Quaternary Research 77 (2012) 289–292

Contents lists available at SciVerse ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Short Paper

Radiocarbon ages of terrestrial gastropods extend duration of ice-free conditions at the Two Creeks forest bed, Wisconsin, USA

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ARTICLE INFO

Article history:
Received 23 May 2011
Available online 21 December 2011

Keywords:
Two Creeks
Bølling–Allerød
Gastropods
Radiocarbon
Laurentide Ice Sheet

ABSTRACT

Analysis of terrestrial gastropods that underlie the late Pleistocene Two Creeks forest bed (~13,800–13,500 cal yr BP) in eastern Wisconsin, USA provides evidence for a mixed tundra-taiga environment prior to formation of the taiga forest bed. Ten new AMS ^{14}C analyses on terrestrial gastropod shells indicate the mixed tundra-taiga environment persisted from ~14,500 to 13,900 cal yr BP. The Twocreekan climatic substage, representing ice-free conditions on the shore of Lake Michigan, therefore began near the onset of peak warming conditions during the Bølling–Allerød interstadial and lasted ~1000 yr, nearly 600 yr longer than previously thought. These results provide important data for understanding the response of continental ice sheets to global climate forcing and demonstrate the potential of using terrestrial gastropod fossils for both environmental reconstruction and age control in late Quaternary sediments.

The Two Creeks type locality, situated on the western shore of Lake Michigan in Wisconsin, USA contains one of the most famous late Pleistocene glacial/interstadial sequences in North America. First studied by J.S. Goldthwait in 1907, the exposure consists of a glacial diamicton overlain by lacustrine silts and sands and capped by the Two Creeks forest bed. The forest bed, which contains stumps and other remains of spruce trees (*Picea mariana* and *Picea glauca*), is itself overlain by lacustrine and glacial deposits (Fig. 1; Black, 1970). Previous ^{14}C dating and counting of growth rings from buried logs and stumps indicated a calibrated age range of ~13,840–13,620 cal yr BP for the forest bed and a minimum lifespan for the forest of ~230 to 250 yr (Broecker and Farrand, 1963; Kaiser, 1994). Subsequent work by Panyushkina and Leavitt (2007) and Leavitt et al. (2007) indicated a minimum lifespan of 329 yr and an age range of 13,760–13,530 cal yr BP. Constraining the age and duration of ice-free conditions at the Two Creeks locality is important for understanding the response of the Laurentide Ice Sheet to global climate forcing (Lowell, 2000). The existing age control suggests that the Twocreekan interval began ~1000 yr after the beginning of the Bølling–Allerød interstadial (14,740 ± 60; Lemieux-Dudon et al., 2010) and was of relatively short duration (~330 yr).

To reconstruct environmental conditions prior to formation of the forest bed and to determine the duration of ice-free conditions, we collected gastropod shells from just below the Two Creeks forest bed at the Two Creeks type locality (Fig. 1). Approximately 10 liters of the top (upper 3 cm) of the gray silt unit was collected, soaked in water, and sieved to isolate gastropod shells. Shells were classified and separated based on shell morphology. The terrestrial gastropod fauna was compared to 171 modern stations from Alaska, Manitoba, and Quebec (Nekola, 2010) through global non-metric multidimensional scaling (Minchin, 1987). Pairwise dissimilarity values were calculated using the Czekanowski index (Faith et al., 1987) on site presence–absence data. NMDS in two dimensions was then performed on 50 initial random starting configurations, with 200 maximum iterations, a stress-ratio stopping value of 0.9999, and a small-stress stopping value of 0.01. Unique solutions were identified using a Procrustes transformation, with the number of runs falling onto each solution being enumerated. The modal solution was identified and used to generate the ordination diagram. Terrestrial gastropod shells were processed for AMS ^{14}C dating at Miami University using standard methods (Rech et al., 2011).

The top of the gray silt unit contains aquatic and terrestrial gastropods representing the transition from an aquatic to terrestrial environment. Terrestrial gastropod shells include at least twelve different taxa (*Columella columella* [48 shells], *Columella simplex* [2], *Discus cronkhitei* [71], *Euconulus fulvus* [23], *Pupilla muscorum* [17],

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doi:10.1016/j.yqres.2011.11.007

