

## Rapid Communication

JQS

Calibration of the *in situ* cosmogenic  $^{14}\text{C}$  production rate in New Zealand's Southern AlpsIRENE SCHIMMELPFENNIG,<sup>1\*</sup> JOERG M. SCHAEFER,<sup>1</sup> BRENT M. GOEHRING,<sup>2</sup>  
NATHANIEL LIFTON,<sup>2</sup> AARON E. PUTNAM<sup>1</sup> and DAVID J. A. BARRELL<sup>3</sup><sup>1</sup>Lamont-Doherty Earth Observatory, Palisades, New York 10964<sup>2</sup>Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana<sup>3</sup>GNS Science, Dunedin, New Zealand

Received 15 March 2012; Revised 11 June 2012; Accepted 14 June 2012

**ABSTRACT:** *In situ* cosmogenic  $^{14}\text{C}$  (*in situ*  $^{14}\text{C}$ ) analysis from quartz-bearing rocks is a novel isotopic tool useful for quantifying recent surface exposure histories (up to  $\sim 25$  ka). It is particularly powerful when combined with longer-lived cosmogenic isotopes such as  $^{10}\text{Be}$ . Recent advances in the extraction of *in situ*  $^{14}\text{C}$  from quartz now permit the routine application of this method. However, only a few experiments to calibrate the production rate of *in situ*  $^{14}\text{C}$  in quartz have been published to date. Here, we present a new *in situ*  $^{14}\text{C}$  production rate estimate derived from a well-dated debris flow deposit in the Southern Alps, New Zealand, previously used to calibrate  $^{10}\text{Be}$  production rates. For example, based on a geomagnetic implementation of the Lal/Stone scaling scheme we derive a spallogenic production rate of  $11.4 \pm 0.9$  atoms  $^{14}\text{C}$  (g quartz) $^{-1}$  a $^{-1}$  and a  $^{14}\text{C}/^{10}\text{Be}$  spallogenic production rate ratio of  $3.0 \pm 0.2$ . The results are comparable with production rates from previous calibrations in the northern hemisphere. Copyright © 2012 John Wiley & Sons, Ltd.

**KEYWORDS:** *in situ*  $^{14}\text{C}$ ; New Zealand; production rate calibration; short-lived cosmogenic nuclide; Southern Alps.

## Introduction

Surface exposure dating with *in situ* cosmogenic nuclides such as  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^3\text{He}$  and  $^{21}\text{Ne}$  is widely used to quantify landscape processes. The potential of the relatively short-lived *in situ*  $^{14}\text{C}$  (half-life 5730 years) to constrain recent and complex surface exposure histories has long been recognized (e.g. Lal, 1991), but its extraction from terrestrial silicates has proven challenging. Unlike the longer-lived (e.g.  $^{10}\text{Be}$ , half-life 1.39 Ma) and stable ( $^3\text{He}$  and  $^{21}\text{Ne}$ ) nuclides, *in situ*  $^{14}\text{C}$  is less sensitive to prior exposure, because components inherited from periods before  $\sim 25$  ka ago have decayed below detection limits. Furthermore, pairing of short-lived *in situ*  $^{14}\text{C}$  in combination with a longer-lived nuclide allows investigation of complex surface exposure histories, including those involving erosion and surface burial.

First attempts to extract  $^{14}\text{C}$  from terrestrial whole rocks were reported over two decades ago (Jull *et al.*, 1989). However, at that time reliable measurements were limited by the difficulty of efficiently isolating the small amounts of *in situ*  $^{14}\text{C}$  from ubiquitous atmospheric  $^{14}\text{C}$ . It was the breakthrough achieved by Lifton *et al.* (2001), based on an improved protocol and the use of quartz separates, that allowed this tool to be applied successfully to problems of Earth-surface processes (Matmon *et al.*, 2005; Miller *et al.*, 2006; Anderson *et al.*, 2008; Goehring *et al.*, 2011; White *et al.*, 2011).

