drop in temperature occurred both in Antarctica, known as Antarctic Cold Reversal (ACR) (Petit et al., 1999), and in the Northern Hemisphere, known as the Younger Dryas (YD) (NGRIP members 2004).

20 The ACR slightly predates the YD. Both high-latitude cold events were likely able to sig-nificantly affect the low-latitude temperatures (Clement et al., 2004; Chiang and Bitz, 2005) and thus to provide favourable conditions for the Late Glacial advances in the Eastern Cordilleras between ~11 and 13 ka. The earlier advances dated to 15 ka may coincide with the Heinrich 1 event, during which very cold conditions are documented

25 in the North Atlantic region.

Based on climate modelling, Clement et al. (2004) suggested that, in contrast to glacial forcing by high-latitude temperatures, precessional solar forcing has only a mi-nor influence on tropical temperatures. Nevertheless, we point out that the significant

EGU

Late Glacial advances dated to ~11–13 ka coincide with the minimum austral summer insolation (December). Their large extent relative to the LGM advances may therefore partly be due to direct insolation forcing, i.e. reduced ablation.

4.4.4 Glaciation – the role of precipitation

It has previously been suggested that glacial advances in the Central Andes were synchronous with massive pre-LGM and Late Glacial wet phases on the Altiplano (Choqueyapu I and Choqueyapu II advances, and the 'Minchin' and 'Tauca' phases, respectively) (e.g. Servant and Fontes, 1978; Clayton and Clapperton, 1995; Clapperton et al., 1997; Clayton and Clapperton, 1997; Sylvestre et al., 1999). A recent study applying ^{14}C and U/Th dating techniques could, however, not corroborate the existence of the Minchin wet period (Placzek et al., 2006). Shorelines from three deep paleolakes on the Altiplano were dated to 120–98 ka (called "Ouki"), 18–14 ka ("Tauca") and 13–11 ka ("Coipasa"). Only shallow lakes existed between 98 and 18 ka. Note that these findings do not necessarily disagree with sediment-core records in the Salar de Uyuni indicating wet conditions from ~25 to 15 ka (Baker et al., 2001b). This is because the cores do not only provide information about the local hydrological conditions, but also record overflow of Lake Titicaca to the north. There, several lake level proxies show high moisture availability since 25 ka except for the dry Mid-Holocene (Baker et al., 2001a).

With regard to the glacial history, the precipitation records on the Altiplano are interpreted as follows: Glaciers in the relatively "wet" Eastern Cordilleras are sensitive to temperature changes and therefore advanced at ~20–25, ~15 and ~11–13 ka. Of course, very humid conditions during the Tauca and Coipasa phase provided favourable conditions for Late Glacial glacier advances. This is corroborated by high accumulation-ablation-ratios (AARs ~0.8) reconstructed for the respective moraines (Kull et al., 2007). On the other hand, glaciation in the "dry" areas further south and west is much more sensitive to moisture availability (Kull, 1999; Kull and Grosjean, 2000; Kull et al., 2007). This is reflected by the lack of LGM moraines. Instead, mas-

Surface exposure dating in Bolivia

R. Zech et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◄	►
◄	►
Back	Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

sive Late Glacial glacier advances on the Altiplano and the Western Cordillera have been described and dated for example by Clapperton et al. (1997) and Clayton and Clapperton (1997).

5 Conclusions

We conducted [10]Be surface exposure dating on 28 boulders from moraines in three research areas in the Cordillera Real and the Cordillera Cochabamba. Being aware of sample-specific uncertainties, like pre-exposure, landform surface instability and rock surface erosion, we tentatively established a glacial chronology applying the "oldest age model". Maximum glaciation is dated to ~22–25 ka, and Late Glacial advances occurred between 11 and 13 ka. Our results are in good agreement with previously published exposure age chronologies from the Eastern Cordillera in Bolivia and Peru (Farber et al., 2005; Smith et al., 2005a; Smith et al., 2005b), provided that the same calculation schemes are applied. We argue that the application of the recently published scaling system of Lifton et al. (2005) yields more accurate exposure ages than the still most widely used calculation scheme of Stone (2000). Apart from the selection of the scaling system, exposure age uncertainties are due to the choice of the reference production rate, i.e. the choice of the calibration sites. In the Andes, exposure ages may require large corrections for persistent altitude-pressure anomalies.