Succineidae spp. [93], *Vallonia gracilicosta* [4], *Vertigo cristata* [1], *Vertigo elatior* [135], *Vertigo hannai* [9], *Vertigo modesta arctica* [8], *Vertigo oughtoni* [14]). Comparison of these taxa with modern assemblages collected throughout North America suggests a mixed tundra-taiga environment, although the fossil assemblage does not match directly that of any modern locality (Fig. 2). Assuming that these different taxa lived contemporaneously, the closest modern analogs to the Two Creeks fauna are found in 1) a lowland tundra and tamarack-spruce forest in Churchill, Manitoba (*C. columella*, *E. fulvus*, *Pupilla* sp., Succineidae spp., *V. elatior*, *V. hannai*, *V. modesta*, *V. oughtoni*); 2) a transitional tundra-taiga site along the St. Lawrence River in eastern Quebec (*D. cronkhitei*, *C. columella*, *E. fulvus*, *Pupilla* sp., Succineidae spp., *V. gracilicosta*, *V. elatior*, *V. modesta*); 3) a taiga site near Anchorage Alaska, (*D. cronkhitei*, *E. fulvus*, Succineidae spp., *V. modesta*); and 4) a boreal grassland-aspen forest on steep, south-facing slopes in central Alaska (*D. cronkhitei*, *E. fulvus*, Succineidae spp., *V. gracilicosta*) (Fig. 2). Alternatively, the faunal assemblage may represent a transition from tundra to taiga environment if individual specimens are not contemporaneous.

To better constrain the duration of ice-free conditions, we dated ten aliquots of shell material of five different taxa (*D. cronkhitei*, *E. fulvus*, *P. muscorum*, *V. elatior*, Succineidae) by AMS ^{14}C. Radiocarbon ages ranged from 12,390 ± 70 to 12,090 ± 90 ^{14}C yr BP, representing a calibrated age range from 14,520 ± 440 to 13,950 ± 180 cal yr BP (Table 1; Fig. 3). Although terrestrial gastropod shells have long been avoided for radiocarbon dating due to their potential for incorporating ^{14}C-deficient carbon from limestone during shell mineralization (Goodfriend and Stipp, 1983), many

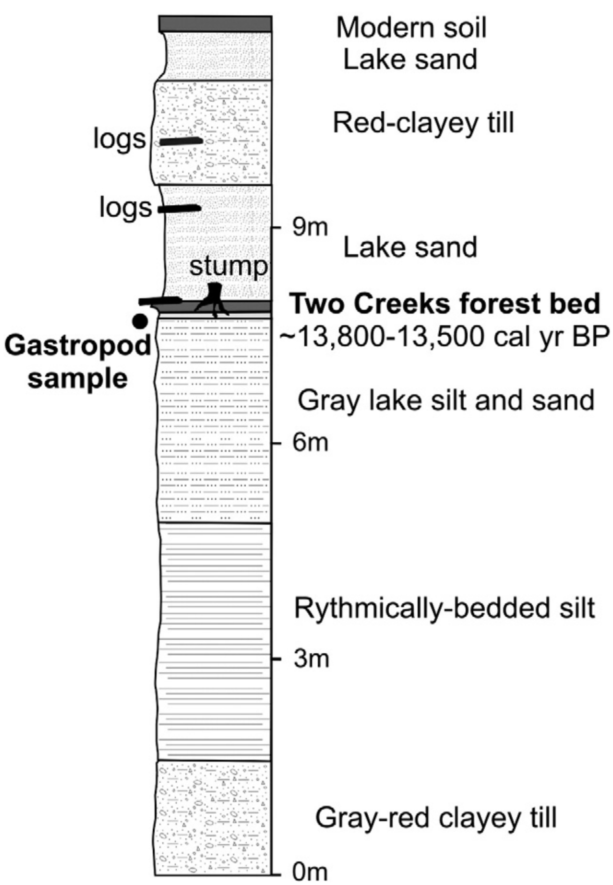

Figure 1. Stratigraphic section of Two Creeks type locality (Black, 1970) and location of terrestrial gastropod sample.

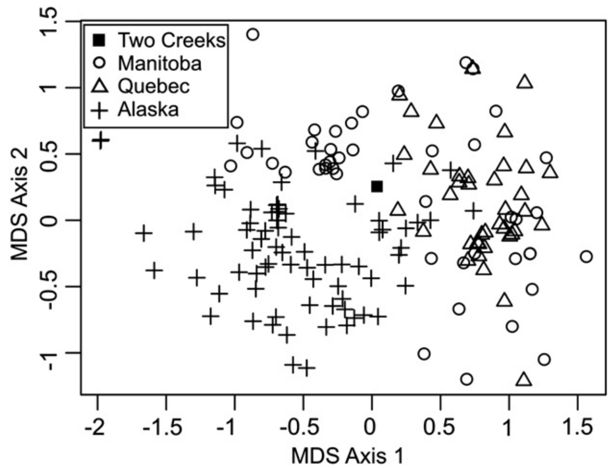

Figure 2. Comparison of the Two Creeks terrestrial gastropod fauna with modern North American tundra-taiga faunas from Manitoba, Quebec, and Alaska using global, non-metric multidimensional scaling. Output was scaled in half-change units, so that an interpoint distance of 1.0 corresponds to a 50% turnover in species composition.