Successful application of cosmogenic nuclides for surface exposure dating requires that the production rate (the number of atoms produced per gram of target material per year) be well known. The production rate of a given nuclide can be determined by measuring the nuclide concentration in a surface with a simple, well-constrained exposure history (i.e. no intermittent shielding or significant erosion, and a reliable independently estimated exposure age). Because cosmogenic nuclide production rates depend on the altitude,

geographic position and exposure duration, the resulting local production rate is, by convention, scaled to present day and to a 'sea level/high latitude' (SLHL) reference position by applying one of the several published scaling methods (e.g. Lal, 1991; Stone, 2000; Dunai, 2001; Desilets *et al.*, 2006; Lifton *et al.*, 2005).

The first experimental calibrations of *in situ*  $^{14}\text{C}$  production rates using the improved extraction procedure were conducted with samples from sites in the northern hemisphere by Lifton *et al.* (2001), followed by Pigati (2004; data in Miller *et al.*, 2006) and Dugan *et al.* (2008).

In this study, we present the first *in situ*  $^{14}\text{C}$  production rate from the southern middle latitudes, obtained from a debris flow deposited 9.7 ka ago in the Southern Alps of New Zealand. This site has a robust radiocarbon age and forms the basis for a  $^{10}\text{Be}$  production rate calibration (Putnam *et al.*, 2010). Four of the seven original  $^{10}\text{Be}$  calibration samples had sufficient material left for the *in situ*  $^{14}\text{C}$  production rate calibration. Using these four samples, we derive the local *in situ*  $^{14}\text{C}$  production rate in quartz at the Macaulay calibration site. We also present SLHL spallogenic production rates using the five scaling methods implemented in the CRONUS-Earth online calculator (Balco *et al.*, 2008) and compare and combine the results with previously published calibrations.

## Calibration site

The geomorphology of the calibration site in the central Southern Alps of New Zealand is described in detail in Putnam *et al.* (2010). It consists of a bouldery debris-flow deposit that overran a vegetated alluvial terrace at Macaulay River on South Island, at  $43.6^\circ\text{S}$  latitude and 1030 m altitude. This burial event has been dated to  $9690 \pm 50$  calendar years before 2008 Common Era (CE) based on ten radiocarbon dates on plant macrofossils from the soil horizon buried by the debris flow. Following Putnam *et al.* (2010), we interpret this date to represent the depositional age of the landform and thus the

\*Correspondence: I. Schimmelpfennig, as above.  
E-mail: schimmel@ldeo.columbia.edu

**Table 1.** Sample data

Sample	Latitude (°S)	Longitude (°E)	Altitude (m)	Thickness (cm)	Thickness correction factor	Shielding factor
MR-08-03	43.57452	170.60805	1029.4	2.55	0.979	0.988
MR-08-05	43.57435	170.60760	1032.1	2.39	0.980	0.991
MR-08-13	43.57751	170.60695	1027.6	1.41	0.988	0.991
MR-08-14	43.57787	170.60493	1032.0	2.35	0.980	0.991

beginning of cosmogenic nuclide production in the boulders exposed at its surface.

The altitudes of the four calibration samples range from 1028 to 1032 m. Sample data are summarized in Table 1.

### *In Situ* $^{14}\text{C}$ analysis, production rates and $^{14}\text{C}/^{10}\text{Be}$ ratio

The *in situ*  $^{14}\text{C}$  extraction procedure and details of the production rate calculations are given in the online Supporting information, Appendix S1. The blank-corrected  $^{14}\text{C}$  concentrations of the four samples, also corrected for topographic shielding and sample thickness effects, range between  $180 \times 10^3$  and  $214 \times 10^3$  atoms (g quartz) $^{-1}$  and give an arithmetic mean value and standard deviation of  $(194 \pm 15) \times 10^3$  atoms (g quartz) $^{-1}$  (Tables 2a and 2b). While the  $1\sigma$  accelerator mass spectrometry measurement uncertainties on the individual measurements are low ( $\sim 2\%$ ), the scatter in the *in situ*  $^{14}\text{C}$  dataset (standard deviation  $\sim 8\%$ ) is higher than that in the corresponding  $^{10}\text{Be}$  dataset (standard deviation  $\sim 1\%$ ), and no correlation is observed between individual higher or lower *in situ*  $^{14}\text{C}$  and  $^{10}\text{Be}$  concentrations (Tables 2a and 2b). The scatter in the *in situ*  $^{14}\text{C}$  dataset therefore mostly reflects contributions from the extraction procedure.

