# GSA DATA REPOSITORY 2014131

# Late Holocene fluctuations of Qori Kalis outlet glacier, Quelccaya Ice Cap, Peruvian Andes

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## DATA REPOSITORY FIGURES AND TABLES

Figures DR1-DR10 provide descriptions of all $^{10}$Be ages and interpreted moraine ages as well as photos of boulders sampled. To interpret the moraine ages, we excluded $^{10}$Be ages based on their contribution to the reduced chi-squared ($\chi_R^2$) value (e.g. Kaplan and Miller, 2003). Similar to the approach used by Putnam et al. (2012), we rejected samples until the $\chi_R^2$ value of $^{10}$Be ages of a moraine was close to one. We also used the stratigraphic order of moraines to reject or retain samples. Fig. DR10 is a comparison of moraine ages based on all $^{10}$Be ages and those based on $^{10}$Be ages were not rejected based on the above criteria. Table DR1 provides data for calculating $^{10}$Be ages. Table DR2 shows the interpreted moraine ages. All ages reported herein are in years before CE 2009 (yr).

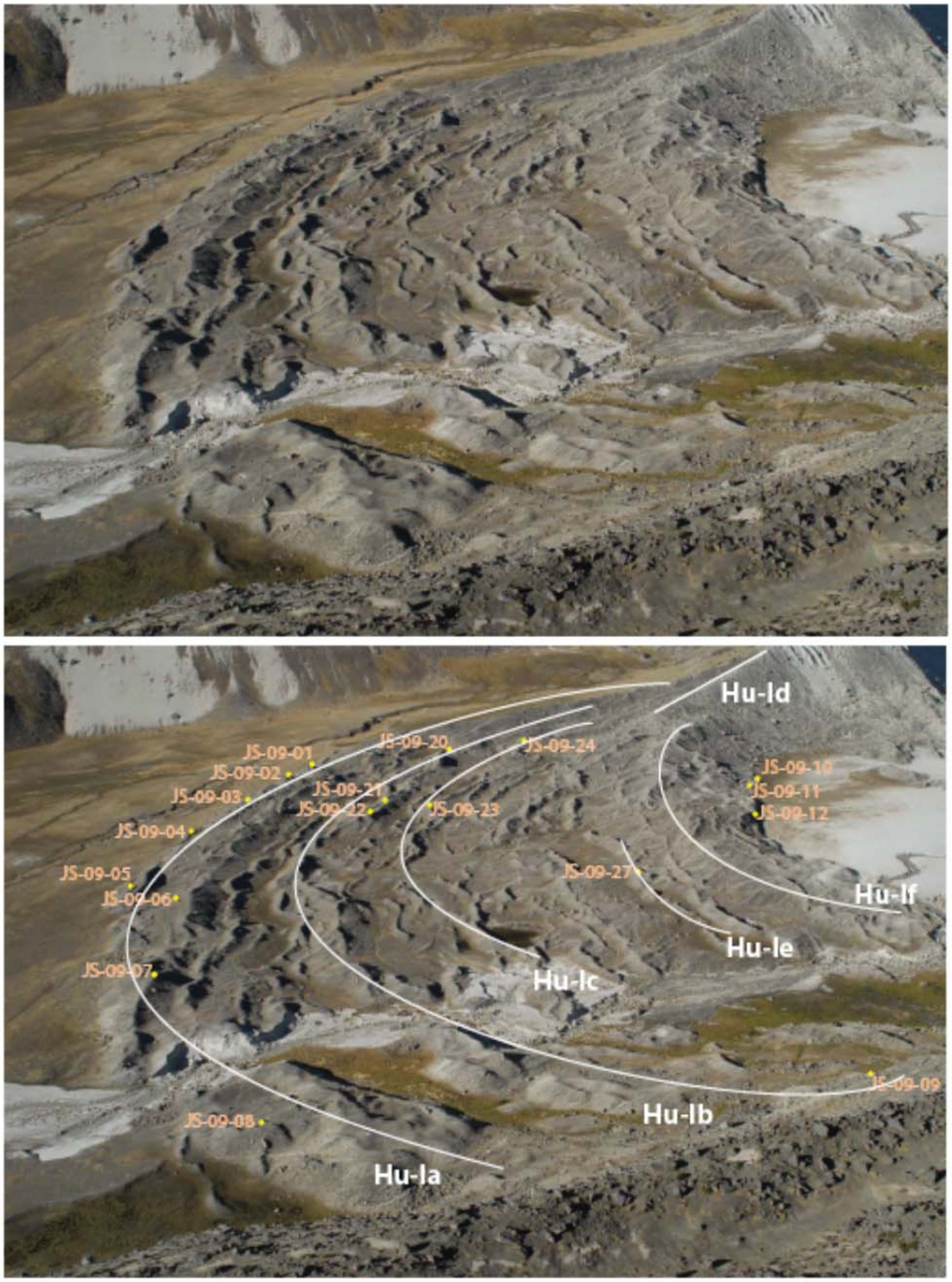



Fig. DR1. Top: Photo of Qori Kalis moraines looking north. Qori Kalis glacier is off the photo to the right (east). Bottom: Approximate moraine positions (labeled Hu-Ia to Hu-If) are marked in white and correspond to the geomorphic map (Fig. 1). $^{10}$Be sample locations are shown in yellow. Crosscutting of the Hu-Ia, Hu-Ib and Hu-Ic moraines by the Hu-Id moraine is apparent in the upper right of the image, indicating that the Hu-Id moraine was deposited by a readvance.