Our glacial chronology derived from surface exposure dating is consistent with published radiocarbon data, lake sediment analyses, and results from glacier-climate-modelling. Glaciation in the relatively wet areas of the Andes are mainly temperature-sensitive, i.e. roughly synchronous with the global LGM and the cold reversals during the Late Glacial (YD and ACR). On the other hand, glaciation in the drier parts of the Andes is mainly precipitation-sensitive; glaciers therefore reached a maximum extent synchronous with the 'Tauca' and "Coipasa" humid phase during the Late Glacial.

Overall, our study highlights (i) the limitations of exposure studies due to sample-specific uncertainties and the resultant need for a large exposure age dataset, (ii) the

EGU

limitations due to systematic uncertainties and the resultant need for local calibration studies, and (iii) the huge potential of surface exposure dating for the reconstruction of the glacial and climate history in the Central Andes, and a better understanding of the forcings and mechanisms of Late Quaternary climate change in general.

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EGU

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Title Page

Abstract   Introduction

Conclusions   References

Tables   Figures

◄   ►

◄   ►

Back   Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

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Surface exposure dating in Bolivia

R. Zech et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

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Surface exposure dating in Bolivia

R. Zech et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

Back   Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

Table 1. Sample data and exposure ages calculated according to Lifton et al. (2005), Pigati and Lifton (2004) ("P & L") and Stone (2000). Reference production rates are 5.87, 5.41 and 5.1 atoms a^{-1} g^{-1} SiO_2, respectively, calculated from the calibrations sites used by Stone (2000).

Sample	Latitude	Longitude	Altitude	^{10}Be	AMS SD[a]	Topographic Shielding Factor[b]	Exposure Ages[c] Lifton [ka]	Exposure Ages P & L	Exposure Ages Stone
	°S	°W	[m a.s.l.]	[10^5 at/g SiO_2]	[%]				
Valle San Francisco:									
SF12	15.97	68.53	4752	10.78	4.3	1	**15.3** ± 0.7	15.1	18.2
SF13	15.97	68.53	4750	15.19	3.9	1	**20.3** ± 0.8	20.1	25.7
SF21	15.94	68.53	4600	6.32	4.5	0.98	**10.4** ± 0.5	10.2	11.6
SF23	15.94	68.53	4601	6.02	4.5	0.98	**10.0** ± 0.5	9.8	11.0
SF32	15.97	68.55	4690	12.05	4.0	1	**17.2** ± 0.7	16.9	20.9
SF33	15.98	68.55	4691	13.85	3.2	1	**19.3** ± 0.6	19.1	24.0
SF41	15.98	68.54	4665	12.95	4.4	1	**18.5** ± 0.8	18.2	22.7
SF42	15.98	68.54	4666	16.42	3.5	1	**22.6** ± 0.8	22.3	28.8
SF43	15.98	68.54	4667	17.87	3.5	1	**24.1** ± 0.9	23.8	31.3
SF51	16.00	68.54	4470	5.40	6.1	1	**9.4** ± 0.6	9.2	10.3
SF52	16.00	68.54	4471	7.64	4.3	1	**12.9** ± 0.6	12.6	14.6
SF53	16.00	68.54	4472	6.80	4.0	1	**11.5** ± 0.5	11.3	13.0
Valle de Rio Suturi:									
RM13	17.23	66.44	3930	5.33	5.8	0.97	**12.2** ± 0.7	12.0	13.3
RM14	17.23	66.44	3931	4.40	6.8	0.97	**10.3** ± 0.7	10.1	10.9
RM22	17.23	66.46	3801	4.02	7.6	0.97	**10.1** ± 0.8	9.9	10.7
RM31	17.23	66.46	3780	5.24	5.9	0.97	**13.0** ± 0.8	12.8	14.0
RM33	17.23	66.46	3780	4.61	5.2	0.97	**11.6** ± 0.6	11.4	12.3
RM41	17.22	66.47	3863	10.30	5.6	0.98	**22.0** ± 1.2	21.9	26.3
RM42	17.22	66.47	3868	5.23	7.0	0.98	**12.2** ± 0.9	12.0	13.3
RM51	17.22	66.41	4344	3.59	7.6	0.97	**7.0** ± 0.5	6.9	7.3
Valle Huara Loma:									
HH11	17.22	66.26	4380	7.74	4.7	1	**13.3** ± 0.6	13.1	15.1
HH22	17.21	66.26	4360	6.56	3.7	1	**11.5** ± 0.4	11.4	12.9
HH31	17.21	66.27	4212	5.25	4.9	0.98	**10.4** ± 0.5	10.2	11.3
HH32	17.21	66.27	4213	5.61	3.8	0.98	**11.0** ± 0.4	10.8	12.1
HH41	17.20	66.26	4225	6.20	4.6	1	**11.8** ± 0.5	11.5	13.0
HH43	17.20	66.26	4225	6.04	4.4	1	**11.4** ± 0.5	11.3	12.6
HH51	17.21	66.26	4222	9.41	3.6	1	**16.9** ± 0.6	16.7	19.8
HH52	17.21	66.26	4223	7.93	3.5	1	**14.6** ± 0.5	14.4	16.7

