Development of a new Earth surface thermochronometer using cosmogenic noble gases

Motivation: Temperature in continental settings is one of the most important yet difficult to constrain properties of the Earth's past climate. Climate models unequivocally predict several-degree global temperature increases in the coming centuries, but estimates for how temperature changes will influence climate in continental environments—the environments we humans live in and depend on—are much less certain **(1)**. This is largely because proxies from non-marine settings often record relative changes in climate but rarely constrain absolute temperature through time. Robust records of terrestrial paleotemperatures are also much sought after as a tool for studying geodynamic processes such as tectonically driven surface uplift **(2)**.

^{3}He and ^{21}Ne are stable nuclides produced in the upper few meters of the Earth's crust by cosmic ray interactions with atomic nuclei, making them attractive targets for studying processes happening at the Earth's surface. Several studies found evidence for significant diffusive loss of ^{3}He from quartz **(3-5)** and ^{21}Ne loss from feldspars **(6)** at Earth surface temperatures. The open-system behavior of cosmogenic ^{3}He and ^{21}Ne in these common minerals, thus far only viewed as a fatal limitation for geologic applications, could potentially be utilized as a record of past Earth surface temperatures, much in the same way that thermochronometers like (U-Th)/He in apatite are used to reconstruct the thermal histories of rocks as they are exhumed to the Earth's surface. Only a few studies have attempted to quantify the kinetics of ^{3}He and ^{21}Ne diffusion in these minerals **(6-7)**, and applications of open-system behavior remain entirely unexplored.

Hypotheses: I propose to conduct fundamental experimental research to quantify the diffusion kinetics of ^{3}He and ^{21}Ne in quartz and feldspars, and a combination of mathematical modeling and calibrated geologic tests to explore the possibility of using cosmogenic ^{3}He and ^{21}Ne in these phases as a new, Earth surface thermochronometer. Through this integrative experimental, modeling, and observational approach, I will address the following questions: How do the chemical and physical properties of quartz and feldspars influence diffusion kinetics? Do laboratory-determined diffusion kinetics apply in nature? Over what temperature ranges and timescales will diffusive loss of cosmogenic ^{3}He and ^{21}Ne from quartz and feldspars occur? And most importantly, where could this new technique be applied to constrain past Earth surface temperatures and expand our knowledge about climatic and geodynamic processes?

Research plan: To quantify the kinetics of ^{3}He and ^{21}Ne diffusion, I am conducting stepwise heating and degassing experiments on proton-irradiated quartz and feldspar grains at the BGC noble gas thermochronometry lab. Proton irradiation produces ^{3}He and ^{21}Ne through equivalent nuclear transmutations as cosmogenic ^{3}He and ^{21}Ne but in much higher concentrations and with a uniform distribution, which allows experiments to be carried out on single crystal fragments **(8)**. In each experiment, I progressively heat an irradiated quartz or feldspar sample to specific temperatures and durations and then measure the isotopic abundances of He and Ne degased in each step. Using the mathematics of diffusion **(9)**, I can calculate diffusion coefficients for each heating step and from that the kinetic parameters governing ^{3}He and ^{21}Ne diffusion for each sample. By conducting these experiments on quartz and feldspar grains from variable lithologies and with different grain sizes, chemical compositions, and crystallographic defects, I will explore how each of these parameters affects the diffusion of ^{3}He and ^{21}Ne.

With the diffusion kinetics observed for these suites of quartz and feldspar samples, I will use the principles of thermochronometry to model the simultaneous production and diffusion of cosmogenic ^{3}He and ^{21}Ne. This will allow me to characterize the time-temperature sensitivity of these cosmogenic noble gas-mineral systems and identify places in the terrestrial geologic record where this new Earth surface thermochronometer can be applied. I will also pair my modeling results with measurements of cosmogenic ^{3}He and ^{21}Ne in quartz and feldspars from settings with independently constrained exposure and temperature histories. These calibrated geologic tests will enable me to assess whether laboratory-determined diffusion kinetics are representative of cosmogenic ^{3}He and ^{21}Ne diffusion in natural settings.

