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Discussion

Response to Discussion by Wolfe et al. on Bierman et al. (Geomorphology 25 (1999) 25–39)

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On the basis of radiocarbon ages in lake sediments collected near our field site in the Pangnirtung Fjord area and elsewhere on Baffin Island, Wolfe et al. argue for continued acceptance of the "traditional weathering zone model" and the existence of glacier-free highlands that functioned as refugia through at least the last glacial maximum (LGM). Although our original paper (Bierman et al., 1999) considers both of these topics only in passing, we appreciate the opportunity to discuss Wolfe et al.'s ideas in light of new results, both ours and theirs, obtained and/or published after our original paper was submitted in 1997.

In contrast to the certainty with which Wolfe et al. declare the continued validity of the weathering zone model and the existence of extensive ice-free refugia throughout Wisconsinan time, we still believe that data pertinent to defining the extent and duration of ice cover on the highlands of Baffin Island remain contradictory (Steig et al., 1998; Bierman et al., 1999; Marsella et al., 2000). However, on the local scale, specifically in the Pangnirtung Fjord area that we studied in detail, cosmogenic nuclide analyses of over 140 samples indicate that weathering zones do not represent time–stratigraphic boundaries (Marsella et al., 2000). The same data set mandates that ice covered the highlands transporting erratics during the LGM (Table 1). Thus, the extensive highlands surrounding Pangnirtung Fjord could not have been refugia during the last glaciation.

Weathering zones and unglaciated enclaves on Baffin Island—were the highlands exposed during the LGM?

The concept of weathering zones, as summarized by Ives (1978) and advocated by Wolfe et al., is simple. Nested moraines are bathtub rings left by thinning ice sheets, the size of which was hypothesized to shrink steadily during a glacial cycle, such as the Wisconsinan, leaving more and more of the highland terrain ice-free, while the remaining ice covered the intervening lowlands. Thus, ice-free uplands were thought to serve as biological refugia for plants and perhaps animals, while the lowlands were buried under ice, the nunatak hypothesis (Blytt, 1876, 1882; Fernald, 1925; Dahl, 1955).

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The weathering zone concept is based primarily on the observation that rock surfaces and boulders in higher terrain are more weathered than in lower terrain (Ives, 1966, 1978; Nesje et al., 1987, 1988). If the weathering zone concept is correct, upland rock surfaces should have been exposed longer than lowlands. However, there are alternative explanations for the preservation of old, weathered landscapes under glacial ice (Dahl, 1963, 1966, 1987; Sugden and Watts, 1977; Klemen, 1994; Klemen and Borgstrom, 1994, 1996; Klemen and Stroeven, 1997), some of which involve the presence of cold-based ice frozen to the bed.

For many years, the weathering zone concept and the nunatak hypothesis were untestable; however, recent advances in dating techniques have allowed the age of rock surfaces in different weathering zones to be estimated directly. Accelerator mass spectrometric (AMS) ^{14}C ages of very small organic samples collected from lake sediment cores (Abbott and Stafford, 1996; Wolfe and Haertling, 1996) and AMS analysis of in situ-produced cosmogenic nuclides in samples from exposed rock surfaces (Brook et al., 1996; Marsella et al., 2000) have been used to constrain the timing of ice retreat. Unfortunately, results from these two methods are difficult to reconcile in the Pangnirtung Fjord area.

As Wolfe et al. point out, when taken at face value, finite radiocarbon ages from lake sediments are consistent with biological activity before, during, and after the LGM (see their Fig. 1). However, dating lake sediments with low organic content is uncertain (Abbott and Stafford, 1996), as older organic material may be reworked (see Ridge et al., 1999 for examples from further south, where the deglacial chronology is more certain). While low-activity blanks, such as Wolfe et al. describe, are necessary for dating such material, such blanks do not guarantee the validity of radiocarbon ages. The original age assignments of >60 (Dyke, 1977, 1979) and 55 ka (Hyatt, 1992) by amino acid racimization and AMS ^{14}C for the Duval moraines, now known to be late Wisconsinan (10–20 ka) in age (Marsella et al., 2000), were apparently the result of dating reworked shell material.