[a] AMS SD = 1σ standard deviation of the AMS measurement
[b] all ages are additionally corrected with a sample thickness factor of 0.97 ($\sim$3–4 cm)
[c] with the propagated 1σ standard deviation of the AMS measurement

Surface exposure dating in Bolivia

R. Zech et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version
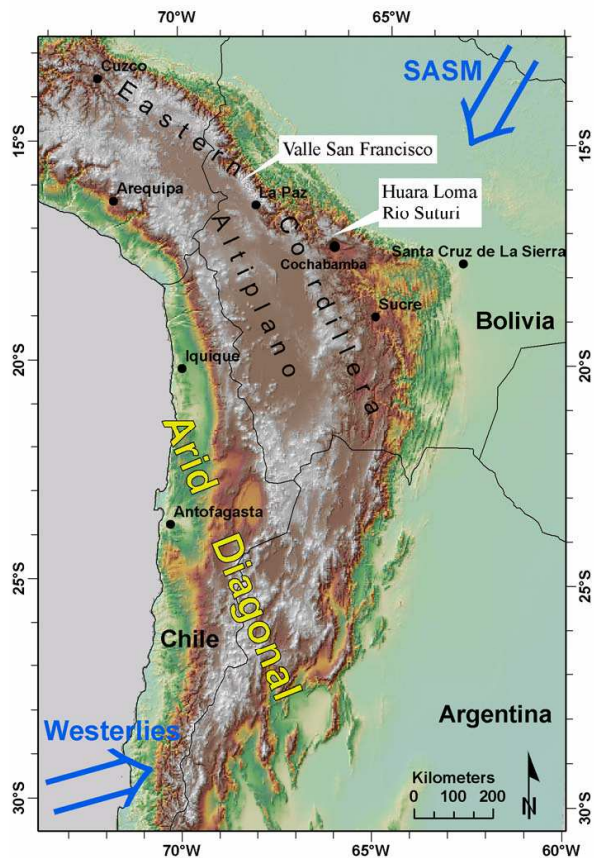
Interactive Discussion

EGU

Fig. 1. Location of the research areas. The Valle San Francisco (Cordillera Real) and the Valle de Rio Suturi and Huara Loma (Cordillera Cochabamba) are situated at the north-eastern transition zone from the Altiplano to the lowlands of Bolivia and the Amazon Basin. SASM = South American Summer Monsoon.
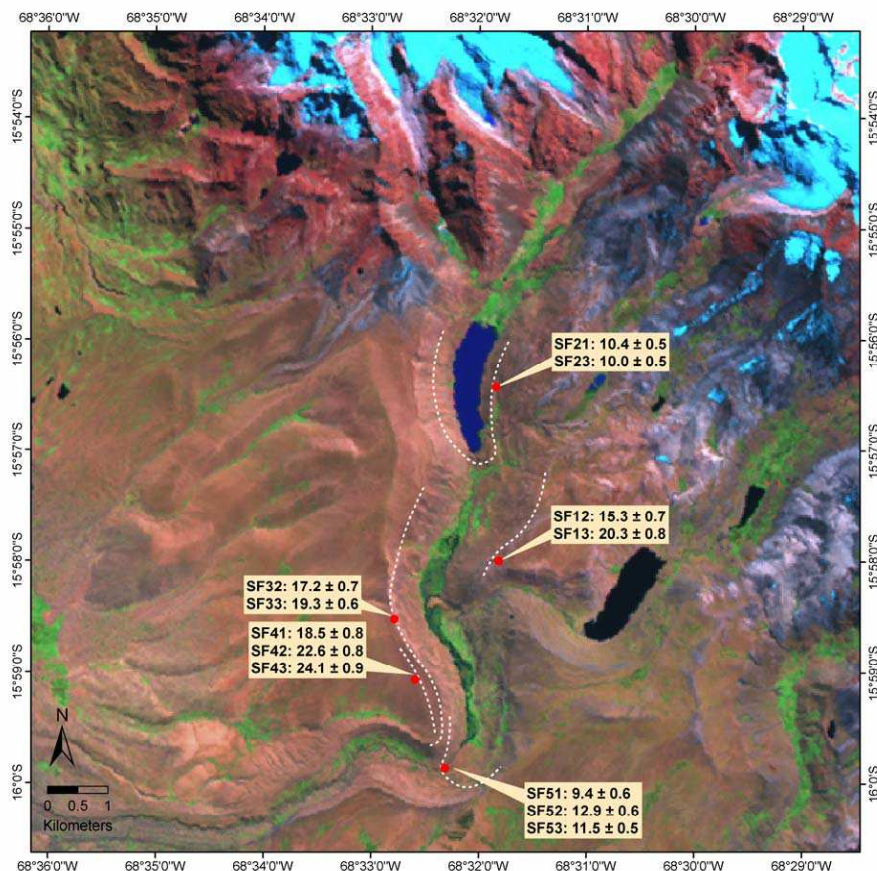
EGU