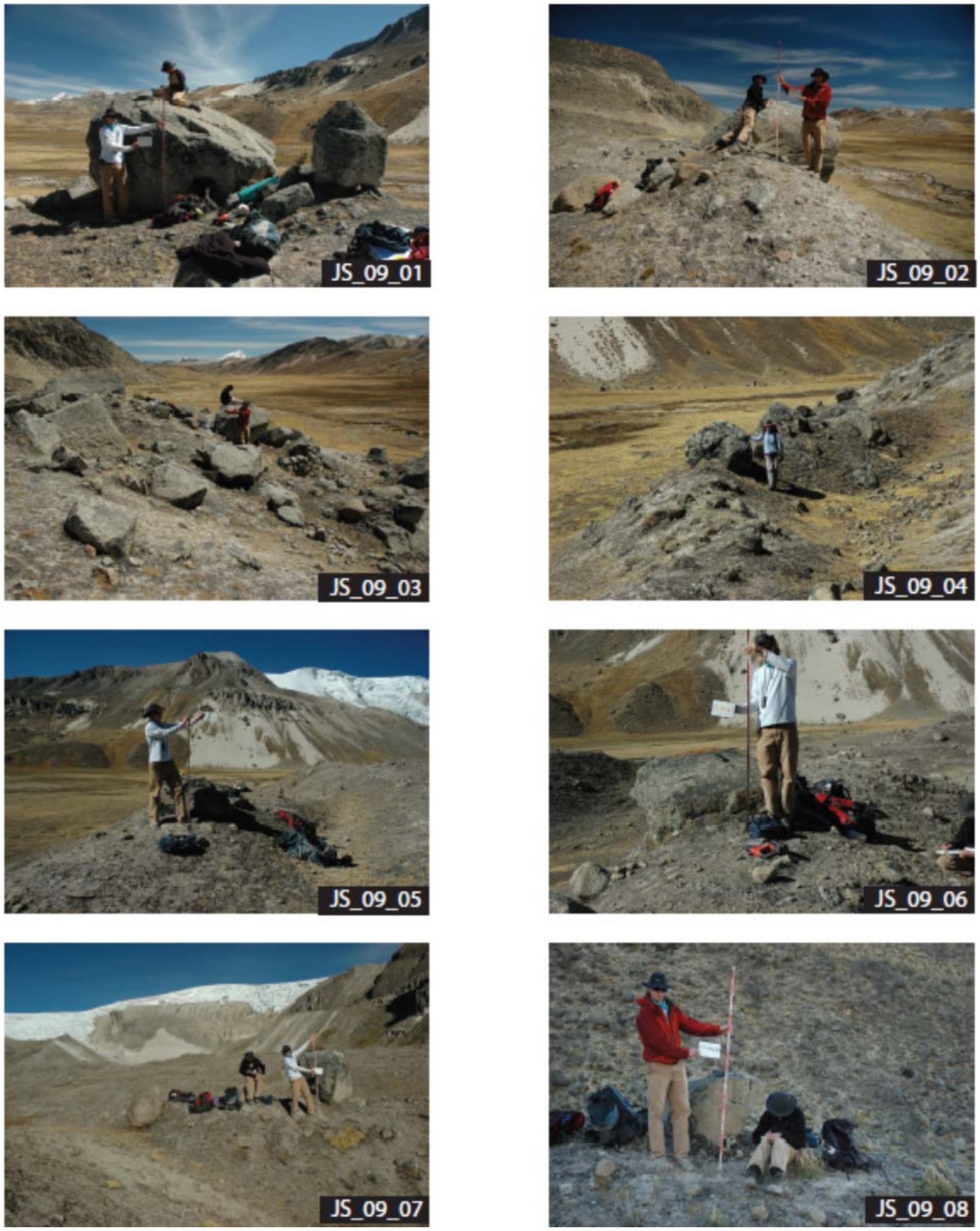
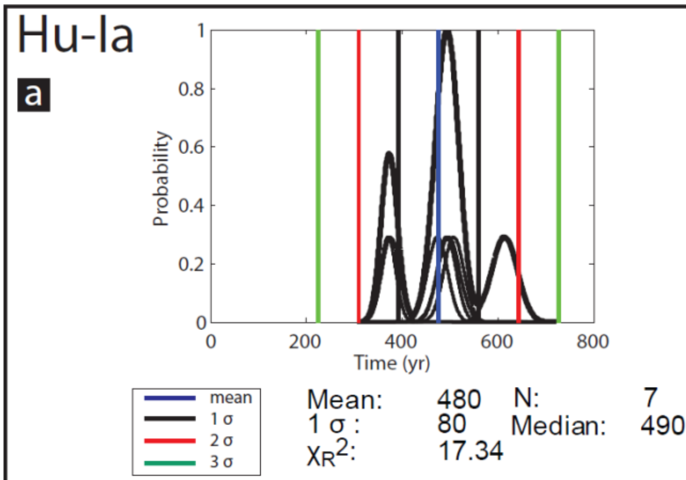
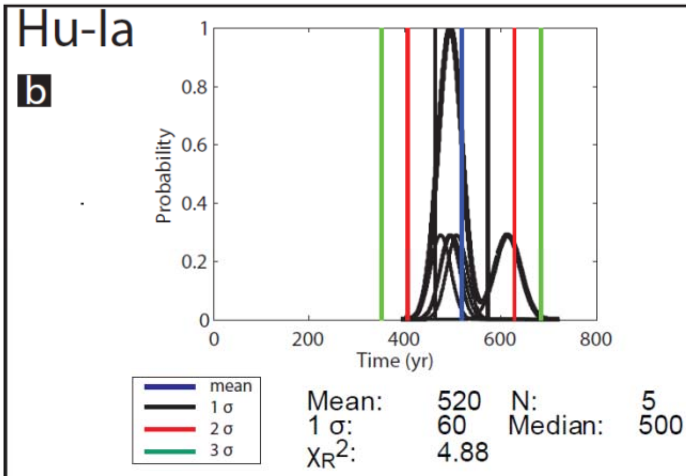


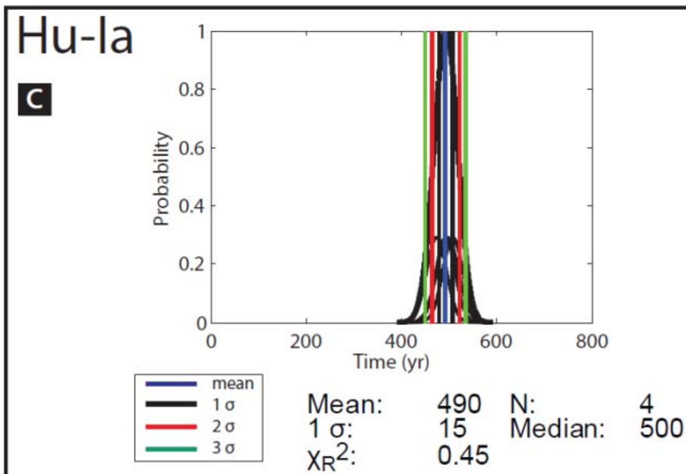

Fig. DR2. Photos of boulders sampled on the Hu-Ia moraine.




| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| JS-09-01 | 371 | 16 | Hu-1a |
| JS-09-02 | 474 | 21 | Hu-1a |
| JS-09-03 | 376 | 18 | Hu-1a |
| JS-09-04 | 508 | 21 | Hu-1a |
| *JS-09-05* | *4747* | *145* | *Hu-1a* |
| JS-09-06 | 493 | 20 | Hu-1a |
| JS-09-07 | 497 | 23 | Hu-1a |
| JS-09-08 | 614 | 27 | Hu-1a |

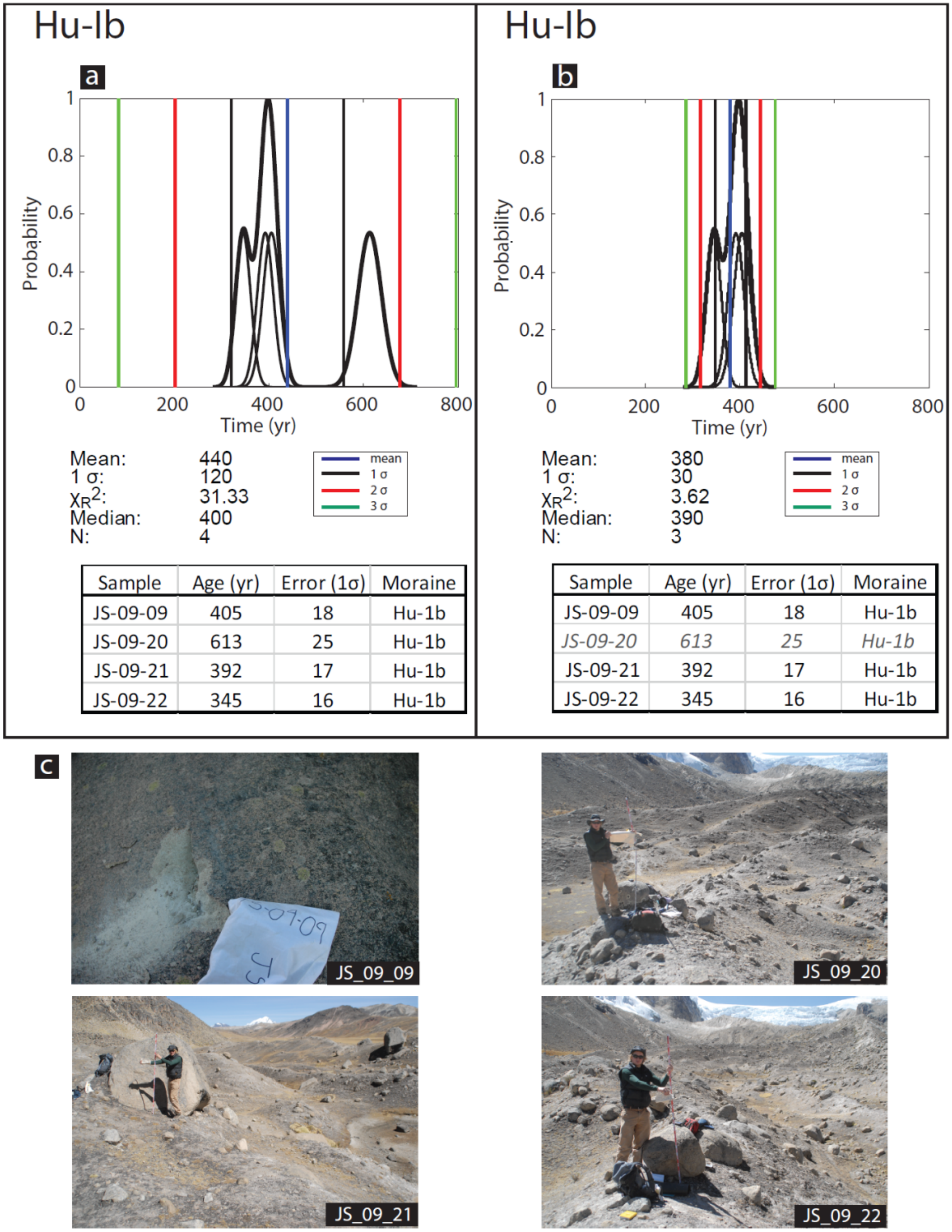



| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| *JS-09-01* | *371* | *16* | *Hu-1a* |
| JS-09-02 | 474 | 21 | Hu-1a |
| *JS-09-03* | *376* | *18* | *Hu-1a* |
| JS-09-04 | 508 | 21 | Hu-1a |
| *JS-09-05* | *4747* | *145* | *Hu-1a* |
| JS-09-06 | 493 | 20 | Hu-1a |
| JS-09-07 | 497 | 23 | Hu-1a |
| JS-09-08 | 614 | 27 | Hu-1a |




| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| *JS-09-01* | *371* | *16* | *Hu-1a* |
| JS-09-02 | 474 | 21 | Hu-1a |
| *JS-09-03* | *376* | *18* | *Hu-1a* |
| JS-09-04 | 508 | 21 | Hu-1a |
| *JS-09-05* | *4747* | *145* | *Hu-1a* |
| JS-09-06 | 493 | 20 | Hu-1a |
| JS-09-07 | 497 | 23 | Hu-1a |
| *JS-09-08* | *614* | *27* | *Hu-1a* |

Fig. DR3. Statistics summary for $^{10}$Be ages of the Hu-Ia moraine. Plots (a, b and c) are probability distribution functions of $^{10}$Be ages. Vertical lines indicate the means (blue) and standard deviations at the 1σ, 2σ and 3σ confidence levels (black, red, and green lines, respectively). Statistics associated with the age populations are shown below the probability distribution functions. Tables (a, b and c) show sample numbers and unrounded $^{10}Be$ ages. The samples excluded from the associated statistical analysis are shown in gray italics. a) All $^{10}Be$ ages of the Hu-Ia moraine excluding outlier JS-09-05 are included in the calculated statistics. Sample JS-09-05 is a clear outlier and is omitted from moraine age interpretations. With the exclusion of JS-09-05, $^{10}Be$ ages (n=7) of the Hu-Ia moraine yielded a $\chi_R^2$ value of 17.34. b) To lower the $\chi_R^2$ value, we rejected samples JS-09-01 and -03. This yielded a $\chi_R^2$ value of 4.88. c) Rejecting sample JS-09-08 further lowered the $\chi_R^2$ value to 0.45; however, there is no geologic evidence that this sample should be removed. Therefore, we retained sample JS-09-08 and consider 520±60 yr as the age of the Hu-Ia moraine. $^{10}Be$ ages of boulders on moraines may be apparently older than the age of a moraine if boulders contain $^{10}Be$ from a prior period of exposure. $^{10}Be$ ages of boulders on moraines may be apparently younger than the age of a moraine if boulders were covered by sediment, snow or vegetation, if they were exhumed from within the landform subsequent to the time of landform deposition, or if sub-aerial erosion acted on the boulder surface. As noted in Table DR1, it is unlikely that boulders sampled for this study were influenced by snow or vegetation cover; however, boulders may have been covered with sediment that was removed prior to our investigation. We were careful to sample only boulders on moraine crests and those that did not show evidence of exhumation.




| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| JS-09-09 | 405 | 18 | Hu-1b |
| JS-09-20 | 613 | 25 | Hu-1b |
| JS-09-21 | 392 | 17 | Hu-1b |
| JS-09-22 | 345 | 16 | Hu-1b |

| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| JS-09-09 | 405 | 18 | Hu-1b |
| *JS-09-20* | *613* | *25* | *Hu-1b* |
| JS-09-21 | 392 | 17 | Hu-1b |
| JS-09-22 | 345 | 16 | Hu-1b |

Fig. DR4. Statistics summary for $^{10}$Be ages of the Hu-Ib moraine (a and b) and photos of boulders sampled on the Hu-Ib moraine (c). a) and b) Same statistical calculations as Fig. DR3. a) All $^{10}$Be ages of the Hu-Ib moraine are included in the calculated statistics. b) Sample JS-09-20 was excluded because it is older than $^{10}$Be age of the Hu-Ia moraines located downvalley and likely indicates $^{10}$Be from a prior period of exposure (Figs. 1, DR3). Excluding this sample yielded a $\chi_R^2$ value of 3.62 and an interpreted moraine age of 380 ± 30 yr.

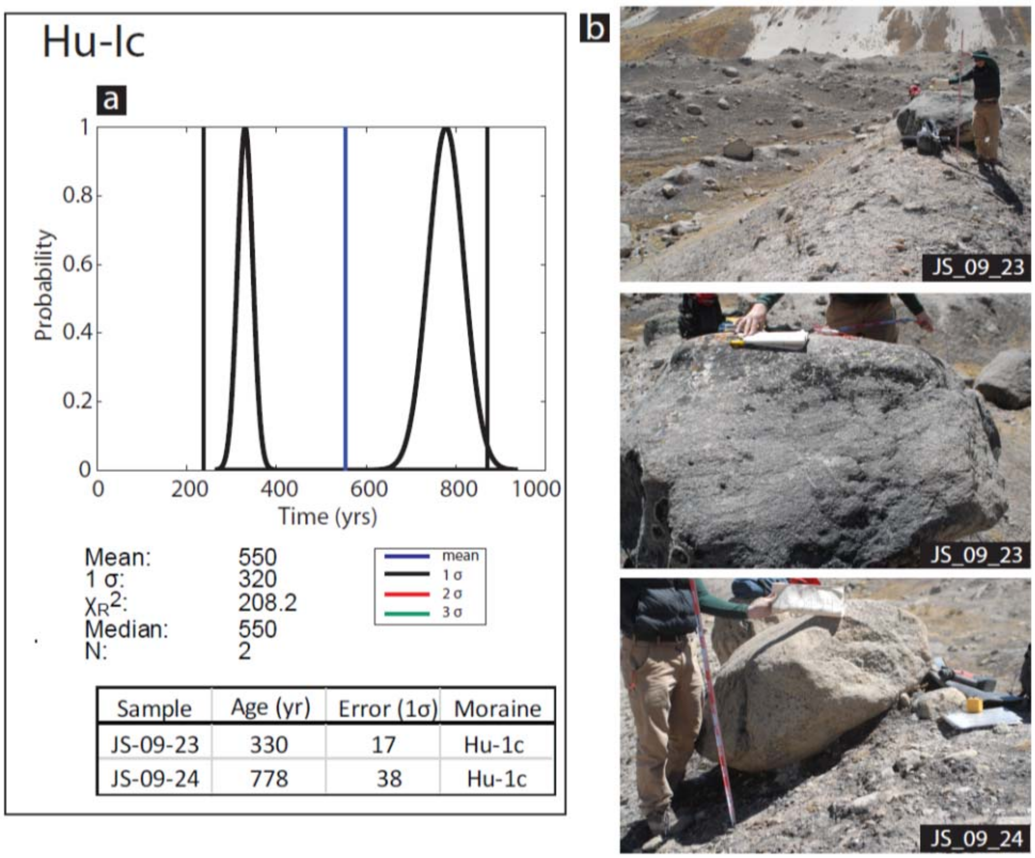



Fig. DR5. Statistics summary for $^{10}$Be ages of the Hu-Ic moraine (a) and photos of boulders sampled on the Hu-Ic moraine (b). a) Same statistical calculations as Fig. DR3. All $^{10}$Be ages of the Hu-Ic moraine are included in the calculated statistics. Sample JS-09-24 was rejected because it is older than $^{10}$Be ages of moraines located downvalley and likely indicates $^{10}$Be from a prior period of exposure (Fig. 1, Figs. DR3, DR4). Since there is only one $^{10}$Be age remaining on this moraine, no $\chi_R^2$ value is reported. We interpret the age of the Hu-Ic moraine as 330±20 yr. b) The center image (sample JS-09-23) shows a striated boulder surface.