A series of young cosmogenic model ages appear to stand in stark contrast to Wolfe et al.'s old radiocarbon ages from highland lake sediments. Most germane is sample KM-95-111 (Fig. 1; Table 1), one of many large, subangular, erratic boulders sitting directly on the weathered uplands east of Pangnirtung Fjord. These weathered bedrock surfaces were the focus of Bierman et al. (1999). The erratic could only have been deposited upon the weathered tors on this extensive high-elevation plateau by flowing ice. The erratic contains an order of magnitude lower concentration of cosmogenic nuclides than the weathered bedrock surface (KM-95-110) on which it sits, the equivalent of only 9.4 ka of exposure (Table 1). Therefore, sample KM-95-111 unequivocally demonstrates that glacial ice capable of transporting erratics, but incapable of eroding much if any rock, occupied the highlands surrounding Pangnirtung Fjord during the latest Pleistocene or early Holocene. The erratic could not have been transported by

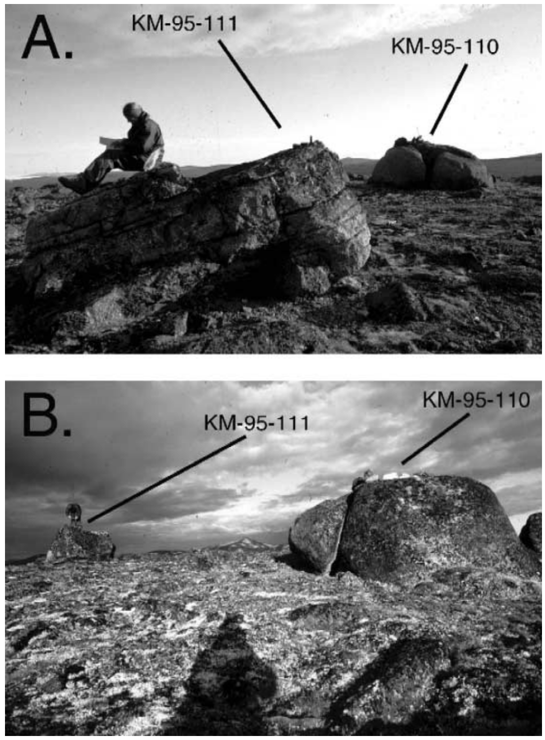

Fig. 1. Sample sites on the glaciated highlands above Pangnirtung Fjord. (A) Erratic, subangular boulder (sample KM-95-111, average exposure age 9.4 ka) sitting on weathered bedrock surface. Sample site on weathered tor (KM-95-110, total history >700 ka) labeled in background. (B) Different view of same samples emphasizing difference in rounding of edges between the tor and the erratic.

Table 1
Isotopic data for high-level glaciated bedrock surfaces on Baffin Island

Sample	Elevation (m asl)	^{10}Be[a] (10^6 atom g^{-1})	^{26}Al[a] (10^6 atom g^{-1})	$^{26}Al/^{10}Be$	Single-nuclide interpretation[b]		Paired-nuclide interpretation[c]			
					Minimum ^{10}Be model age (ka)	Minimum ^{26}Al model age (ka)	Minimum exposure (ka)	Minimum burial (ka)	Minimum total history (ka)	Maximum erosion rate (m Ma^{-1})
KM-95-18	723	0.084 ± 0.003	0.482 ± 0.028	5.8 ± 0.4	13.9 ± 0.7	13.2 ± 0.5	NA[d]	NA	NA	NA
KM-95-20	524	0.063 ± 0.003	0.463 ± 0.027	7.4 ± 0.6	10.4 ± 0.6	12.6 ± 0.8	NA[d]	NA	NA	NA
KM-95-21	559	0.064 ± 0.004	0.451 ± 0.031	7.0 ± 0.6	10.6 ± 0.7	12.3 ± 0.9	NA[d]	NA	NA	NA
KM-95-110	660	0.720 ± 0.020	3.060 ± 0.160	4.3 ± 0.2	122 ± 5	87 ± 5	162	573	735	0.551
KM-95-111	660	0.055 ± 0.003	0.348 ± 0.034	6.3 ± 0.7	9.2 ± 0.5	9.5 ± 0.9	NA[d]	NA	NA	NA

[a] Normalized to sea level and $> 60°$ using Lal (1991) considering only spallation.
[b] Uncertainty reflects only AMS and stable isotope measurements.
[c] Assuming half-lives for ^{10}Be and ^{26}Al of 1.5 and 0.7 Ma, respectively, and using approach at Bierman et al., 1999.
[d] NA $= {}^{26}Al/{}^{10}Be$ ratio ≥ 6.0 at one σ.

the snowfields that Wolfe et al. postulate for the highlands, nor could the refugia for which they argue have existed in this area through the late Wisconsinan.

