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Reply

Reply to comment by D.J. Easterbrook (Quaternary Research 2003, 59 #1, 132–134) on "Determination of ^{36}Cl Production Rates from the Well-Dated Deglaciation Surfaces of Whidbey and Fidalgo Islands, Washington"

Introduction

The main premise of Easterbrook's (2003) comment is that our ^{36}Cl production rates (Swanson and Caffee, 2001) are 20% lower than those of Zreda et al. (1991) because a 2000-yr error has been made in assigning a ^{14}C age to the time of exposure of calibration sites on Whidbey and Fidalgo islands. He contends that the time of exposure that should be used (i.e., ~11,500 ^{14}C yr B.P.; 13,200 cal yr B.P.) is 2000 yr younger than that reported by us (~13,200 ^{14}C yr B.P.; ~15,500 cal yr B.P.). He further contends that our ^{36}Cl production rates could be reconciled with those of Zreda et al. (1991) if we used his proposed younger exposure age for our calibration sites.

In his introductory paragraph, Easterbrook states that Swanson and Caffee's "production rates are 20% lower than those of Zreda et al., 1991," whereas, in fact, we report (Swanson and Caffee, 2001; Table 1, p. 367) that our production rates are ≥20% higher than those of Phillips et al. (1996) (a report, coauthored by Zreda, that supersedes the rates adopted by Zreda et al., 1991). His statement is based on an apparent misunderstanding of the relationship between the age of a calibration surface (time of exposure) and the derivation of the respective production rate. In his introductory statement, he reasons that our production rates are 20% lower than those of Zreda et al. (1991) because we excluded from consideration all extant ^{14}C ages of wood and marine shells in the Puget-Fraser Lowland. However, use of his proposed 13,200 cal yr B.P. calibration age would actually yield an even greater disparity between our production rates and those of Zreda et al. (1991) and Phillips et al. (1996). Simply stated, if we follow Easterbrook's interpretations and suggestions regarding the timing of deglaciation and exposure history for Whidbey and Fidalgo islands, the difference between our production rates and those of Phillips et al. (1996) would increase from 20% to 40%!

Despite this apparent misreading of our basic approach to determining the exposure age and production rate of a calibration surface, it is important to address the purported 2000 yr error. Easterbrook lists three causes of this inferred error in his letter, which we discuss in order.

Initial subaerial exposure of ^{36}Cl-dated boulders

Easterbrook contends that Swanson and Caffee (2001) "assume that the first exposure of boulders to cosmic rays is specified by the age of the shells in the underlying glaciomarine drift." He further states that because boulders initially were submerged beneath marine water, "subaerial exposure significantly postdated deposition of the sediment used for calibration of Swanson and Caffee." This misstates our inferred relationship between the timing of exposure of till boulders and the ages of shells in glacialmarine drift (GMD). Our time of deglaciation (exposure age) of sample sites on Whidbey and Fidalgo islands is not simply based on shell ages collected from our calibration area. Instead, we placed our greatest reliance on basal ^{14}C ages of terrestrial peat, wood, and gyttja from postglacial lakes and bogs lying south (e.g., Mercer Slough, Lake Washington, and Lake Carpenter) and north (e.g., Nooksak River Valley and Sedro Wooley) of our calibration sites (Porter and Swanson, 1998; Swanson and Caffee, 2001, Table 2). These postglacial ^{14}C ages of terrestrial organic matter show that Whidbey and Fidalgo islands were deglaciated prior to the oldest minimum limiting ^{14}C ages lying north (12,900 ± 330 ^{14}C yr, Rubin and Alexander, 1958; 12,596 ± 90 ^{14}C yr, Kovanen and Easterbrook, 2001) and south (13,600 ± 280 ^{14}C yr, Leopold et al., 1982; 13,700 ± 100 ^{14}C yr, Amundsen et al., 1994) of our calibration sites. Our deglaciation age of ca. 15,500 cal yr for Whidbey Island is based on the oldest postglacial gyttja, detrital clay, and wood ages obtained near our calibration sites. The ^{14}C ages of the oldest GMD shells that we collected on Whidbey Island are consistent with these wood and peat ages (reported in Dethier et al., 1995; Porter and Swanson, 1998, Table 1 and Swanson and Caffee, 2001, Table 2.).

Easterbrook points out that relative sea level was as much as 100 m higher than present during deglaciation and that subaerial exposure of our calibration sites significantly postdated deposition of the glacialmarine sediment. He further proposes that the initial exposure of the calibration sites occurred when sea level dropped below the elevation of the sampled boulders. We certainly concur that emergence of the landscape is an important component of the

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rapidly changing postglacial environment and that some of the boulders and rock surfaces we sampled lie below the marine limit. However, the critical words are "significantly postdated," for if emergence is rapid, the resulting potential error will be small. The postglacial marine limit in this sector of the Puget Lowland rises gradually from <30 m on Southern Whidbey Island to ca. 90 m on southern Fidalgo Island (Dethier et al., 1995, Fig. 3). A majority of our calibration sites (65%) lie above the marine limit near the southern end of Whidbey Island (Swanson and Caffee, 2001, Fig. 1). Of the remaining sites, most of those on Whidbey Island lie <30 m below the marine high stand. Radiocarbon dating of postglacial deltas indicates that uplift rates averaged between 10 and 30 cm per year following deglaciation (Dethier et al., 1995). Mosher and Hewitt (2004, Fig. 14 and Table 2) derive an emergence rate of ca. 23 cm/yr for the initial 47 m of emergence in the eastern Strait of Juan de Fuca, west of Whidbey and Fidalgo Islands; thus, calibration sites lying within 30 m of the marine limit would have emerged rapidly (within 90–300 yr), an interval that we do not consider as "significantly" postdating deglaciation for purposes of our calibration effort.