Fig. 2. Landsat image (RGB 742) showing the geomorphological and stratigraphical situation in the Valle San Francisco. Sampling locations and exposure ages in ka (calculated according to Lifton et al., 2005, and a reference production rate of 5.87 atoms a^{-1} g^{-1} SiO_2) are indicated. The dotted lines illustrate the unambiguous extent of the sampled moraines.
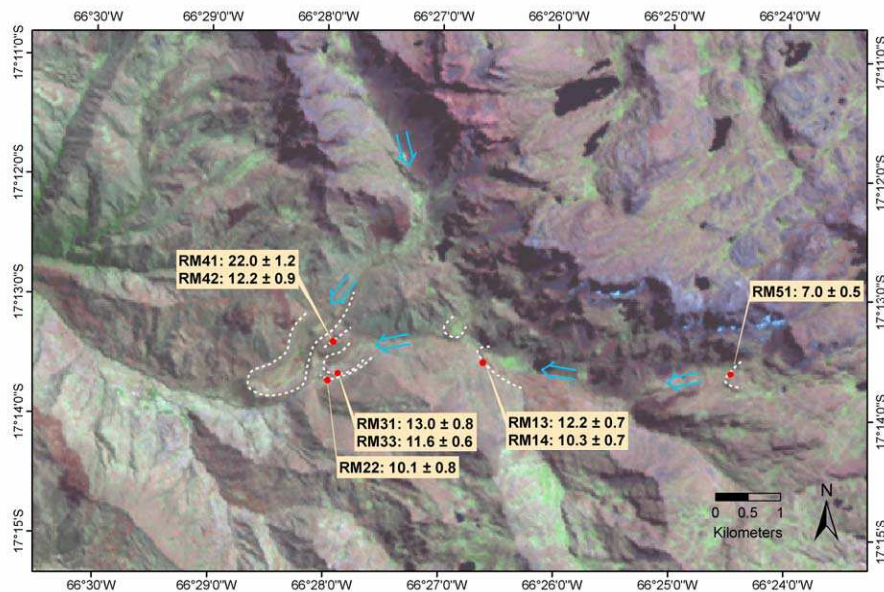
Fig. 3. Same as Fig. 2 for the Valle de Rio Suturi. The arrows show the former ice-flow direction.