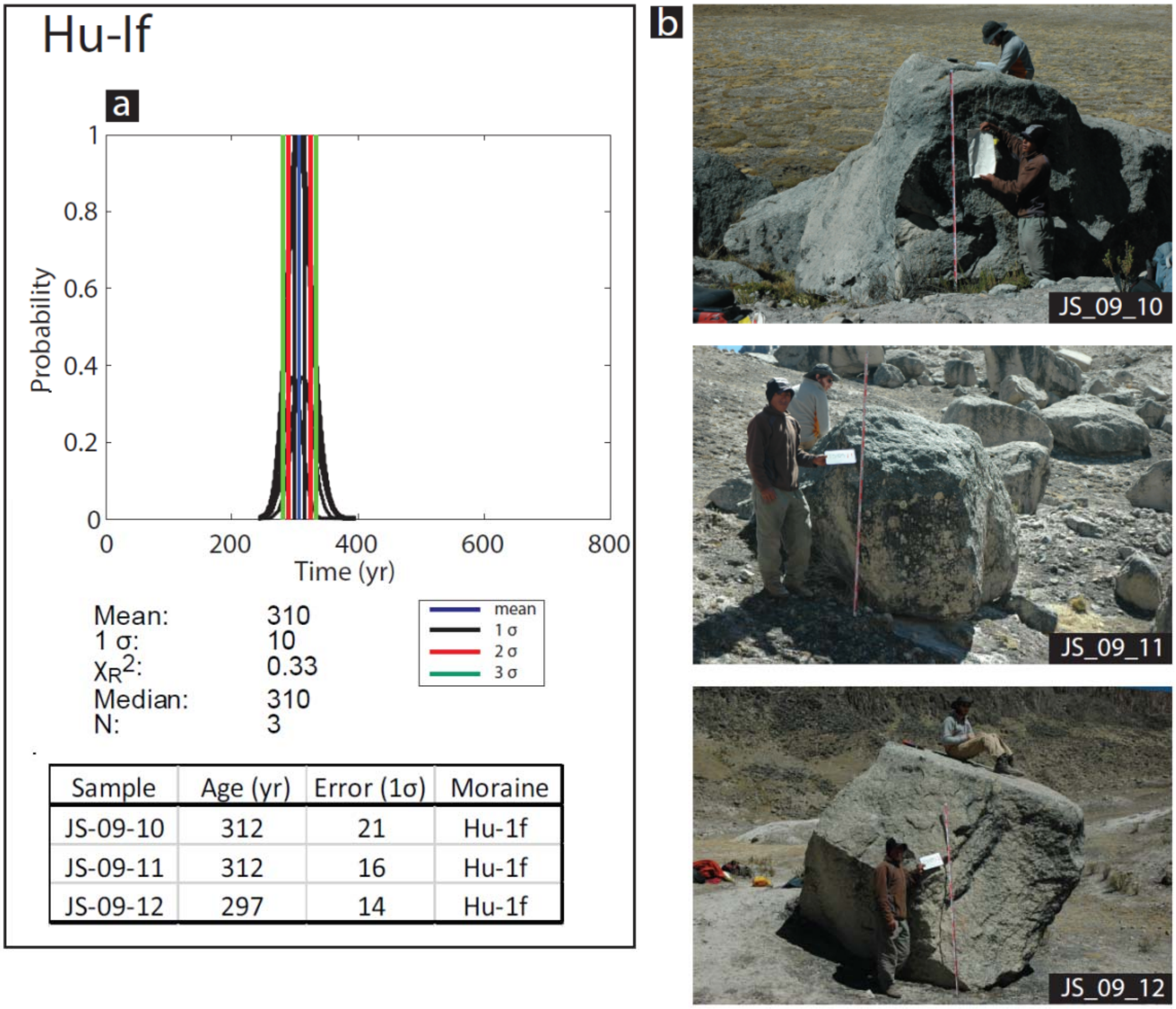
Hu-Ie

a

| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| JS-09-27 | 393 | 22 | Hu-1e |

b


Fig. DR6. Table of the $^{10}$Be age of the Hu-Ie moraine (a) and photo of the boulder sampled on the Hu-Ie moraine (b). This sample was rejected because it is out of stratigraphic order with the $^{10}$Be ages of the Hu-Ic and Hu-If moraines. Therefore, we do not interpret an age of the Hu-1e moraine.




| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| JS-09-10 | 312 | 21 | Hu-1f |
| JS-09-11 | 312 | 16 | Hu-1f |
| JS-09-12 | 297 | 14 | Hu-1f |

Fig. DR7. Statistics summary for $^{10}Be$ ages of the Hu-If moraine (a) and photos of boulders sampled on the Hu-If moraine (b). a) Same statistical calculations as Fig. DR3. We interpret the age of the Hu-If moraine age as 310±10 yr.