The local time-integrated *in situ*  $^{14}\text{C}$  production rate determined from the four measurements at the site in New Zealand is  $34.0 \pm 2.7$  atoms (g quartz) $^{-1}$  a $^{-1}$  (arithmetic mean  $\pm$  standard deviation, Tables 2a and 2b). This value represents the total *in situ*  $^{14}\text{C}$  production from spallation and muon capture. We calculated the spallogenic  $^{14}\text{C}$  production rate by first subtracting the muogenic  $^{14}\text{C}$  contribution for each sample estimated from Heisinger *et al.* (2002a,b) [3.8 atoms (g quartz) $^{-1}$  a $^{-1}$  at SLHL], and then deriving the best-fit spallogenic production rates referenced to SLHL. To do this, we applied the chi-squared minimization approach of Balco *et al.* (2009) and the five production-rate scaling schemes incorporated in the CRONUS-Earth calculator (Balco *et al.*, 2008), modified to utilize *in situ*  $^{14}\text{C}$ . Depending on the scaling scheme used, the time-integrated best-fit spallogenic production rates range from  $11.4 \pm 0.9$  atoms (g quartz) $^{-1}$  a $^{-1}$  ('Lm': time-dependent adaptation of the method by Lal, 1991, accounting for paleomagnetic corrections) to  $12.7 \pm 1.0$  atoms (g quartz) $^{-1}$  a $^{-1}$  ('Li': method by Lifton *et al.*, 2005) (Table 3, Fig. 1).

The ratio of  $^{14}\text{C}/^{10}\text{Be}$  spallogenic production rates in our quartz samples is  $3.0 \pm 0.2$  for all five scaling methods. This value is in good agreement with the ratio of  $^{14}\text{C}$  and  $^{10}\text{Be}$  spallogenic production rates in quartz of 3.12 derived from numerical modeling by Masarik and Reedy (1995).

We note that the muogenic *in situ*  $^{14}\text{C}$  contribution (for our samples  $\sim 24\%$  of total  $^{14}\text{C}$  production at SLHL following Heisinger *et al.*, 2002a,b) is not yet well constrained (Balco *et al.*, 2008), and therefore our experimentally determined  $^{14}\text{C}$  spallogenic production rates and  $^{14}\text{C}/^{10}\text{Be}$  spallogenic production rate ratio might change with future refinements of muogenic production rates.

