GSA DATA REPOSITORY 2010117

APPENDIX DR1

Methodology: Cosmogenic ^{10}Be exposure dating

The cosmogenic ^{10}Be samples were processed at the University of Colorado cosmogenic radionuclide laboratory using procedures according to Kohl and Nishiizumi (1992), Ivy-Ochs (1996), and Ochs and Ivy-Ochs (1997). The isotopic ratios were measured at PRIME Laboratory, Purdue University. The ratios of our samples were determined using an ICN revised ^{10}Be standard (07KNSTD; ^{10}Be $t_{1/2} = 1.36 * 10^6$ yrs; Nishiizumi et al., 2007). We ran three process blanks altogether and used their average ratio of $1.9493 \pm 0.7947 \times 10^{14}$ for correction of the measured isotopic ratios. Exposure ages were calculated using the CRONUS-Earth online age calculator (version 2.2; http://hess.ess.washington.edu) (Balco et al., 2008). The scaling of production rate to sample latitude and elevation follows Stone (2000). Based on these assumptions, the CRONUS-Earth calculator uses a sea level, high latitude production rate of 4.49 $\pm$ 0.43 atoms ^{10}Be/g qtz/yr from neutron spallation (abbreviated "St" in Balco et al., 2008). The CRONUS-Earth calculator assumes an attenuation length scale of 160 g/cm^2. We do not include an erosion rate in the calculation of exposure ages, as each of these samples is collected from glacial polish and has therefore seen no erosion since deglaciation.

Snow shielding correction:

For the snow shielding correction we use snow water content data from ten snow courses in Yosemite National Park and its vicinity from the California Department of Water Resources (http://cdec.water.ca.gov) (Table 3). These datasets record the monthly snow water content for

four months per year from February to May. In an attempt to cover the entire snow year, we assigned values for January and June to be 50% of the average mean in February and May, respectively. In addition, to constrain shielding at a higher elevation site, we use the average annual snow water content measured between 1931-1970 on Maclure Glacier in the headwaters of Lyell Canyon (Dean, 1974). Based on these data, the annual mean snow water content at each site is calculated, which in turn is employed in the calculation of the snow shielding factor using the approach by Gosse and Phillips (2001):

$$S = e^{-[(z_{snow} * \rho_{water})/\Lambda]} \quad (1)$$

Here z_{snow} is the annual mean in snow water content [cm], ρ is the density of water [g/cm^3], and Λ is the attenuation length of 160 g/cm^2. The calculated snow-shielding factor varies between 80 and 90% (Table 4; see also Figure 1). Six of the ten sites, however, have a shielding factor of between 83 – 85%, motivating our use of 0.85 the snow-shielding factor, resulting in a 15% increase in calculated ages. We did not correct CRN samples that were collected below an elevation of 1800 m above sea level; average annual snow cover at lower elevations is relatively minor. We note that the use of our uniform snow-shielding factor may overestimate the increase in age at elevations that are close to the 1800 m contour line.