EGU

Surface exposure dating in Bolivia

R. Zech et al.

EGU

HH41: 11.8 ± 0.5
HH43: 11.4 ± 0.5

HH51: 16.9 ± 0.6
HH52: 14.6 ± 0.5

HH31: 10.4 ± 0.5
HH32: 11.0 ± 0.4

HH22: 11.5 ± 0.4

HH11: 13.3 ± 0.6
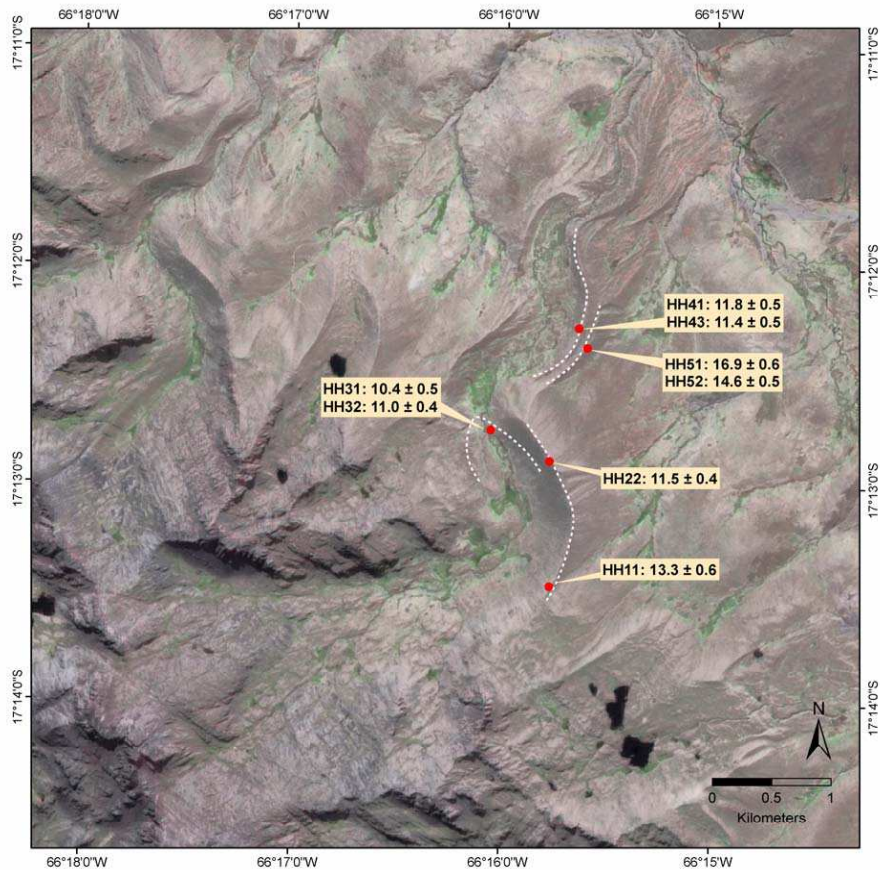
Fig. 4. Same as Fig. 2 for the Huara Loma (here a Corona image was draped over the Landsat data, RGB 742).

EGU
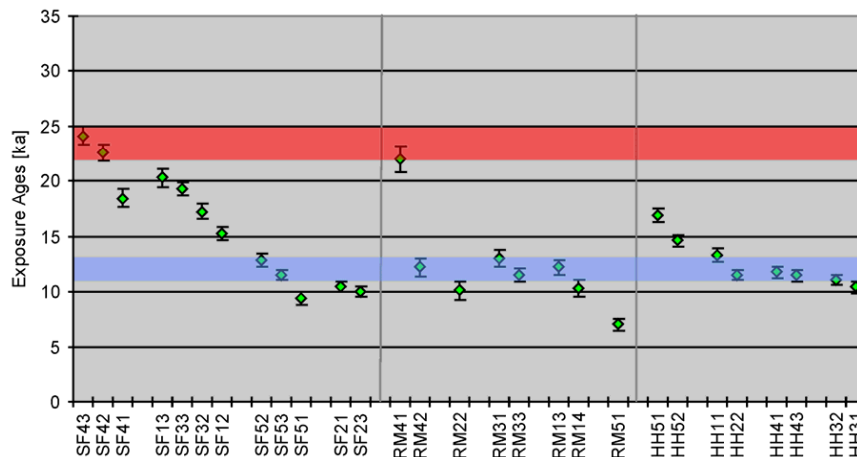
Fig. 5. Exposure ages from all three research areas arranged in stratigraphic order. Calculations according to Lifton et al. (2005) with a reference production rate of 5.87 atoms a^{-1} g^{-1} SiO_2. Errors bars illustrate the 1σ AMS errors. The shaded red bar indicates the LGM glacial advances (22–25 ka), the blue bar the Late Glacial ones (11–13 ka).