### Comparison with previous *in situ* $^{14}\text{C}$ production rate calibrations

*In situ*  $^{14}\text{C}$  production rate calibrations were previously performed with samples from two locations in the northern hemisphere, the Bonneville shoreline at Promontory Point (Utah, USA;  $41^\circ\text{N}$ ,  $112^\circ\text{W}$ , 1600 m altitude) and two landslide deposits in the north-western Scottish Highlands (Corrie nan arr and Maol-Chean-dearg, UK;  $57^\circ\text{N}$ ,  $5^\circ\text{W}$ , 100–500 m altitude) (Lifton *et al.*, 2001; Pigati, 2004; Miller *et al.*, 2006; Dugan *et al.*, 2008). For direct comparison with our results, we recalculated the *in situ*  $^{14}\text{C}$  spallation production rates for these northern hemisphere sites using the same protocol as reported here for the Macaulay site. For Promontory Point we employed the exposure age of  $17.4 \pm 0.2$  cal ka BP originally used in Lifton *et al.* (2001), based on the radiocarbon chronology of Lake Bonneville by Oviatt *et al.* (1992). It should be noted, however, that aspects of this chronology are continuing to evolve as additional age control becomes available (e.g. Miller *et al.*, 2011). In Dugan *et al.* (2008), the exposure age at the Scottish calibration site is assumed to be  $11.6 \pm 0.2$  ka based on the geomorphic relationship between landslide deposits and glacial landforms, which are assumed to date to the end of the Younger Dryas period  $\sim 11.6$  ka ago. The recalculated best-fit *in situ*  $^{14}\text{C}$  spallation production rates from Promontory Point and Scotland are shown and compared with those from the Macaulay valley in Table 3 and Fig. 1. The combined *in situ*  $^{14}\text{C}$  spallation production rates from Promontory Point and Scotland range from  $12.5 \pm 0.9$  to  $14.1 \pm 1.0$  atoms (g quartz) $^{-1}$  a $^{-1}$ , depending on the scaling method used (Table 3), and agree within  $1\sigma$  uncertainties with those from the Macaulay valley. The arithmetic means and standard deviations of the best-fit values from all three sites are between  $12.1 \pm 0.6$  and  $13.5 \pm 0.7$  atoms (g quartz) $^{-1}$  a $^{-1}$  (Table 3, Fig. 1).

### Conclusions

In this study we present the first estimate of the *in situ*  $^{14}\text{C}$  production rate in the southern hemisphere, thus enhancing knowledge of the geographic distribution of *in situ*  $^{14}\text{C}$  production rates. The spallogenic production rates from this calibration site in New Zealand, calculated with five different scaling methods, agree within  $1\sigma$  with previous estimates from the northern hemisphere. The  $^{14}\text{C}/^{10}\text{Be}$  spallogenic production rate ratio of  $\sim 3$  inferred from our calibration samples agrees well with  $^{14}\text{C}/^{10}\text{Be}$  ratios deduced from numerical spallation production rate simulations.

### Acknowledgement

J.M.S. acknowledges NSF support of this study (grant no. EAR-0345835). This work was also supported by funding from the International Balzan Foundation. We thank Tom Guilderson and the staff of the LLNL Center for Accelerator Mass Spectrometry for the  $^{14}\text{C}$  measurements. This is LDEO

**Table 2a.** *In situ* <sup>14</sup>C extraction results.

Sample	Quartz weight (g)	V <sub>Co2</sub> (cc STP)	V <sub>dilute</sub> (cc STP)	CAMS number	F <sub>m</sub> measured	[ <sup>14</sup> C] blank corrected (10 <sup>3</sup> atoms g <sup>-1</sup> )	Blank correction proportion	[ <sup>14</sup> C] (10 <sup>3</sup> atoms g <sup>-1</sup> ) shielding/ thickness-corrected	[ <sup>10</sup> Be] (10 <sup>3</sup> atoms g <sup>-1</sup> ) shielding/ thickness-corrected	[ <sup>14</sup> C]/[ <sup>10</sup> Be]	Local <sup>14</sup> C production rate (atoms <sup>14</sup> C (g a) <sup>-1</sup> )
MR-08-03	5.03	0.2061 ± 0.0024	1.573 ± 0.018	152042	0.0259 ± 0.0002	206.87 ± 9.44	11%	213.92 ± 9.76	90.23 ± 1.74	2.37 ± 0.12	37.5 ± 1.7
MR-08-05	5.01	0.1178 ± 0.0013	1.456 ± 0.017	152040	0.0243 ± 0.0001	174.73 ± 9.25	12%	179.90 ± 9.52	91.71 ± 2.50	1.96 ± 0.12	31.5 ± 1.7
MR-08-13	5.01	0.1812 ± 0.0021	1.573 ± 0.018	152043	0.0244 ± 0.0001	193.16 ± 9.34	11%	197.24 ± 9.54	91.68 ± 1.82	2.15 ± 0.11	34.6 ± 1.7
MR-08-14	5.01	0.0992 ± 0.0011	1.492 ± 0.017	152041	0.0243 ± 0.0002	179.81 ± 9.30	12%	185.07 ± 9.58	90.47 ± 1.85	2.05 ± 0.11	32.4 ± 1.7
					Mean ± SD	194.03 ± 15.12 (7.8%)			91.02 ± 0.78 (0.9%)	2.13 ± 0.18 (8.3%)	34.0 ± 2.7