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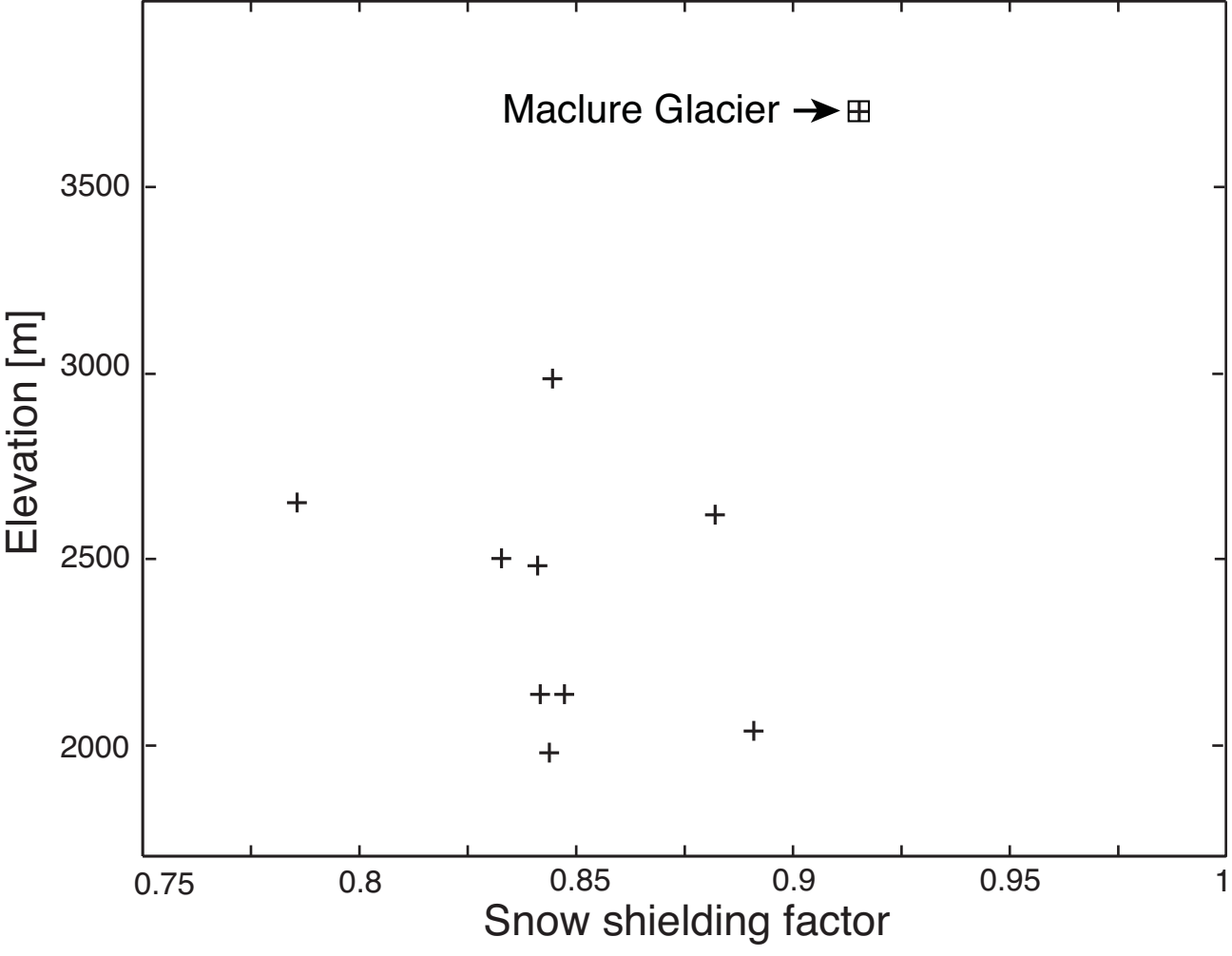
Figure DR1.

Elevation of snow course locations plotted against snow shielding factor. The majority of the snow sites show shielding corrections of about +15%.


Maclure Glacier
3500
3000
2500
2000
Elevation [m]
0.75
0.8
0.85
0.9
0.95
1
Snow shielding factor

APPENDIX TABLE DR1. SAMPLE NAMES, LOCATIONS, PROFILE LENGTH, PROFILE ORIENTATION, NUMBER OF MEASURED FRACTURES, AND MEAN FRACTURE SPACING