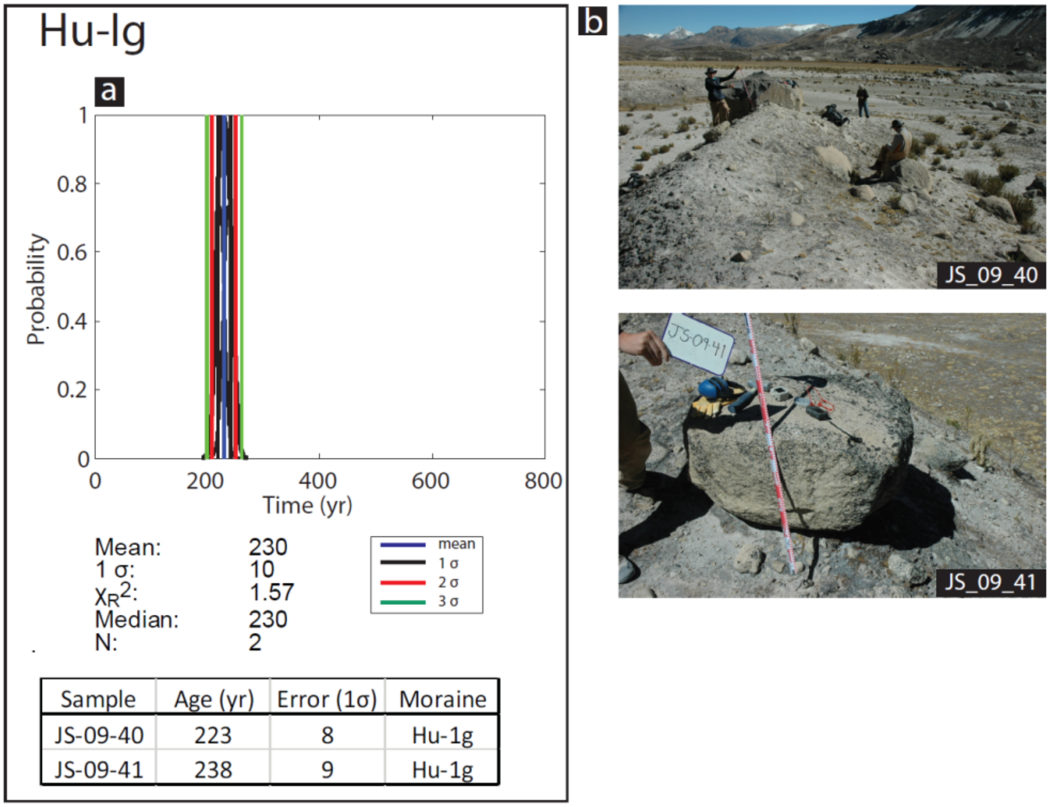
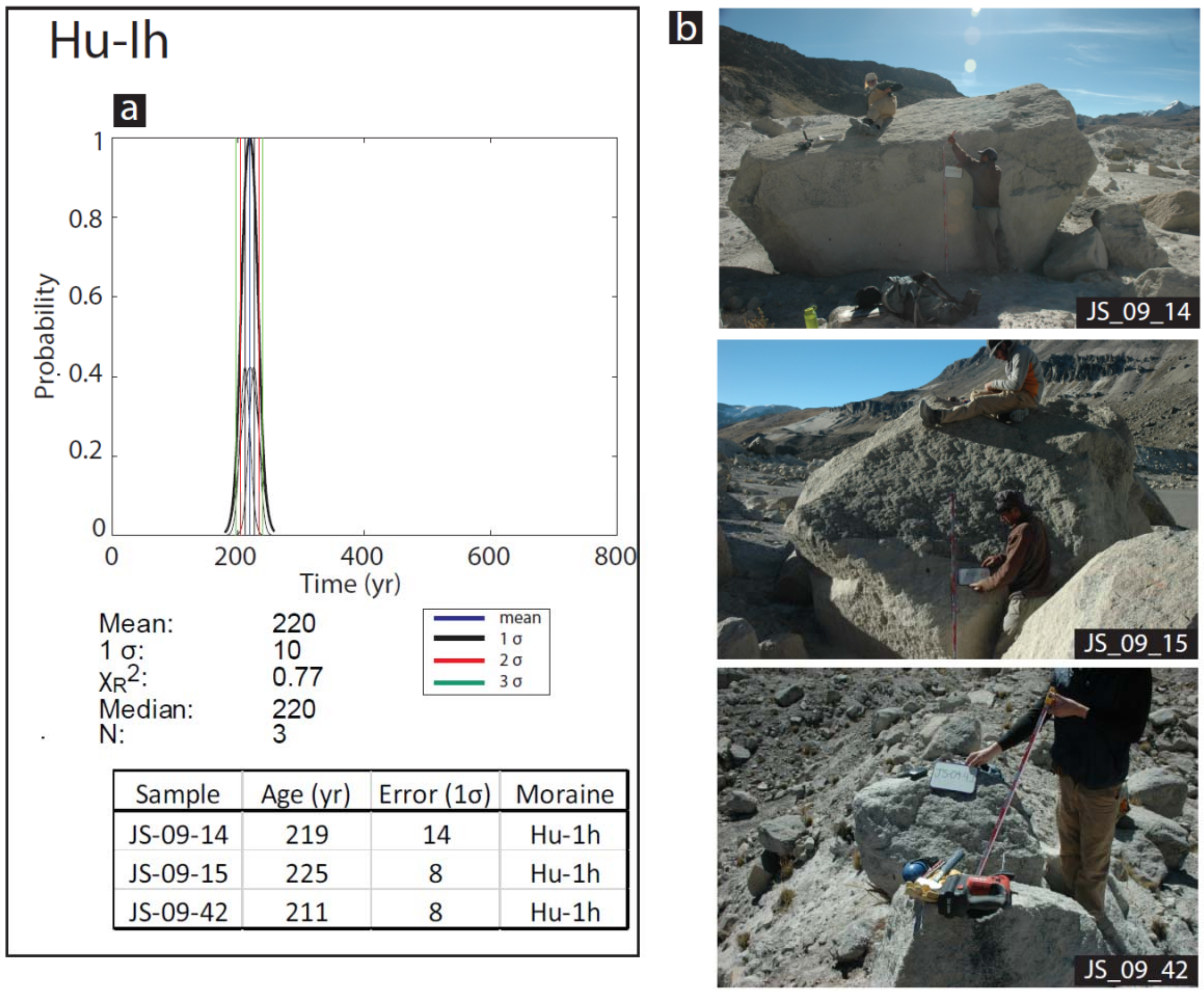



Fig. DR8. Statistics summary for $^{10}$Be ages of the Hu-Ig moraine (a) and photos of boulders sampled on the Hu-Ig moraine (b). a) Same statistical calculations as Fig. DR3. We interpret the age of the Hu-Ig moraine age as 230±10 yr.




| Sample | Age (yr) | Error (1σ) | Moraine |
|---|---|---|---|
| JS-09-14 | 219 | 14 | Hu-1h |
| JS-09-15 | 225 | 8 | Hu-1h |
| JS-09-42 | 211 | 8 | Hu-1h |

Fig. DR9. Statistics summary for $^{10}$Be ages on the Hu-Ih moraine (a) and photos of boulders sampled on the Hu-Ih moraine (b). a) Same statistical calculations as Fig. DR3. The Hu-Ih moraine marks an ice-margin position similar to that observed in the CE 1963 air photos. The three ages are consistent with one another with a mean age of 220±10 yr. These data likely indicate the ice margin position at CE 1963 and at 220 yr was similar. The $^{10}$Be ages on the Hu-Ih moraine are consistent with ice retreat from the Hu-Ig moraines. The ice position between ~220±10 yr and 1963 is unknown but it was likely at or smaller than the Hu-g and Hu-Ih moraine positions.