Age of the glacialmarine drift

Easterbrook contends that the time of emergence (time of exposure) for our calibration sites was ~11,500 ^{14}C yr B.P. (~13,200 cal yr B.P.) based on some of the youngest of the published shell ages reported in Easterbrook (1969) and shown in Fig. 1 of Easterbrook (2003). However, whereas the 141 radiocarbon dates plotted in his Figure 1 show glacialmarine sedimentation occurring as recently as ca. 11,000 ^{14}C yr ago, nearly all these dates are from the northern lowland, well north of our calibration area. Furthermore, only a few are relevant to the timing of deglaciation. The oldest dates in his plot show that at least some sites between 48.2° and 49.2°N were deglaciated by 13,000 ^{14}C yr ago. We maintain that the oldest shells at a site provide a minimum age (possibly close minimum?) for deglaciation of that site. Accordingly, only shells at the base of a glacialmarine section will provide a reasonably close minimum age for deglaciation, while younger unreworked shells higher in the section reflect persistence of glacialmarine sedimentation after deglaciation of the site, or may simply represent emergence ages of the isostatically compensated postglacial shoreline. Thus, the oldest glacialmarine shells from our study area provide a minimum age for ice withdrawal and exposure of nearby rock surfaces that stood above the marine limit.

We would like to point out a further problem pertaining to the radiocarbon dating of shells from glacialmarine drift that generally is overlooked or not considered. Marine shells incorporated in glacialmarine sediments begin to dissolve after deposition, with an alteration front that moves slowly inward. The conversion of initial shell aragonite into calcite means that the unaltered interior of a shell will be older than the altered exterior. To test this inference, we dated a portion of a robust shell (*Saxidomus giganteus*) obtained from glacialmarine drift at Fort Ebey on Whidbey Island, then redated additional portions after removing 15% and 75% of the remaining outer part of the shell. The whole-shell age of 12,340 ± 60 yr increased to 12,460 ± 60 yr after the first etching, and to 12,870 ± 70 yr after the final etching. In this example, therefore, the untreated shell produced an age 530 ^{14}C yr younger than when all but the core of the shell was etched away. This result suggests that radiocarbon ages of untreated shells or of bulk samples likely underestimate the true age by an unknown, but potentially significant, amount. Prior to the 1980s, pretreatment of this type was not routinely carried out or reported.

Marine ^{14}C reservoir value

One of the reasons we place less reliance on dated glacialmarine shells than on terrestrial organic matter for determining the timing of deglaciation and calibrating the ^{36}Cl production rates is that an arbitrary reservoir correction must be applied to radiocarbon ages of marine shells. Amundsen et al. (1994) used a correction of −760 yr for Puget Sound waters (versus −400 yr for open ocean waters, following Stuiver et al., 1986) at Lake Carpenter, which was deglaciated by ca. 13,550 ^{14}C yr ago. However, they cautioned that the reservoir correction beyond 12,000 ^{14}C yr B.P. should be less than the value of −760 yr that they used. Easterbrook (2003, Fig. 2b) suggests that their dates are inconsistent, but the three gyttja (not wood) dates they obtained are statistically identical in age (at 1 sigma SD) and average 13,555 yr; the corrected age of a marine shell interstratified between these gyttja samples is statistically identical to them (13,310 ± 190 ^{14}C yr B.P.).

Easterbrook (2003) advocates using a correction of −1100 yr, based on paired shell and wood ages from the Fraser Lowland, well north of Whidbey and Fidalgo islands. However, this correction may not apply to late-glacial samples from across the broad region farther south because late-glacial water chemistry must have differed regionally within the geographically complex inland waters of the Puget Sound basin, as well as through time. The mixing of old marine water with meltwater from glacier ice of highly variable age means that a single reservoir correction for the entire Puget Lowland likely is inappropriate. The sites in the Fraser Lowland where Easterbrook's paired calibration samples were obtained were deglaciated about 1000 yr later than sites to the south on Whidbey and Fidalgo islands where our calibration sites lie. As J. Southern has pointed out, ^{14}C production may have been lower during the earlier of these intervals (Swanson and Caffee, 2001, p. 369).

For these and other reasons, we assigned only secondary significance to shell ages related to deglaciation and favored terrestrial organic matter for calibration control. We recognize that assigning a single discrete age to deglaciation of the calibration area is an oversimplification because deglaciation was transgressive across the landscape. We nevertheless believe that the date of 15,500 ± 500 yr is a realistic average value for Whidbey Island that is consistent with independently dated ice retreat in the central and southern Puget Lowland. We reiterate, as well, that independent support for the derived production rates comes from the Ring Creek Lava Flow in southwestern British Columbia, the age of which is bracketed by radiocarbon dates (Brooks and Friele, 1992; Swanson and Caffee, 2001, p. 375–376). Therefore, we believe that the Central and Northern Puget Lowland remains one of the most promising areas in the American West for obtaining reliable cosmogenic isotope production rates spanning late- and postglacial time.

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