Sample Name	Latitude (°N)	Longitude (°W)	Profile Length (m)	Profile Orientation*	Number of Measured Fractures	Arithmetic Mean Fracture Spacing (m)
LyCy-1/-2	37.755	-119.259	20	N-S	36	0.6
			8.3	E-W	15	0.6
			13.4	E-W	17	0.8
			7	N-S	9	0.8
LyCy-3	37.760	-119.261	9	N-S	14	0.7
			3.5	E-W	13	0.3
			15.5	N-S	19	0.9
			9.2	E-W	12	1.0
LyCy-4	37.763	-119.258	16	N-S	36	0.4
			12	E-W	11	1.1
			6.3	E-W	14	0.5
			9.7	E-W	18	0.6
			11	E-W	18	0.6
LyCy-5	37.778	-119.261	6	N-S	9	0.5
			10	E-W	23	0.5
			4	E-W	8	0.4
LyCy-6	37.865	-119.307	12.3	NE-SW	7	1.8
			20	SE-NW	8	2.5
			20	SE-NW	6	3.3
			19	NE-SW	12	1.6
LEMD-1	37.882	-119.348	18	NE-SW	9	2.3
			20	SE-NW	15	1.4
			12.1	SE-NW	9	1.5
LEMD-2	37.882	-119.347	20	SE-NW	7	2.9
			20	NE-SW	9	2.0
POTD-1	37.880	-119.393	40	N-S	10	3.6
			40	E-W	8	4.4
TUOME-1	37.901	-119.399	40	N-S	2	10.9
			40	E-W	12	3.1
TUOME-2	37.900	-119.400	20	N-S	6	2.9
			20	E-W	12	1.4
			20	N-S	9	2.0
			20	E-W	4	4.0
TUFA-1	37.905	-119.418	13	NE-SW	11	1.1
			20	SE-NW	22	0.9
			20	NE-SW	18	1.1
			12	SE-NW	16	0.7
CAFA-1	37.915	-119.445	No data available			
WHFA-1/-2	37.932	-119.467	15	N-S	20	0.7
			15.4	N-S	18	0.6
			16	E-W	14	1.1
			15	E-W	14	1.1
MUGO-1	37.931	-119.516	40.8	E-W	9	4.5
			24	N-S	3	8.0
			41.8	E-W	6	7.0
MUGO-2	37.933	-119.558	13.5	N-S	15	0.9
			11.8	E-W	24	0.5
PATE-1	37.933	-119.595	10.8	N-S	29	0.4
			13.5	E-W	12	1.1
WOLF-1	37.920	-119.622	31.2	NE-SW	33	0.9
			17.4	SE-NW	27	0.6
			14.4	SE-NW	16	1.0
WOLF-2	37.912	-119.633	45.2	NE-SW	35	1.3
			14.3	SE-NW	14	1.0
			19.3	NE-SW	13	1.5
			19.3	SE-NW	17	1.1
WOLF-3	37.908	-119.642	42.9	NE-SW	18	2.4
			26	SE-NW	19	1.4
			24.6	SE-NW	18	1.4
			37	SE-SW	21	1.9
			15.4	NE-SW	14	1.1
			19.9	NE-SW	18	1.1
HH-1	37.882	-119.923	15	NE-SW	21	0.7
			18.3	NE-SW	26	0.7
			20	SE-NW	36	0.6
HH-2	37.958	-119.784	40	E-W	15	2.5
			20	SE-NW	6	2.9
			18	SE-NW	3	4.0

TENA-1	37.827	-119.471	20	NE-SW	30	0.7
			16	SE-NW	14	1.1
			15.5	NE-SW	11	1.6
TENA-2	37.827	-119.470	20	NE-SW	23	0.9
			20	SE-NW	7	2.5
TENA-3	37.829	-119.473	20	N-S	27	0.7
			14	E-W	12	1.1
OLM-1	37.814	-119.484	20	NE-SW	7	3.2
			7.9	SE-NW	26	0.3
			7.4	SE-NW	14	0.6
OLM-2	37.810	-119.487	20	N-S	26	0.8
			19	E-W	16	1.2
			20	E-W	13	1.5

* N – North, E – East, S – South, W – West, NE – Northeast, SE – Southeast, SW – Southwest, NW - Northwest

We use a 1.25 m bin size for the fit of our measured fracture data, and we found a gamma probability distribution (Borradaile, 2003, p.75) most appropriate for our data.

APPENDIX TABLE DR2. SAMPLE NAMES, LOCATIONS, SAMPLE BACKGROUND INFORMATION, AND CALCULATED PRODUCTION RATES USING CRONUS-EARTH CALCULTAOR (VERSION 2.2)