Sample weight, gas volume after carbon extraction from quartz (V<sub>Co2</sub>) and after addition of a <sup>14</sup>C-free dilution gas (V<sub>dilute</sub>) (cc STP = cubic centimeters at standard temperature and pressure), measured fraction modern (F<sub>m</sub> = the <sup>14</sup>C/<sup>13</sup>C ratio of the sample vs. that of a standard, both corrected to δ<sup>13</sup>C = -2.5‰ VPDB and to 1950 CE), blank-corrected <sup>14</sup>C concentrations with analytical uncertainties, blank correction proportion (number of atoms of <sup>14</sup>C in blank divided by number of atoms of <sup>14</sup>C in sample), and <sup>14</sup>C concentrations additionally corrected for topographic shielding and sample thickness effect (cf. Table 1). Also given are <sup>10</sup>Be concentrations (Putnam *et al.*, 2010), <sup>14</sup>C/<sup>10</sup>Be concentration ratios and local time-integrated *in situ* <sup>14</sup>C production rates for each sample, including all production mechanisms and corrected for radioactive decay, with mean value and standard deviation.

**Table 2b.** *In situ* <sup>14</sup>C blank data produced with the samples in Table 2a.

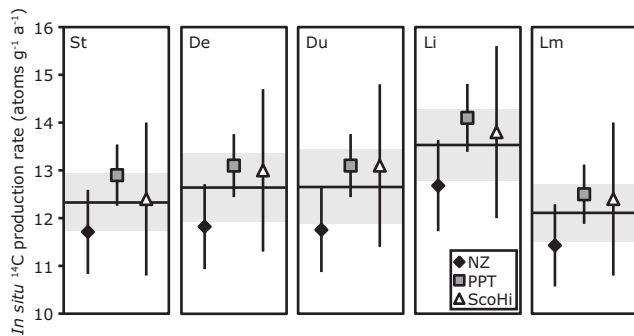
	V <sub>Co2</sub> (cc STP)	V <sub>dilutes</sub> (cc STP)	CAMS number	F <sub>m</sub> measured	No. of atoms <sup>14</sup> C (10 <sup>3</sup> atoms)
Blank 5-11-11	0.01571 ± 0.00018	1.346 ± 0.015	151903	0.0061 ± 0.0001	150.16 ± 12.82
Blank 6-1-11	0.01667 ± 0.00019	1.379 ± 0.016	152039	0.0053 ± 0.0001	119.65 ± 13.02

*In situ* <sup>14</sup>C blank data produced with the samples in (a). Blank 5-11-11 was processed before and Blank 6-1-11 after the samples, respectively. For the blank correction of the sample measurements, the arithmetic mean and standard deviation of the nine blanks processed at LDEO since the year 2010 [(124.67 ± 42.56) × 10<sup>3</sup> atoms <sup>14</sup>C, Goehring *et al.* (2012)] were used.

**Table 3.** Best-fit spallogenic production rates (PR) referenced to SLHL and present time (1950 CE) using five different scaling methods.