Another series of young cosmogenic model ages (Marsella et al., 2000) have been measured in the highlands west of Pangnirtung Fjord, above the Kolik River valley. Two bedrock samples from the lip of the Ukalik Lake basin have average ^{10}Be and ^{26}Al ages of 11.5 ka (KM-95-20 and -21). A boulder in the Amarok Lake valley (KM-95-18) has an average exposure age of 13.5 ka. In contrast, sediments from Ukalik and Amorak Lakes have radiocarbon ages as old as 38 ka (Wolfe, 1996; Wolfe and Haertling, 1996).

In short, cosmogenic exposure ages clearly support recent ice cover on the highlands on both sides of Pangnirtung Fjord. In contrast, the existence in lake sediments of organic material with old finite and some infinite radiocarbon ages implies either episodically ice-free lake basins, where biological activity could continue, or the reworking of older material either alone or in combination with young organic debris, to give mixed but older ages.

Appraising ice cover and weathering zone history using cosmogenic nuclide data—^{10}Be and ^{26}Al suggest big, non-erosive, Late Pleistocene ice

Our full cosmogenic data set unequivocally shows that the traditional interpretation of weathering zones and the adjacent moraine systems advocated by Wolfe et al. is not valid in the Pangnirtung Fjord area (Davis et al., 1995, 1996a,b, 1999; Marsella and Bierman, 1995; Marsella et al., 1996, 1997, 1998; Marsella, 1998).

For example, cosmogenic nuclide data show that zones of differing weathering intensity, separated by the type-Duval moraines and once thought to represent time stratigraphic boundaries (Dyke, 1977, 1979), appear to have no chronological significance in Pangnirtung Fjord (Marsella, 1998; Marsella et al., 2000). Our results contrast those of Steig et al. (1998) who suggest that further east on Baffin Island, moraines having different cosmogenic model ages do indeed demarcate weathering zone boundaries. However, weathering data for their moraines,