Sample Name	Latitude (°N)	Longitude (°W)	Elevation (m a.s.l.)	Sample thickness (cm)	Lithology	Topo. shielding correction	Quartz Mass (g)	Be Carrier* Mass (g)	Prod. rate spallation (atoms/g/yr)	Production rate muons (atoms/g/yr)
LyCy-1	37.755	-119.259	3271	2	Kkc	0.9805	17.551	3.032E-04	40.7	0.496
LyCy-2	37.755	-119.259	3271	0.5	Kkc	0.8375	16.266	2.911E-04	35.21	0.501
LyCy-3	37.760	-119.261	3373	2	Kkc	0.9990	12.948	3.073E-04	43.96	0.510
LyCy-4	37.763	-119.258	3215	2	Kkc	0.9929	15.226	3.231E-04	39.91	0.488
LyCy-5	37.778	-119.261	2964	2	Kkc	0.9907	15.700	3.130E-04	34.36	0.455
LyCy-6	37.865	-119.307	2710	0.5	Kcp	0.9988	19.324	3.216E-04	30.11	0.426
LEMD-1	37.882	-119.348	2872	0.75	Kcp	0.9998	15.484	2.957E-04	33.25	0.447
LEMD-2	37.882	-119.347	2873	1	Kcp	0.9987	18.680	3.186E-04	33.16	0.446
POTD-1	37.880	-119.393	2679	2	Kcp	0.9993	19.282	2.942E-04	29.20	0.419
TUOME-1	37.901	-119.399	2666	0.5	Kcp	0.9991	21.298	3.001E-04	29.34	0.421
TUOME-2	37.900	-119.400	2621	0.5	Kcp	0.9916	18.689	3.305E-04	28.31	0.415
TUFA-1	37.905	-119.418	2501	0.5	Khd	0.9989	8.775	2.851E-04	26.43	0.400
CAFA-1	37.915	-119.445	2397	0.5	Kt	0.9850	20.266	2.997E-04	24.38	0.388
WHFA-1	37.932	-119.467	1900	0.5	Kt	0.9568	20.969	3.033E-04	16.97	0.333
WHFA-2	37.932	-119.466	1916	1.25	Kt	0.9212	21.789	3.214E-04	16.42	0.334
MUGO-1	37.931	-119.516	1703	1	Kt	0.9275	12.432	2.994E-04	14.27	0.313
MUGO-2	37.933	-119.558	1465	0.5	Kec	0.9190	19.935	3.058E-04	11.96	0.290
PATE-1	37.933	-119.595	1330	1.5	Kg	0.9764	13.392	3.190E-04	11.41	0.277
WOLF-1	37.920	-119.622	1405	1.5	Kg	0.9760	9.509	3.097E-04	12.06	0.284
WOLF-2	37.912	-119.633	1752	1	Kyc	0.9862	19.610	3.222E-04	15.71	0.318
WOLF-3	37.908	-119.642	2091	1	Kyc	0.9958	19.534	3.184E-04	20.05	0.353
HH-1	37.882	-119.923	759	2	Kar	0.9622	15.517	3.103E-04	7.24	0.230
HH-2	37.958	-119.784	1242	1	Kec	0.9780	8.818	2.907E-04	10.76	0.270
TENA-1	37.827	-119.471	2492	0.25	Khd	0.9981	20.261	3.265E-04	26.26	0.399
TENA-2	37.827	-119.470	2495	0.5	Khd	0.9981	18.990	3.095E-04	26.27	0.4
TENA-3	37.829	-119.473	2535	0.25	Khd	0.9979	20.890	3.210E-04	26.99	0.405
OLM-1	37.814	-119.484	2642	2	Khd	0.9998	18.163	3.076E-04	28.52	0.414
OLM-2	37.810	-119.487	2557	0.5	Khd	0.9973	18.770	3.125E-04	27.30	0.407

* The concentration of the Be carrier is 1000 ± 3 μg Be/g.

Kkc, Kuna Crest Granodiorite; Kcp, Cathedral Peak Granodiorite; Khd, Half Dome Granodiorite; Kt, Taft Granite; Kec, El Capitan Granite; Kg, undivided granitic rocks;

Kyc, Yosemite Creek Granodiorite; Kar, Arch Rock Granodiorite (after Huber et al., 2003)

APPENDIX TABLE DR3. SAMPLE NAMES, AMS-MEASURED ^{10}BE CONCENTRATIONS AND CALCULATED EXPOSURE AGES AND UNCERTAINTIES USING CRONUS-EARTH CALCULATOR (VERSION 2.2)