Scaling method	NZ <sup>14</sup> C PR (atoms <sup>14</sup> C g <sup>-1</sup> a <sup>-1</sup> )	NZ <sup>10</sup> Be PR (atoms <sup>10</sup> Be g <sup>-1</sup> a <sup>-1</sup> )	PPT <sup>14</sup> C PR (atoms <sup>14</sup> C g <sup>-1</sup> a <sup>-1</sup> )	ScoHi <sup>14</sup> C PR (atoms <sup>14</sup> C g <sup>-1</sup> a <sup>-1</sup> )	PPT + ScoHi <sup>14</sup> C PR (atoms <sup>14</sup> C g <sup>-1</sup> a <sup>-1</sup> )	Mean <sup>14</sup> C PR (NZ + PPT + ScoHi) (atoms <sup>14</sup> C g <sup>-1</sup> a <sup>-1</sup> )
St	11.7 ± 0.9 (7.5%)	3.9 ± 0.1	12.9 ± 0.6	12.4 ± 1.6	12.8 ± 0.9	12.3 ± 0.6
De	11.8 ± 0.9 (7.5%)	3.9 ± 0.1	13.1 ± 0.7	13.0 ± 1.7	13.1 ± 0.9	12.6 ± 0.7
Du	11.8 ± 0.9 (7.5%)	3.9 ± 0.1	13.1 ± 0.7	13.1 ± 1.7	13.1 ± 0.9	12.7 ± 0.8
Li	12.7 ± 1.0 (7.5%)	4.2 ± 0.1	14.1 ± 0.7	13.8 ± 1.8	14.1 ± 1.0	13.5 ± 0.7
Lm	11.4 ± 0.9 (7.5%)	3.8 ± 0.1	12.5 ± 0.6	12.4 ± 1.6	12.5 ± 0.9	12.1 ± 0.6

St = Stone (2000), Du = Dunai (2001), De = Desilets *et al.* (2006), Li = Lifton *et al.* (2005), Lm = time-dependent version of Li (1991). NZ refers to the Macaulay valley in New Zealand (*in situ* <sup>14</sup>C from this study, <sup>10</sup>Be from Putnam *et al.*, 2010). PPT denotes the Bonneville shoreline at Promontory Point (Lifton *et al.*, 2001; Pigati, 2004; Miller *et al.*, 2006; Dugan *et al.*, 2008). ScoHi refers to two sites in the Scottish Highlands (Dugan *et al.*, 2008). PPT + ScoHi indicates the combination of all measurements from Promontory Point and Scottish Highlands. The *in situ* <sup>14</sup>C extractions from PPT and ScoHi samples were performed on the flow-through and the recirculating extraction systems at the University of Arizona. Replicate measurements were averaged before the production rate calculations. The last column shows the arithmetic means and standard deviations of the best-fit values from the three calibration sites. All uncertainties correspond to 1σ.



**Figure 1.** Comparison of the best-fit *in situ* <sup>14</sup>C spallogenic production rates determined at the three calibration sites, Macaulay valley in New Zealand (NZ), Promontory Point (PPT) and Scottish Highlands (ScoHi), shown for each of the five scaling methods, St, Du, De, Li and Lm (same references as in Table 3), used to reference the local production rates to SLHL and present time (1950 CE). The horizontal line and gray band show the arithmetic mean and standard deviation of the best-fit values from the three sites.

contribution 7549. Comments from Joe Licciardi and one anonymous reviewer greatly improved the manuscript.

*Abbreviations.* CE, Common Era; SLHL, sea level/high latitude.

## Supporting information

Additional supporting information can be found in the online version of this article:

Appendix S1. Details of the *in situ* <sup>14</sup>C extraction and production rate calculations.

Please note: This supporting information is supplied by the authors, and may be re-organized for online delivery, but is not copy-edited or typeset by Wiley-Blackwell. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.