Progress and anticipated results: In my first year of graduate school I focused on developing cosmogenic noble gas thermochronometry in quartz. I conducted nine experiments on proton-irradiated quartz and built models constrained by the experiments that suggest ^{3}He will generally experience diffusive loss at sub-zero temperatures on 10^4-10^7 yr timescales, while ^{21}Ne is quantitatively retained at temperatures $\leq$ 45°C. The models are consistent with measured cosmogenic abundances in a quartz sample with a well-constrained Holocene temperature and exposure history. My preliminary research therefore suggests that the cosmogenic ^{3}He/^{21}Ne-quartz system can record temperature histories in polar and high altitude environments, with ^{3}He providing information about temperature and ^{21}Ne providing information about time.

Over the next three years, I plan to conduct diffusion experiments, modeling, and geologic tests to evaluate the potential of the cosmogenic ^{21}Ne-quartz/feldspar paired system as an Earth surface thermochronometer. Based on the findings of **(6)**, I anticipate that feldspars will be partially retentive to ^{21}Ne at temperatures characteristic of most latitudes and therefore less restricted than the ^{3}He/^{21}Ne-quartz system in its applicability. However, I also anticipate that the diffusion kinetics of ^{21}Ne will be more complex than in quartz due to the chemical and structural variability of feldspars **(10)** and will require more experiments and time to characterize. In addition to testing the modeled sensitivity of the ^{21}Ne-quartz/feldspar paired system, I will also conduct geologic tests for consistency between cosmogenic-based thermochronometers and preexisting paleotemperature proxies, such as stable isotopes in fossil soil carbonates.

Broader impacts: My research will lay the groundwork for practical development of cosmogenic noble gas thermochronometry, which has the potential to advance discovery in several areas of research, including paleoclimatology, geodynamics, glaciology and geomorphology. The potential of this technique to bridge the gap between paleoclimate proxies and climate model predictions is especially important as scientists and policymakers collaborate to assess how rising temperatures will impact the continental environments society depends on.

I have presented my research on quartz thus far in four talks, two at the Geochemical Society's 2013 Goldschmidt Conference and two delivered to undergraduate and graduate students at UC Berkeley. I am also presently preparing manuscripts on both the theory of cosmogenic noble gas thermochronometry and the diffusion kinetics of ^{3}He and ^{21}Ne in quartz. Through the UC Berkeley NERDS program, I will continue mentoring undergraduate research interns over the next two summers and involve them in the preparation, design, and execution diffusion experiments on feldspars. I have also developed a curriculum to teach middle-school age students about diffusion through hands-on chromatography and water tank experiments. I will implement the curriculum this spring at the UC Berkeley Expanding Your Horizons conference for middle school girls and then over the following year as I take on leadership of my department's hands-on teaching activities in Oakland middle schools through BASIS.

References: **(1)** IPCC, 2007, Synthesis Report, 104 p.; **(2)** D.B. Rowley, C.N. Garzione, 2007, *Ann. Rev. Earth Planet. Sci.* 35, 463-508; **(3)** T.E. Cerling, *Quat. Res.*, 1990 33, 148-156; **(4)** E.J. Brook, M.D. Kurz, 1993, *Quat. Res.* 39, 1-10; **(5)** T.W. Trull *et al.*, 1995, *Chem Geo.* 119, 191-207; **(6)** L. Gourbet *et al.*, 2012, *Geochim. Cosmochim. Acta* 86, 21-36; **(7)** D.L. Shuster, K.R. Farley, 2005, *Geochim. Cosmochim. Acta* 69, 2349-2359; **(8)** D.L. Shuster *et al.*, 2004, *Earth & Planet. Sci. Lett.* 217,19-32; **(9)** H. Fechtig, S. Kalbitzer in *Potassium-Argon Dating,* O. A. Schaeffer, J. Zahringer, Eds. (Springer, 1966) p. 68–106; **(10)** W.S. Cassata, P.R. Renne, 2013, *Geochim. Cosmochim. Acta* 112, 251-287.