EGU
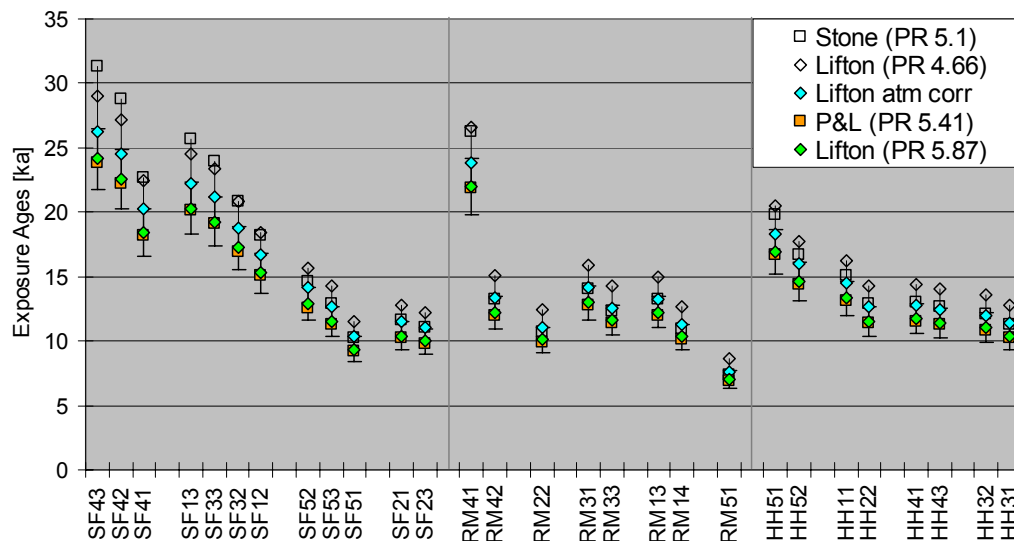
Fig. 6. Exposure ages calculated according to Lifton et al. (2005) with a reference production rate (PR) of 5.87, Pigati and Lifton (2004) PR 5.41, Stone (2000) PR 5.1, Lifton et al. (2005) including an estimated atmospheric correction, and Lifton et al. with a PR of 4.66 (Breque calibration site). Error bars: 10% for Lifton et al. (2005), PR 5.87.
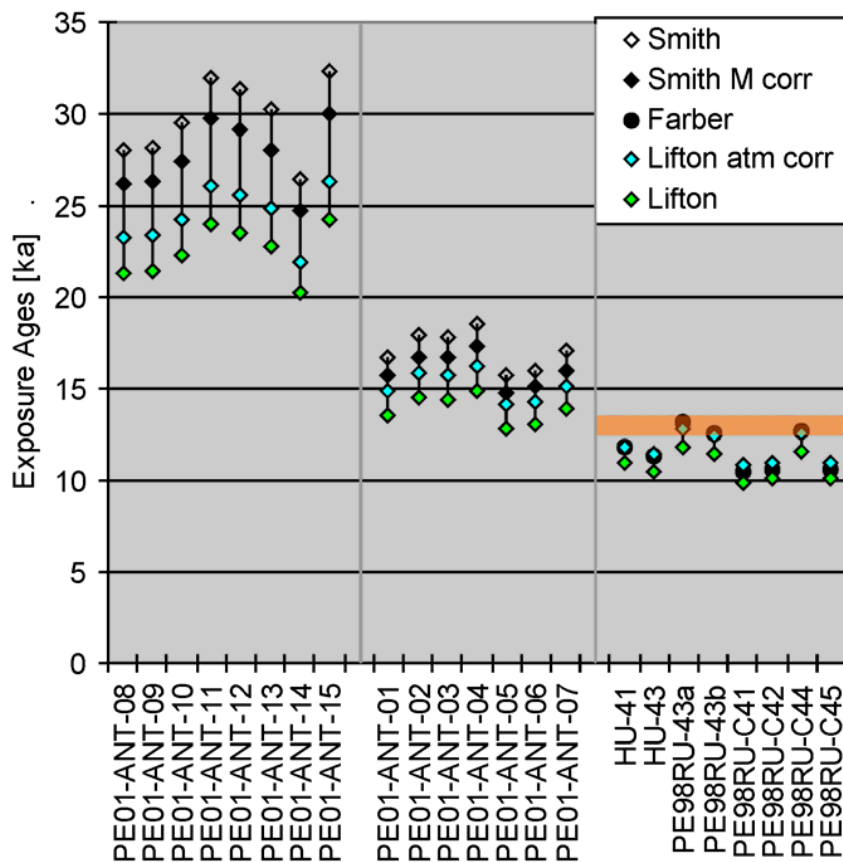
Fig. 7. Recalculated exposure ages (using Lifton et al., 2005, PR 5.87) from the Valle Anta-cocha (Smith et al., 2005a, b; open diamonds: uncorrected; black diamonds: geomagnetically corrected) and the "Breque" moraine (Farber et al., 2005: black circles). The orange box illus-trates the ^{14}C age of the Breque moraine, a potential but controversial calibration site.

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