AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL070100

Key Points:

- Deep accumulation of cosmogenic isotopes in Earth's crust influences cosmogenic nuclide exposure ages
- Uniform inheritance at a site in Norway yields a cluster of erratic ^{10}Be ages at 20 ka, ~2000 year older than independent chronologies
- Modeled ^{10}Be accumulation at the site reveals glacial plucking depths of >2.5 m and likely 4 m

Correspondence to:
J. P. Briner,
jbriner@buffalo.edu

Citation:
Briner, J. P., B. M. Goehring, J. Mangerud, and J. I. Svendsen (2016), The deep accumulation of ^{10}Be at Utsira, southwestern Norway: Implications for cosmogenic nuclide exposure dating in peripheral ice sheet landscapes, *Geophys. Res. Lett.*, *43*, doi:10.1002/2016GL070100.

Received 19 JUN 2016
Accepted 17 AUG 2016
Accepted article online 22 AUG 2016

The deep accumulation of ^{10}Be at Utsira, southwestern Norway: Implications for cosmogenic nuclide exposure dating in peripheral ice sheet landscapes

Jason P. Briner[1], Brent M. Goehring[2], Jan Mangerud[3,4], and John Inge Svendsen[3,4]

[1]Department of Geology, University at Buffalo, Buffalo, New York, USA, [2]Department of Earth and Environmental Science, Tulane University, New Orleans, Louisiana, USA, [3]Department of Earth Science, University of Bergen, Bergen, Norway, [4]Norway and Bjerknes Centre for Climate Research, Bergen, Norway

Abstract Cosmogenic nuclide exposure dating is a widely used method for constraining past ice sheet histories. We scrutinize a recently published data set of cosmogenic ^{10}Be data from erratic boulders in Norway used to constrain the deglaciation of the western Scandinavian Ice Sheet to 20 ka. Our model of the ^{10}Be inventory in glacial surfaces leads us to conclude that the chronology may be afflicted by the deep subsurface accumulation of ^{10}Be during long-lasting ice-free periods that resulted in ^{10}Be ages >10% too old. We suggest that the majority of the dated erratic boulders contain a uniform level of inherited muon-produced ^{10}Be and were derived from bedrock depths >2.5 m and most likely ~4 m. The implication of our finding is that for landscapes that experience long ice-free periods between brief maximum glacial phases, glacial erosion of >5 m is required to remove detectable traces of inherited ^{10}Be.

1. Introduction

Knowing the precise age of the Last Glacial Maximum (LGM) extent of ice sheets and their deglaciation is fundamental to ice age theory [*Hays et al.*, 1976; *Broecker and Denton*, 1990], for understanding the coupled climate-cryosphere system and deciphering the phase relationships between orbital forcing and the cryosphere response [*Martinson et al.*, 1987; *Shackleton*, 2000; *Lisiecki and Raymo*, 2005]. As such, eustatic sea level records are instrumental in constraining the timing of globally integrated maximum ice volume; however, dating individual ice sheet sectors remains critical for elucidating interhemispheric manifestations of global climate change [*Clark et al.*, 2009].

Methods available for dating maximum ice extent during the LGM are limited, and many have significant uncertainties. Radiocarbon dating below and above LGM tills has proven useful in some settings, although these are typically limited to a few terrestrial sites along the southern margins of Northern Hemisphere ice sheets [e.g., *Lowell*, 1995; *Glover et al.*, 2011; *Hughes et al.*, 2016]. Many ice sheet margins terminated on continental shelves, where sedimentary analysis and radiocarbon dating of marine sediment cores constrain the timing of maximum extent in some cases [e.g., *Sejrup et al.*, 2016]. Cosmogenic-nuclide exposure dating has emerged in the past two decades as a useful tool for dating LGM ice extents [e.g., *Balco et al.*, 2002; *Balco*, 2011]. Although not without limitations [*Colgan et al.*, 2002], cosmogenic-nuclide exposure dating of terminal moraine boulders has allowed the constraint of additional chronologies of LGM ice extent from locations otherwise difficult to date [e.g., *Balco et al.*, 2002; *Rinterknecht et al.*, 2006; *Nesje et al.*, 2007; *Håkansson et al.*, 2007; *Houmark-Nielsen et al.*, 2012; *Stroeven et al.*, 2014; *Ullman et al.*, 2015].

An example of such a study is that of *Svendsen et al.* [2015], who used ^{10}Be dating to constrain the retreat of the Norwegian Channel Ice Stream (Figure 1), a major artery of the Scandinavian Ice Sheet, from its maximum LGM extent [*Sejrup et al.*, 2003; *Ottesen et al.*, 2016]. The ^{10}Be chronology, which indicates a collapse of the ice stream as early as ~20.3 ka [*Svendsen et al.*, 2015], is at odds with radiocarbon constraints from the seafloor indicating that this occurred 2000 years later, at ~18.5 ka [*Sejrup et al.*, 2009]. Commonly discussed factors such as uncertainty in the ^{10}Be production rate, isotopic inheritance from neutron-produced ^{10}Be, or problematic radiocarbon ages cannot satisfactorily explain the disagreement. Here we explore the possibility that the ^{10}Be ages are made too old by the deep accumulation of muon-produced ^{10}Be. We find that the deep accumulation of muon-produced ^{10}Be may satisfactorily reconcile the discrepancy.

