Erosion rates of moraine crests from *in-situ* and atmospheric cosmogenic nuclide accumulation in boulders and matrix

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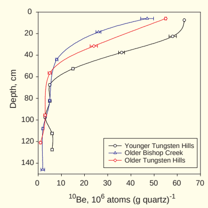
ABSTRACT

We describe the application of *in-situ* and meteoric (atmospheric) cosmogenic nuclides to determining erosion rates of moraines. It builds on our previous approach in which we measured ^{36}Cl in morainal boulders and in the matrix, and developed a statistical model to convert the variance of individual boulder ages into erosion rate. We improved and expanded that early approach by measuring *in-situ* ^{10}Be in the matrix and atmospheric ^{10}Be in the soil profile, and by including boulder erosion in the statistical model. The complete system consists of measurements of four nuclide inventories: *in-situ* ^{36}Cl in the boulders, *in-situ* ^{36}Cl in the matrix, *in-situ* ^{10}Be in the matrix, and atmospheric ^{10}Be in the matrix (in soil profile). Each measured inventory is a function of the same two variables: landform age and erosion depth.

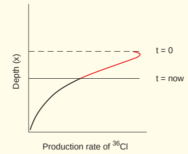
We measured cosmogenic nuclides in samples from a set of moraines in Bishop Creek, the Sierra Nevada, California, and determined time-integrated erosion rates and erosion-corrected ages of these landforms (not discussed here). The erosion rates of moraine crests range from 3 cm/ky to 11 cm/ky (ky = 1000 years), integrated over the ages of the moraines (75-150 ky). Erosion rates calculated using different combinations of measurements are usually consistent within a factor of two. These combinations of erosion rates and ages result in the total lowering of the moraine crests between 3 m and 15 m, which we consider reasonable in the arid climate of the Sierra Nevada. Accounting for lowering of moraine crests significantly reduces the uncertainty in the calculated cosmogenic age of the moraine. Work in progress concentrates on two tasks: a rigorous error analysis, and combining a physical model of moraine erosion with accumulation of cosmogenic nuclides. Both will make the model more realistic and

2. ISOTOPE SYSTEMS

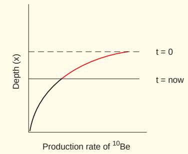
Meteoric ^{10}Be in soil profile. Produced in the atmosphere, transported with precipitation to ground surface, infiltrated with soil water, and finally adsorbed on soil particles. Here, >90% of ^{10}Be is retained in the top 1 m of soil (figure). Inventory is a function of deposition rate (known), age, and erosion rate. Analysis requires the surface concentration of ^{10}Be and the total inventory in the profile.



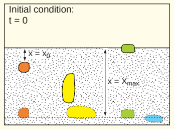
***In-situ* ^{36}Cl in matrix.** Produced in mineral grains by spallation of Ca and K, muon capture by Ca, and neutron activation of Cl, it remains in place except removal by erosion and/or weathering. Inventory is a function of production rate (known; depends on chemistry and depth), age, and erosion rate. Analysis requires measured surface value or soil profile, and involves integration of depth-and-time-variable production rates (red line in graph).

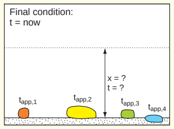


***In-situ* ^{10}Be in matrix.** Produced in quartz (used here) by spallation of O and muon capture by O, it remains in place except removal by erosion and/or weathering. Inventory is a function of production rate (known in quartz; depends on depth), age, and erosion rate. Analysis as above.



***In-situ* ^{36}Cl in boulders.** Produced in mineral grains by spallation of Ca and K, muon capture by Ca, and neutron activation of Cl, it remains in place except removal by erosion and/or weathering. Inventory is a function of production rate (known; depends on chemistry and depth), age, and erosion rate of matrix and boulder tops. Analysis requires measured ^{36}Cl in multiple boulders. The mean and variance of apparent boulder ages are related to moraine age and erosion rate (or total erosion depth) of the moraine crest.





3. SAMPLES

Samples are from a Late Pleistocene (75-150 ky old) moraine complex in Bishop Creek, eastern Sierra Nevada, California. The moraines are outside of glacial valleys, in the piedmont, and were not obliterated by younger glaciers. The entire sequence is shown below (map and two panoramic photographs, one from the ground, the other from an aircraft). In addition, detailed views of one moraine (site H in map) are shown in the three photographs at the bottom of this section.

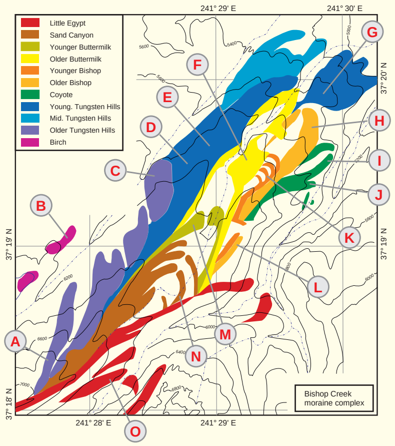
We collected the following types of samples:

(1) Multiple boulders from each moraine, for statistical analysis of *in-situ* ^{36}Cl data.

(2) Soil profiles from three moraines, for profiles of atmospheric ^{10}Be.

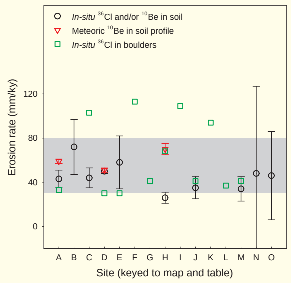
(3) Soil profiles and surface matrix from moraine crests, for *in-situ* ^{36}Cl.

(4) Soil profiles and surface matrix from moraine crests, for *in-situ* ^{10}Be.



4. RESULTS

Erosion rates (of moraine matrix) range from 30 mm/ky to over 110 mm/ky (figure and table below), with average of 55±25 mm/ky (1s, grey bar in graph). For sites where multiple isotopic inventories were used, the calculated erosion rates agree within a factor of two. The discrepancies are due to the analytical uncertainties and due to possible differences in the retention of different nuclides in different parts of the moraines. Work in progress is design to solve these and other problems related to the systematics of cosmogenic nuclides in moraine deposits.



Erosion rates (mm/ky) of moraine crests.

Site letter (see map)	*In-situ* ^{36}Cl and ^{10}Be in matrix	Meteoric ^{10}Be in soil profile	*In-situ* ^{36}Cl in boulders
A	43±8	59±2	33
B	72±25	---	260
C	44±9	---	103
D	50±2	51±2	30
E	58±24	---	30
F	---	---	113
G	---	---	41
H	26±5	70±5	68
I	---	---	109
J	35±10	---	41
K	---	---	94
L	---	---	37
M	34±11	---	41
N	48±79	---	---
O	46±40	---	---

Note: there are no uncertainties on the values in the last column because we do not know how to estimate them. We are working on error analysis.

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