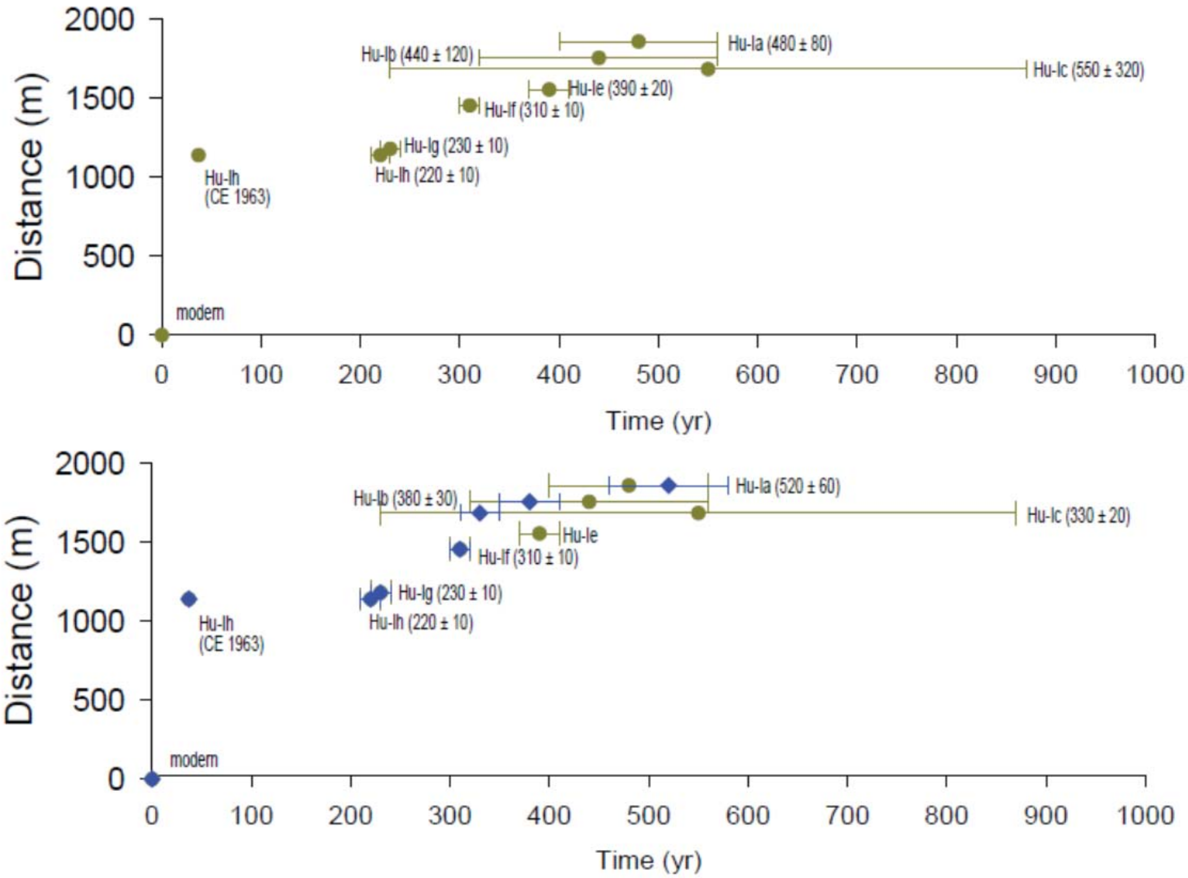



Fig. DR10. Top: The green circles and bars show the mean ages and $1\sigma$ uncertainties of all $^{10}Be$ ages on the Qori Kalis moraines plotted on a graph of distance (down valley from the modern ice margin) and time (excluding sample JS-09-05 on the Hu-Ia moraine). Bottom: The green bars and circles are the same as the top panel. The blue bars and diamonds show the interpreted mean ages and $1\sigma$ of moraines based on our exclusion of $^{10}Be$ ages. Each moraine is labeled with an interpreted moraine age (Figs. 1, 2 and Table DR2). Both plots indicate younger moraine ages trending upvalley, a pattern consistent with the stratigraphic order of moraines (Figs. 1 and DR1).

## TABLE DR1. BOULDER SAMPLE INFORMATION AND $^{10}$BE DATA

| Sample ID | CAMS number | Latitude (°N) | Longitude (°W) | Elevation (m asl) | Thickness (cm) | Shielding correction | Quartz wt. (g) | $^{9}$Be Carrier (mg)* | $^{10}$Be/$^{9}$Be ± 1σ ($10^{-14}$)† | $^{10}$Be Conc. ± 1σ (at $g^{-1}$)§ | Age ± Uncertainty (yr)# |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hu-Ia | | | | | | | | | | | |
| JS-09-01** | BE30981 | -13.9001 | -70.8478 | 4946 | 2.194 | 0.998 | 15.7239 | 0.2044†† | 1.8851 ± 0.0702 | 16376 ± 610 | 370 ± 20 |
| JS-09-02 | BE30982 | -13.9000 | -70.8481 | 4947 | 2.824 | 0.976 | 15.9589 | 0.2052†† | 2.3666 ± 0.0886 | 20338 ± 761 | 470 ± 20 |
| JS-09-03** | BE32652 | -13.9000 | -70.8487 | 4944 | 2.413 | 0.979 | 20.6724 | 0.1985 | 2.5296 ± 0.1023 | 16230 ± 656 | 380 ± 20 |
| JS-09-04 | BE30988 | -13.9000 | -70.8492 | 4932 | 2.215 | 0.929 | 15.5140 | 0.2070†† | 2.3269 ± 0.0794 | 20750 ± 708 | 510 ± 20 |
| JS-09-05** | BE32893 | -13.9004 | -70.8503 | 4935 | 1.551 | 0.902 | 18.3590 | 0.1903 | 27.3528 ± 0.5147 | 189421 ± 3564 | 4750 ± 150 |
| JS-09-06 | BE32653 | -13.9008 | -70.8503 | 4937 | 1.962 | 0.928 | 20.6103 | 0.1946 | 3.2032 ± 0.1037 | 20207 ± 654 | 490 ± 20 |
| JS-09-07 | BE30983 | -13.9015 | -70.8513 | 4932 | 2.318 | 0.966 | 15.7745 | 0.2062†† | 2.4120 ± 0.0940 | 21074 ± 821 | 500 ± 20 |
| JS-09-08 | BE32654 | -13.9024 | -70.8520 | 4931 | 2.560 | 0.877 | 20.5978 | 0.1960 | 3.7128 ± 0.1390 | 23613 ± 884 | 610 ± 30 |
| Hu-Ib | | | | | | | | | | | |
| JS-09-09 | BE32894 | -13.9043 | -70.8510 | 4947 | 2.173 | 0.982 | 14.7193 | 0.1953 | 1.9812 ± 0.0751 | 17566 ± 666 | 410 ± 20 |
| JS-09-20** | BE32655 | -13.9007 | -70.8470 | 4949 | 2.413 | 0.908 | 15.9614 | 0.1961 | 2.9962 ± 0.0973 | 24599 ± 799 | 610 ± 30 |
| JS-09-21 | BE30987 | -13.9008 | -70.8481 | 4941 | 2.507 | 0.989 | 15.4057 | 0.2013†† | 1.9536 ± 0.0691 | 17057 ± 603 | 390 ± 20 |
| JS-09-22 | BE32895 | -13.9009 | -70.8484 | 4935 | 2.464 | 0.902 | 18.6829 | 0.1939 | 1.9692 ± 0.0797 | 13659 ± 552 | 350 ± 20 |
| Hu-Ic | | | | | | | | | | | |
| JS-09-23 | BE32896 | -13.9012 | -70.8483 | 4939 | 2.180 | 0.962 | 17.4106 | 0.1940 | 1.8804 ± 0.0880 | 14003 ± 656 | 330 ± 20 |
| JS-09-24** | BE32656 | -13.9011 | -70.8465 | 4948 | 1.915 | 0.920 | 20.6218 | 0.1949 | 5.0284 ± 0.2136 | 31766 ± 1349 | 780 ± 40 |
| Hu-Ie | | | | | | | | | | | |
| JS-09-27** | BE32897 | -13.9028 | -70.8491 | 4940 | 2.473 | 0.988 | 20.3720 | 0.1946 | 2.6716 ± 0.1378 | 17057 ± 880 | 390 ± 20 |
| Hu-If | | | | | | | | | | | |
| JS-09-10 | BE30984 | -13.9029 | -70.8467 | 4938 | 2.637 | 0.980 | 15.8135 | 0.2056†† | 1.5434 ± 0.0988 | 13412 ± 858 | 310 ± 20 |
| JS-09-11 | BE30985 | -13.9029 | -70.8469 | 4937 | 1.973 | 0.981 | 15.9237 | 0.2062†† | 1.5576 ± 0.0709 | 13482 ± 614 | 310 ± 20 |
| JS-09-12 | BE30992 | -13.9030 | -70.8475 | 4934 | 2.176 | 0.994 | 15.5024 | 0.2026†† | 1.4874 ± 0.0579 | 12991 ± 506 | 300 ± 10 |
| Hu-Ig | | | | | | | | | | | |
| JS-09-40 | BE32898 | -13.9051 | -70.8465 | 4944 | 2.718 | 0.975 | 52.8348 | 0.1986 | 3.7995 ± 0.1036 | 9546 ± 260 | 220 ± 10 |
| JS-09-41 | BE32899 | -13.9056 | -70.8470 | 4935 | 3.656 | 0.911 | 47.8400 | 0.1943 | 3.4839 ± 0.1049 | 9454 ± 285 | 240 ± 10 |
| H-Ih | | | | | | | | | | | |
| JS-09-42 | BE32659 | -13.9040 | -70.8445 | 4942 | 3.117 | 0.950 | 68.2451 | 0.1957 | 4.5794 ± 0.1445 | 8774 ± 277 | 210 ± 10 |
| JS-09-14 | BE32657 | -13.9053 | -70.8459 | 4948 | 3.458 | 0.983 | 71.8010 | 0.1953 | 5.1839 ± 0.3026 | 9425 ± 550 | 220 ± 10 |
| JS-09-15 | BE32658 | -13.9057 | -70.8455 | 4939 | 2.421 | 0.978 | 71.6553 | 0.1946 | 5.3286 ± 0.1413 | 9670 ± 256 | 230 ± 10 |