terrestrial gastropod taxa in North America incorporate negligible amounts of old carbon into their shells even when living in environments where carbonate rocks are abundant (Pigati et al., 2010). Shells of these taxa, therefore, should yield reliable ^{14}C ages as long as they act as closed systems with respect to carbon over geologic time (Rech et al., 2011). Our data appear to support this hypothesis for several reasons, including 1) the gastropod shell ages (14,520–13,950 cal yr BP) from just beneath the Two Creeks forest bed fall directly prior to the published ages of the forest wood (~13,800–13,500 cal yr BP), 2) the gastropod fauna represents a different paleo-environment from the overlying forest bed, and 3) the ^{14}C ages of gastropod shells cluster tightly between 12,390 ± 70 and 12,090 ± 90 ^{14}C yr BP, which is unlikely if these different taxa contained variable amounts of old carbon.

Our analyses of terrestrial gastropods from just below the late Pleistocene Two Creeks forest bed indicate that a mixed tundra-taiga environment existed prior to the forest bed, representing the most recent tundra environment in the Great Lakes region. Moreover, the radiocarbon ages of these shells indicate that the Twocreekan climatic substage, representing ice-free conditions on the shore of Lake Michigan, began just after the onset of the Bølling–Allerød interstadial (14,740 ± 60; Lemieux-Dudon et al., 2010) and lasted ~1000 yr until ~13,500 ka, nearly 600 yr longer than previously thought.

This new understanding of the environment and age of the Twocreekan climatic substage may help explain several aspects of regional stratigraphy. For example, the Valders interstadial deposit southeast of the Two Creeks locality represents a tundra environment that existed prior to the deposition of a red-clayey till, similar to the till overlying the Two Creeks forest bed (Maher and Mickelson, 1996; Maher et al., 1998; Mickelson et al., 2007). However, based on the presence of tundra flora and an assumed radiocarbon age of 12,200 ^{14}C yr, Maher et al. (1998) concluded that this tundra environment represented an interstadial event prior to the Twocreekan. The terrestrial gastropod data presented here may indicate that these interstadial events were contemporaneous. The extended duration of the Twocreekan as indicated by the gastropod shells may also explain the broad range of ^{14}C ages from the Cheboygen bryophyte bed, which was also interpreted to be contemporaneous with the Two Creeks forest bed (Larson et al., 1994).

https://doi.org/10.1016/j.yqres.2011.11.007 Published online by Cambridge University Press

Table 1
Radiocarbon ages of terrestrial gastropods.

Lab #	AA#	Taxon	N[a]	δ^{13} C PDB	F^{14}C	^{14} C age (ka)	Calibrated age (ka)[b]	P[c]
MU-263	83097	*Discus cronkhitei*	1	−6.6	0.2137 ± 0.0020	12.39 ± 0.070	14.52 ± 0.444	1.00
MU-264	83098	*Discus cronkhitei*	3	−7.1	0.2143 ± 0.0023	12.37 ± 0.090	14.50 ± 0.471	1.00
MU-265	83099	*Discus cronkhitei*	3	−7.0	0.2155 ± 0.0020	12.33 ± 0.080	14.46 ± 0.465	1.00
MU-266	83100	*Euconulus fulvus*	12	−7.2	0.2199 ± 0.0020	12.17 ± 0.070	14.01 ± 0.227	0.99
MU-267	83101	*Pupilla muscorum*	10	−7.3	0.219 ± 0.0022	12.20 ± 0.080	14.17 ± 0.365	1.00
MU-260	83094	Succineidae	2	−4.9	0.2187 ± 0.0020	12.21 ± 0.070	14.05 ± 0.225	0.91
							14.40 ± 0.121	0.09
MU-261	83095	Succineidae	2	−5.8	0.2219 ± 0.0020	12.09 ± 0.070	13.95 ± 0.177	1.00
MU-262	83096	Succineidae	3	−5.0	0.2194 ± 0.0022	12.19 ± 0.080	14.03 ± 0.235	0.92
							14.41 ± 0.115	0.08
MU-268	83102	*Vertigo elatior*	14	−7.5	0.2189 ± 0.0021	12.20 ± 0.080	14.17 ± 0.365	1.00
MU-269	83103	*Vertigo elatior*	20	−7.6	0.2158 ± 0.0020	12.32 ± 0.070	14.44 ± 0.452	1.00

[a] Number of fossil shells used for radiocarbon analysis.
[b] CALIB v. 6.0.0 (Stuiver and Reimer, 1993), IntCal09.14 C dataset (Reimer et al., 2009); limit 50.0 calibrated ka B.P. Calibrated ages are reported as the midpoint of the calibrated range. Uncertainties are given at the 2σ (95%) confidence level and reported as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater. Multiple ages are reported when the probability of a calibrated age range exceeded 0.05.
[c] Probability of the calibrated age falling within the reported range as calculated by CALIB.

