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Cosmogenic nuclide data sets from the Sierra Nevada, California, for assessment of nuclide production models: I. Late Pleistocene glacial chronology

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A B S T R A C T

The Cosmic-Ray prOduced NUclide Systematics on Earth Project (CRONUS-Earth Project) has reused a limited number of 'legacy' ^{10}Be and ^{36}Cl samples from late Pleistocene moraines in the Sierra Nevada for the testing and evaluation of cosmogenic nuclide production rates derived by the CRONUS-Earth Project. A secure glacial chronology for the range is necessary for this purpose. Evidence for the timing of glacial fluctuations is provided by direct radiocarbon ages marking glacial termini at various times and by chronologies on lacustrine cores, marine cores, and speleothem records. Evaluation of these records yields a relatively consistent picture. Tioga 3 glaciers were close to their maximum extent from >20 to about 17 ka. Close to 17 ka they retreated rapidly, then began to readvance at ~16.8 ka. The Tioga 4 readvance culminated at about 16.2 ka and rapid retreat ensued, with the equilibrium line altitude rising by 400 m by 15.7 ka and the range probably virtually ice-free by a short time thereafter. There is no evidence of ice readvance until the Recess Peak glaciation. Dating of this readvance is inconsistent, with direct dates on glacial features and some lacustrine and speleothem records placing it between 14.0 and 13.0 ka, but many regional records are more consistent with an advance during the interval 13.0 to 12.6 ka. After consideration of all the evidence I have assigned ages of 15.75 ± 0.5 ka for Tioga 4 retreat and 13.3 ± 0.25 for the maximum extent of the Recess Peak glaciation.

1. Introduction

Although in principle it is possible to calculate the production rates of terrestrial cosmogenic nuclides from basic physics, in practice it has proved necessary to employ empirical geological calibration sites (Gosse and Phillips, 2001). One of the earliest calibrations reported was for ^{10}Be and ^{26}Al from samples of glacially modified granodiorite from the Sierra Nevada in California, USA (Nishiizumi et al., 1989). This study was published in 1989, but used samples collected in 1986. Similar samples from the Sierra Nevada were used by Evans et al. (1997) to calibrate ^{36}Cl production rates.

The Cosmic-Ray prOduced NUclide Systematics on Earth Project (CRONUS-Earth Project) was funded by the U.S. National Science Foundation in 2005. The purpose of the CRONUS-Earth Project is to resolve inconsistencies in the theoretical and empirical basis for application of terrestrial cosmogenic nuclides in the earth sciences. As part of these activities, new calibrations of ^{10}Be, ^{26}Al, and ^{36}Cl production are being performed. The CRONUS-Earth Project has selected and sampled a suite of new sites to provide the basis for the calibration (Phillips et al., 2016a). However, it has employed historical calibration and application sites for testing the accuracy of the new calibrations. These include a number of studies previously performed in the Sierra Nevada of California. Use of these sites for this purpose requires knowledge of the actual exposure history of the samples, independent of cosmogenic-nuclide dating.

The previous investigators used the best available knowledge at the time to estimate the exposure history of their samples. However, much new information has become available in the past 25 years. The objective of this paper is to evaluate and synthesize the currently available noncosmogenic data bearing on the deglaciation of the Sierra Nevada between 20 and 10 ka, yielding a ^{14}C-based chronology (with minor U-series) that is independent of cosmogenic-nuclide dating. A second paper (Phillips et al., 2016b) will provide descriptions of the sites and a summary of results and assessment of site-specific influences on the samples.

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2. Sierra Nevada glacial chronology

2.1. Introduction

Important syntheses of Sierra Nevada glacial chronology have been published by numerous researchers over the past century (Knopf, 1918; Blackwelder, 1931; Birkeland, 1964; Gillespie, 1982; Fullerton, 1986; Bursik and Gillespie, 1993; Osborn and Bevis, 2001; Clark et al., 2003; Gillespie and Clark, 2011). The generally accepted terminology and conceptual framework for the glacial sequence of the Sierra Nevada was established by Blackwelder in 1931 (Blackwelder, 1931). He named the McGee, Sherwin, Tahoe, and Tioga glacial stages, although without numerical chronology, as the means for such were lacking in his time. Of these, we need be concerned here with only the Tioga, inasmuch as only samples from the Tioga-age features (and younger Recess Peak age) were collected for use in any of the calibration exercises (Nishiizumi et al., 1989, did inadvertently sample pre-Tioga bedrock, but did not use the samples for calibration).

Research subsequent to Blackwelder's time has established that the Tioga glaciation took place during the interval ~30 ka to 15 ka (Benson et al., 1996; Phillips et al., 1996; Menking et al., 1997; Phillips et al., 2009; Rood et al., 2011). For the purpose of establishing the exposure age of the 1986 calibration set, it is the termination of the Tioga glaciation that is pertinent. Scientific understanding of these events has changed considerably since these samples were collected. At that time, the final Tioga glaciers were thought to have retreated close to the very end of the Pleistocene, which was then dated to 10,000 years ago. This disappearance of the Tioga glaciers was thought to have been followed by a series of small-to-medium size advances throughout the Holocene, variously termed Hilgard, Recess Peak, and Matthes (Birman, 1964). The samples for the 1986 study were therefore collected well above the Tioga terminal moraines, in order to be in the strongly erosive basal regime of the glacier (MacGregor et al., 2009), but low enough to be below the presumed Hilgard or other Holocene glacial limit, so that all samples would have been exposed simultaneously by a single major glacial event.