* All samples were prepared at Dartmouth College. Samples marked with an "††" were prepared using the beryllium carrier "Lamont Carrier 5.1". All other samples were prepared using the beryllium carrier "4G Dartmouth Carrier."

† Beryllium measurements were made relative to the 07KNSTD3110 standard (Nishiizumi et al., 2007). Internal AMS uncertainties are reported.

§ $^{10}$Be ages assume zero erosion and are calculated using the CRONUS-Earth online calculator (Balco et al., 2008) with a locally calibrated production rate ($P_{Quel}$; 3.78 ± 0.09 [St] atoms $g^{-1}$ $yr^{-1}$; Kelly et al. (2013).

# External uncertainties for $^{10}$Be age calculations, rounded to the nearest ten years.

** Sample excluded from interpreted moraine ages (DR3-10).

Table DR1. $^{10}$Be sample data and calculated $^{10}$Be surface exposure ages. Shown are Dartmouth sample numbers; Center for Accelerator Mass Spectrometry (CAMS) sample numbers; sample latitudes, longitudes and elevations; sample thicknesses; correction factors for sample surface slopes and topographic shielding (Shielding correction); sample quartz amounts (Quartz wt.); $^{9}$Be carrier amounts; measured $^{10}$Be/$^{9}$Be ratios and 1σ uncertainties; calculated $^{10}$Be concentrations and 1σ uncertainties ($^{10}$Be conc.); and calculated $^{10}$Be ages and external uncertainties (Age).

We collected ~1 kg samples of rock from the center of flat or gently sloping boulder surfaces using a hammer and chisel or the drill-and-blast method of Kelly (2003). Before sample extraction, we used a compass and clinometer to measure the strike and dip of the sample surface as well as horizon angles at 20° azimuth intervals. We used these measurements to calculate topographic shielding. There was no evidence for post-depositional boulder-surface erosion. On some boulder surfaces we observed glacial polish. We considered the effects of snow, sediment and vegetation cover of boulders to be negligible. Due to intense solar radiation, snow cover does not persist on the landscape. We did not observe sediment cover on any boulders. There was little-to-no vegetation on the moraines. All samples were prepared in the cosmogenic nuclide laboratory at Dartmouth College following methods modified from Stone et al. (2001) and similar to those used by Schafer et al. (2009). $^{10}Be/^{9}Be$ ratios were measured at the CAMS at Lawrence Livermore National Laboratory (LLNL) relative to the 07KNSTD3110 standard (Nishiizumi et al., 2007).

TABLE DR2. INTERPRETED MORAINE AGES

| Moraine | Mean ± 1σ (yr) |
|---|---|
| Hu-Ia | 520 ± 60 |
| Hu-Ib | 380 ± 30 |
| Hu-Ic | 330 ± 20 |
| Hu-Id* | 350-300 |
| Hu-If | 310 ± 10 |
| Hu-Ig | 230 ± 10 |
| Hu-Ih | 220 ± 10 and CE1963 |

*See figure caption for explanation of age assignment.

Table DR2. Summary of interpreted moraine ages. The Hu-Id moraine is not directly dated but it crosscuts the Hu-Ia, Ib and Ic moraines (Figs.1 and DR1) and must have been deposited prior to the deposition of the Hu-Ie moraine. The closest minimum-limiting age bracket for the Hu-Id moraine is provided by the age of the Hu-1f moraine. Using the ages from of the Hu-1c (330±20 yr) and the Hu-If (310±10 yr) moraines, we assigned the Hu-Id moraine an age of 350-300 yr.

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