In summary, the revised age of the Twocreekan climatic substage proposed here correlates the initiation of ice-free conditions at Two Creeks with peak warming conditions near the beginning of the Bølling–Allerød interstadial and may help explain several outstanding questions regarding the stratigraphy of ice sheet advances and retreats in the Great Lakes region. Future work with terrestrial gastropods may provide useful data for refining regional stratigraphy and understanding the response of large ice sheets to global climatic forcing.

Acknowledgments

This research was funded by NSF grant EAR-0614647. Dave Mickelson assisted with the location of gastropods below the Two Creeks forest bed and helped with regional stratigraphy. Dan Muhs, Paul Carrara, Gene Ellis, Thomas Lowell, and B. Brandon Curry provided thoughtful reviews of the manuscript. Craig Tully, Eva Fischer-Rech, and Maddy Abowitz assisted with field work.

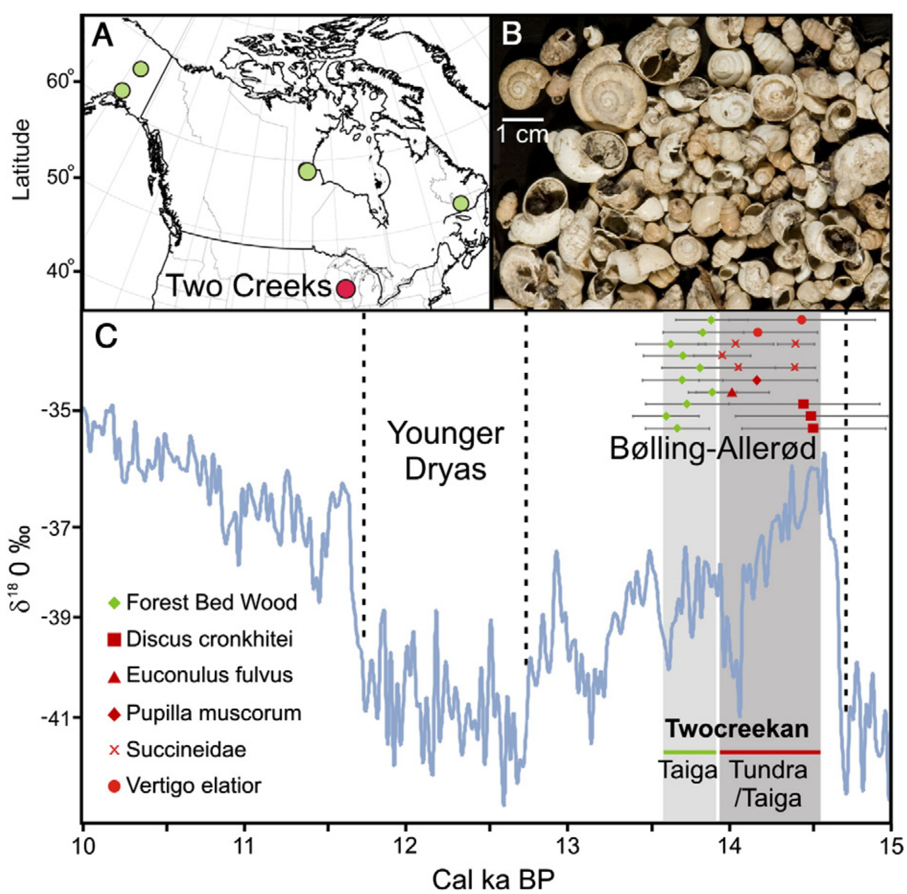

Figure 3. Terrestrial gastropods from the Two Creeks type locality: a) location of Two Creeks (red) and closest analog environments (green) for terrestrial gastropod assemblage from below the forest bed; b) terrestrial gastropod shells from the Two Creeks type locality; c) calibrated AMS ^{14}C ages of terrestrial gastropod shells (this study) and wood (Kaiser, 1994) in relation to oxygen isotope values from a Greenland ice core (NGRIP, 2006).

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