Nishiizumi et al. (1989) surveyed the radiocarbon age control available at that time for the terminal Tioga retreat. Based on this survey, they concluded that the best estimate for the timing of the retreat was 10,000 ^{14}C yr ago. Secular variation of ^{14}C activity in the atmosphere was recognized, and based on the limited control then available, Nishiizumi et al. (1989) adjusted the preferred radiocarbon age to 11,000 calibrated years.

2.2. Current age control

Since 1989 a large amount of new age control, mainly radiocarbon measurements, has been collected on the Tioga glacial retreat and subsequent events. These have led to a major revision of the chronology of terminal Pleistocene events in the Sierra Nevada. Investigations by Clark and Gillespie (1997) demonstrated that there have been only two post-Tioga glacial advances in the range: the Recess Peak and the Matthes. The Recess Peak glaciers advanced only a few thousand years after the Tioga retreat and are therefore very latest Pleistocene rather than Holocene. The Matthes advance was during the late Holocene and culminated during the Little Ice Age. It was much less extensive than the Recess Peak glaciation.

Although cosmogenic exposure ages obviously cannot be used to constrain the chronology for a cosmogenic production rate study, cosmogenic samples can be used to provide context on the general pattern and style of the retreat. Phillips et al. (1996) and (2009) published a large number of ^{36}Cl surface exposure ages from Bishop Creek, within the same region as the ^{10}Be calibration study. In the time interval of interest, Phillips et al. (2009) distinguished three glacial advances: the Tioga 3 at c.a. 18 ka, Tioga 4 at c.a. 15.5 ka, and Recess Peak at c.a. 12.5 ka. The Tioga 4 glaciers advanced down-canyon only about one-third as far as the Tioga 3 advance. The Recess Peak advance was only about one-tenth that of the Tioga 3. Notably, Phillips et al. (2009) found that samples exposed by the retreat of the Tioga 4 glacier had very similar ^{36}Cl ages, about 15.0 ka, regardless of elevation above the Tioga 4 terminal moraines. This indicates that the final Tioga retreat was very rapid, estimated by Phillips et al. (2009) as probably less than 500 years from the initiation of retreat to the complete withdrawal of the glaciers into cirque headwalls. This is consistent with the previous conclusions of Clark (1976), based on geomorphic evidence. This rapid retreat history is advantageous for establishing the chronology of the cosmogenic calibration samples, because the age will be relatively independent of position within the drainage.

I have divided the radiocarbon age control for glacial chronology into two categories: primary and secondary. ‘Primary’ data are samples that (fairly) directly date the actual retreat of a Tioga or Recess Peak glacier. Virtually all of these are samples of organic material taken from cores extracted from lakes or bogs beneath the former course of a glacier. Organic carbon will only begin to accumulate after the glacier has retreated past the point in question and renewed plant growth in the newly uncovered drainage allows organic detritus to be deposited in the basin. The ages from such sources are therefore presumably limiting minimum ages for deglaciation. However, in practice they may either pre- or postdate the actual time of deglaciation, significantly in some cases. This is for three reasons. First, there is likely at least a short time lag between deglaciation and the reestablishment of vegetation in the drainage. Typically, a layer of organic mud and silt is found overlying coarser sediment consisting of sand and gravel, which is presumed to be terminal glacial outwash. However, the rapid deposition of outwash may continue for some time while the glacier retreats up-valley. Given the rapidity of Tioga glacial retreat (discussed above), it seems likely that this time lag before deposition of dateable organic material is small (perhaps a hundred years or less), but must be considered nevertheless. The second reason is that these kinds of samples have been collected over a wide range of elevations. The ^{10}Be calibration samples of Nishiizumi et al. (1989), as well as the ^{36}Cl samples described above, were collected mostly from quite high elevations in the range, but some of the independent age control was from considerably lower elevation. The Tioga glacier retreated in a pulsed fashion, pulling back from a terminal position, then later readvancing to a somewhat higher position and again retreating (Phillips et al., 1996, 2009; Rood et al., 2011). Post-glacial sediment samples from low positions along the course of the glacier are therefore expected to yield ages that may predate ones from high elevation within the drainage. The third reason is more methodological. Cores for lacustrine chronologies have commonly been drilled by hand. Practically speaking, this means that the coring is usually abandoned when severe resistance is encountered, in other words, when the first layer of outwash is reached by the auger. The investigators usually assumed that this corresponded to local deglaciation, but given that there may have been significant Tioga and post-Tioga advances upstream, outwash may have been transported down-canyon and deposited at lower elevations in episodes postdating the local deglaciation. These three considerations indicate that at any elevation a range of basal radiocarbon ages may be measured, but generally the oldest should be preferred as most closely constraining the age of glacial retreat.

The second category of chronological control is termed ‘secondary’ data. These are samples from archives, typically lacustrine

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