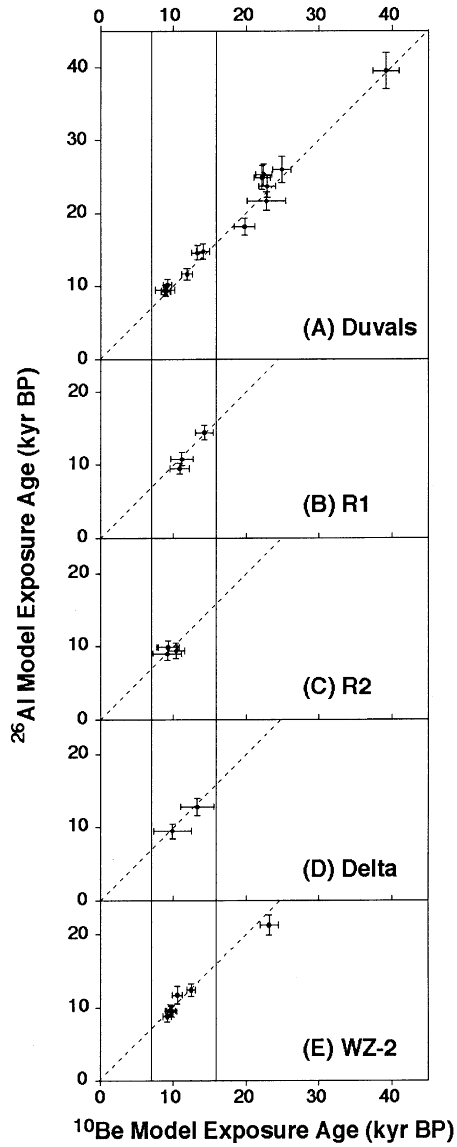

Fig. 2. Scatter plots comparing ^{26}Al and ^{10}Be model exposure ages for (A) Duval and Duval-equivalent moraines, including two bedrock samples, (B) first recessional moraine below Duval moraine, R1, (C) second recessional moraine below Duval moraine, R2, (D) 99-m raised glaciomarine delta fed by meltwater from Duval moraine position, and (E) WZ-2 (above and outside Duval moraines). Error bars represent a production rate uncertainty of 3% (for elevation) propagated along with analytical uncertainties. Bracketed area represents latest deposition on Duval moraines, recessional moraines, and 99-m delta. Dashed lines represent 1:1 ratio of ^{26}Al and ^{10}Be model ages. See Marsella et al. (2000) for further explanation.

such as that summarized by Dyke (1977, 1979) for the Pangnirtung Fjord area, are not available. Furthermore, Steig et al. (1998) did not actually sample the upper weathering zone itself. Further testing elsewhere will determine whether our cosmogenic nuclide data are the exception or the rule. In any case, we now know that weathering zone boundaries defined by the Duval moraines are unreliable indicators of age in and around their type location along Pangnirtung Fjord.

Wolfe et al. propose a "somewhat arbitrary" (their words) scenario to reconcile their data with those in our original paper (Bierman et al., 1999). Indeed, the scenario they suggest is only one of an infinite number that could explain cosmogenic nuclide data in Bierman et al. (1999). However, the story they propose is now in direct conflict with young cosmogenic exposure ages in the highlands both west and east of Pangnirtung Fjord published here (Table 1) and in Marsella et al. (2000).

We propose another scenario for ice behavior in the Pangnirtung Fjord area. The type-Duval moraines and their equivalents around Pangnirtung Fjord have a distinctly bimodal distribution of cosmogenic model exposure ages (Fig. 2). This distribution is inseparable from the age of boulders on the supposedly older weathering zone, WZ-2, just outside the moraine (Fig. 2 and Marsella et al., 2000). The early mode includes ages centered at 23 ka and ranging from 20 to 25 ka. The later mode includes ages centered at 11 ka and ranging from 9 to 13 ka.

Taken at face value, disregarding uncertainties in cosmogenic nuclide production rates and atmospheric ^{14}C contents, comparing Fig. 1 in Wolfe et al.'s comment and our Fig. 2 suggests an interesting possibility. The gap in Wolfe's data set between 24 and 32 ^{14}C ka could reflect an ice advance (cold-based in the highlands) that deposited the early mode of boulders on the Duval moraines and in WZ-2. The highland ice then melted down and exposed the boulders, allowing sediments to again accumulate in Wolfe et al.'s highland lakes and nuclides to accumulate in the boulders. Sometime after 14 ka, nonerosive, cold-based, highland ice rapidly expanded covering but not eroding the older boulders and the lake basins. Meanwhile, warm-based ice continued to stream through the deep fjords. When the highland and valley ice finally ablated about 10 ka, they deposited boulders, the ages of which make up the younger mode on and outside the Duval moraines. This scenario allows older lake sediment ^{14}C ages (Wolfe et al., Fig. 1), explains the enigmatic bimodal cosmogenic nuclide ages on the Duval moraines (Fig. 2), is consistent with the bimodal distribution of lake sediment ages, and explains the young highland erratics (KM-95-18, -20, -21, and -111) overlying weathered bedrock surfaces with complex exposure histories (Bierman et al., 1999).

Conclusions

In situ cosmogenic isotope data from the Pangnirtung Fjord area do not support the traditional interpretation of weathering zones as time–stratigraphic boundaries and suggest a complex exposure history for upland surfaces. Young erratics (^{10}Be age < 10 ka) on top of heavily irradiated (^{10}Be age > 100 ka) and deeply weathered uplands suggest that the last overriding ice was nonerosive (cold-based) and retreated by the early Holocene. These data are difficult to reconcile with lake sediment records indicating biological productivity at times during the late Wisconsinan, unless one postulates several advances and retreats of nonerosive ice that preserved weathered uplands and lake sediments beneath.

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