## References

- Anderson RK, Miller GH, Briner JP, et al. 2008. A millennial perspective on Arctic warming from <sup>14</sup>C in quartz and plants emerging from beneath ice caps. *Geophysical Research Letters* **35**: L01502. DOI: 10.1029/2007GL032057.
- Balco G, Stone J, Lifton N, et al. 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from <sup>10</sup>Be and <sup>26</sup>Al measurements. *Quaternary Geochronology* **3**: 174–195.
- Balco G, Briner J, Finkel RC, et al. 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology* **4**: 93–107.
- Desilets D, Zreda M, Prabu T. 2006. Extended scaling factors for *in situ* cosmogenic nuclides: new measurements at low latitude. *Earth and Planetary Science Letters* **246**: 265–276.
- Dugan B, Lifton N, Jull AJT. 2008. New production rate estimates for *in situ* cosmogenic <sup>14</sup>C. *Geochimica et Cosmochimica Acta* **72**: A231.
- Dunai TJ. 2001. Influence of secular variation of the geomagnetic field on production rates of *in situ* produced cosmogenic nuclides. *Earth and Planetary Science Letters* **193**: 197–212.
- Goehring BM, Schaefer JM, Schluechter C, et al. 2011. The Rhone Glacier was smaller than today for most of the Holocene. *Geology* **39**: 679–682.
- Goehring BM, Schimmelpfennig I, Schaefer JM. 2012. Capabilities of the Lamont-Doherty Earth Observatory *in situ* <sup>14</sup>C extraction laboratory updated. *Quaternary Geochronology*, in press.
- Heisinger B, Lal D, Jull AJT, et al. 2002a. Production of selected cosmogenic radionuclides by muons: 1. Fast muons. *Earth and Planetary Science Letters* **200**: 345–355.
- Heisinger B, Lal D, Jull AJT, et al. 2002b. Production of selected cosmogenic radionuclides by muons: 2. Capture of negative muons. *Earth and Planetary Science Letters* **200**: 357–369.
- Jull AJT, Donahue DJ, Linick TW. 1989. Spallogenic <sup>14</sup>C in high-altitude rocks and in Antarctic meteorites. *Radiocarbon* **31**: 719–724.
- Lal D. 1991. Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. *Earth and Planetary Science Letters* **104**: 424–439.
- Lifton NA, Jull AJT, Quade J. 2001. A new extraction technique and production rate estimate for *in situ* cosmogenic <sup>14</sup>C in quartz. *Geochimica et Cosmochimica Acta* **65**: 1953–1969.
- Lifton N, Bieber J, Clem J, et al. 2005. Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for *in situ* cosmogenic nuclide applications. *Earth and Planetary Science Letters* **239**: 140–161.
- Masarik J, Reedy RC. 1995. Terrestrial cosmogenic-nuclide production systematics calculated from numerical simulations. *Earth and Planetary Science Letters* **136**: 381–395.
- Matmon A, Shaked Y, Porat N, et al. 2005. Landscape development in an hyperarid sandstone environment along the margins of the Dead Sea fault: implications from dated rock falls. *Earth and Planetary Science Letters* **240**: 803–817.
- Miller G, Briner J, Lifton N, et al. 2006. Limited ice sheet erosion and complex exposure histories derived from *in situ* <sup>10</sup>Be, <sup>26</sup>Al and <sup>14</sup>C on Baffin Island, Canada. *Quaternary Geochronology* **1**: 74–85.
- Miller D, Oviatt C, McGeehin J. 2011. *Uncertainties associated with dating and understanding a classic Pleistocene lake: the Provo shoreline, Lake Bonneville, U.S.A. XVIII. In: INQUA Conference, Bern, Abstract ID 3018.*
- Oviatt CG, Currey DR, Sack D. 1992. Radiocarbon chronology of Lake Bonneville, eastern Great Basin, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology* **99**: 225–241.
- Pigati JS. 2004. *Experimental Developments and Application of Carbon-14 and in situ Cosmogenic Nuclide Dating Techniques. PhD thesis, University of Arizona.*
- Putnam AE, Schaefer JM, Barrell DJA, et al. 2010. *In situ* cosmogenic <sup>10</sup>Be production-rate calibration from the Southern Alps, New Zealand. *Quaternary Geochronology* **5**: 392–409.
- Stone JO. 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* **105**: 23 753–23, 759.
- White D, Fülö R-H, Bishop P, et al. 2011. Can *in situ* cosmogenic <sup>14</sup>C be used to assess the influence of clast recycling on exposure dating of ice retreat in Antarctica? *Quaternary Geochronology* **6**: 289–294.