Sample Name	AMS ^{10}Be/^{9}Be (incl. blank correction)	Error AMS ^{10}Be/^{9}Be*	^{10}Be conc. (10^5 atoms/g)	Error ^{10}Be conc. (10^5 atoms/g)*	Exposure age (ka)	Internal uncertainty (ka)*†	External uncertainty (ka)*†	Exposure age incl. snow shielding (ka)
LyCy-1	3.81E-13	1.6118E-14	4.3993	0.1863	10.7	0.5	1.0	12.3
LyCy-2	9.97E-14	5.2539E-15	1.1945	0.0629	3.3	0.2	0.3	3.8
LyCy-3	3.68E-13	1.5594E-14	5.8343	0.2476	13.2	0.6	1.3	15.1
LyCy-4	3.43E-13	1.8244E-14	4.8697	0.2590	12.1	0.6	1.2	13.9
LyCy-5	3.43E-13	1.1008E-14	4.5737	0.1468	13.2	0.4	1.2	15.2
LyCy-6	1.63E-12	3.3035E-14	18.150	0.3677	60.4	1.2	5.5	69.4
LEMD-1	4.09E-13	1.2977E-14	5.2284	0.1658	15.6	0.5	1.4	17.9
LEMD-2	1.20E-12	4.8674E-14	13.650	0.5553	41.0	1.7	4.0	47.2
POTD-1	1.94E-12	3.9169E-14	19.774	0.3998	67.9	1.4	6.2	78.1
TUOME-1	1.69E-12	5.1416E-14	15.961	0.4846	54.4	1.7	5.1	62.5
TUOME-2	5.03E-13	2.6180E-14	5.9441	0.3097	20.8	1.1	2.1	23.9
TUFA-1	2.17E-13	9.6562E-15	4.7146	0.2098	17.6	0.8	1.7	20.3
CAFA-1	3.75E-13	1.1956E-14	3.7095	0.1183	15.0	0.5	1.4	17.3
WHFA-1	2.65E-13	8.7134E-15	2.5640	0.0843	14.9	0.5	1.4	17.1
WHFA-2	2.33E-13	1.0285E-14	2.2990	0.1015	13.8	0.6	1.3	15.8
MUGO-1	4.13E-13	1.7409E-14	6.6564	0.2804	46.2	2.0	4.5	-
MUGO-2	2.11E-13	2.7976E-14	2.1682	0.2871	17.8	2.4	2.8	-
PATE-1	9.55E-14	6.2524E-15	1.5227	0.0996	13.1	0.9	1.4	-
WOLF-1	1.27E-13	3.9094E-14	2.7711	0.8516	22.6	7.0	7.3	-
WOLF-2	2.73E-13	1.4777E-14	3.0004	0.1624	18.8	1.0	1.9	-
WOLF-3	2.73E-13	1.4777E-14	2.9776	0.1611	14.6	0.8	1.5	16.8
HH-1	9.64E-14	5.1421E-15	1.2906	0.0688	17.3	0.9	1.8	-
HH-2	2.25E-13	7.5448E-15	4.9606	0.1664	45.5	1.5	4.3	-
TENA-1	2.61E-13	1.1392E-14	2.8165	0.1228	10.6	0.5	1.0	12.2
TENA-2	2.73E-13	2.0628E-14	2.9752	0.2249	11.2	0.8	1.3	12.9
TENA-3	3.61E-13	1.5324E-14	3.7075	0.1575	13.6	0.6	1.3	15.6
OLM-1	3.75E-13	1.1962E-14	4.2493	0.1355	14.7	0.5	1.4	17.0
OLM-2	3.43E-13	1.0996E-14	3.8143	0.1225	13.8	0.4	1.3	15.9

* All uncertainties are reported as ± one sigma standard deviation. Errors include AMS uncertainty and the uncertainty due to the blank.

† The internal uncertainty includes the AMS error and error introduced by the blank, the external uncertainty additionally includes the uncertainty on the production rate.

APPENDIX TABLE DR4. SNOW STATION NAMES, LOCATIONS, SNOW RECORD LENGTH, MEASURED ANNUAL SNOW WATER CONTENT, AND CALCULATED SNOW SHIELDING FACTOR

Station	Latitude (degree N)	Longitude (degree W)	Elevation (m above sealevel)	Snow record length (yrs)	Mean annual snow water content (cm)	Snow Shielding Factor
1. Beehive Meadows	37.995	119.780	1980	79	27.2	0.84
2. Dana Meadows	37.897	119.257	2985	83	27.1	0.84
3. Gin Flat	37.765	119.773	2135	79	27.6	0.84
4. Ostrander Lake	37.637	119.550	2500	71	29.3	0.83
5. Peregoy Meadows	37.667	119.625	2135	78	26.5	0.85
6. Snow Flat	37.827	119.497	2650	79	38.7	0.79
7. Tenaya Lake	37.838	119.448	2485	79	27.7	0.84
8. Tuolumne Meadows	37.873	119.350	2620	79	20.1	0.88
9. Vernon Lake	38.017	119.717	2040	62	18.5	0.89
10. Maclure Glacier	37.746	119.281	3700	39	14.2	0.92

Data source: California Department of Water Resources (http://cdec.water.ca.gov; Station 1-9); Dean, 1974 (Station 10)