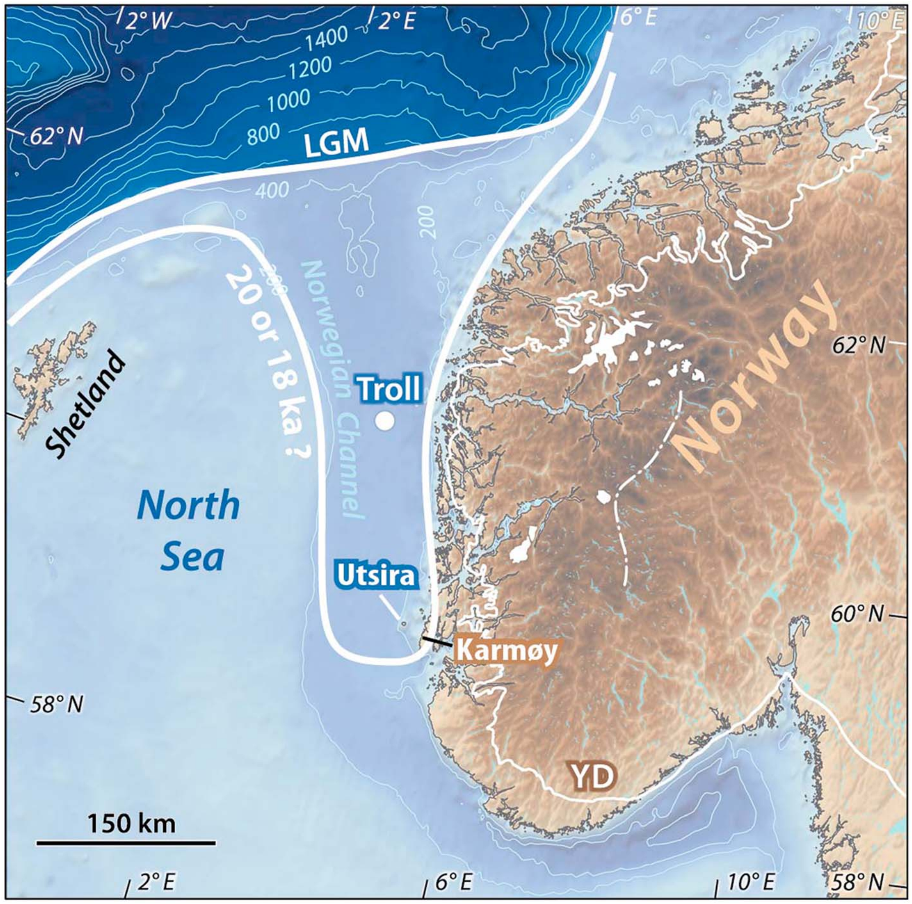

Figure 1. Southwestern Norway showing Norwegian Channel, the extent of the Eurasian Ice Sheet during the LGM and when Utsira became ice free at ~18 or 20 ka, and the location of the Troll core site and the island of Utsira. Modified from *Svendsen et al*. [2015].

2. Utsira, Southwestern Norway

Utsira is an island located on the landward side of the Norwegian Channel (Figure 1), ~400 km south of the position of the terminus of the Norwegian Channel Ice Stream during the LGM [*Hughes et al*., 2016]. The small island lies 16 km offshore, is ~6.1 km^2, and has a maximum elevation of 65 m above sea level (asl) and average elevation of ~ 35 m asl, which is mostly above a marine limit of ~16 m asl [*Svendsen et al*., 2015]. The island consists of glacially plucked and weakly abraded rolling bedrock hills draped with erratic boulders. Rare glacial striations on the barren bedrock surfaces are oriented toward the north [*Undås*, 1948], confirmed during our fieldwork. We therefore assume that Utsira was overridden by the Norwegian Channel Ice Stream just prior to the last deglaciation. The lithology of erratics reflects the underlying bedrock, which alternates between mafic (gabbro) lithologies on the western part of the island, and felsic (quartz diorite) lithologies on the eastern part of the island. Thus, we infer that the erratics are not far traveled and were plucked from either the island itself or the nearby seafloor and deposited not far along the ice stream's northward trajectory.

Utsira rests ~175 km south (up ice flow) of the Troll core site, where radiocarbon dated marine sediment cores provide minimum ages for the deglaciation at 18,140–18,760 cal yr B.P. [*Sejrup et al*., 2009]. To determine the timing of deglaciation up ice stream from the Troll site, *Svendsen et al*. [2015] obtained ^{10}Be ages from seven large (average diameter 2.4 m) erratic boulders resting directly on bedrock surfaces at Utsira. The seven ages are 20.2 ± 0.4, 20.2 ± 0.6, 20.2 ± 0.7, 20.8 ± 0.8, 22.6 ± 0.5, 24.2 ± 0.7, and 25.0 ± 0.6 ka (Figure 2). The distribution exhibits a right skewness indicative of isotope inheritance in the older (22.6 to 25.0 ka) boulders. Thus, the age distribution was interpreted as indicating deglaciation of Utsira at 20.3 ± 0.3 ka (the average age of the four

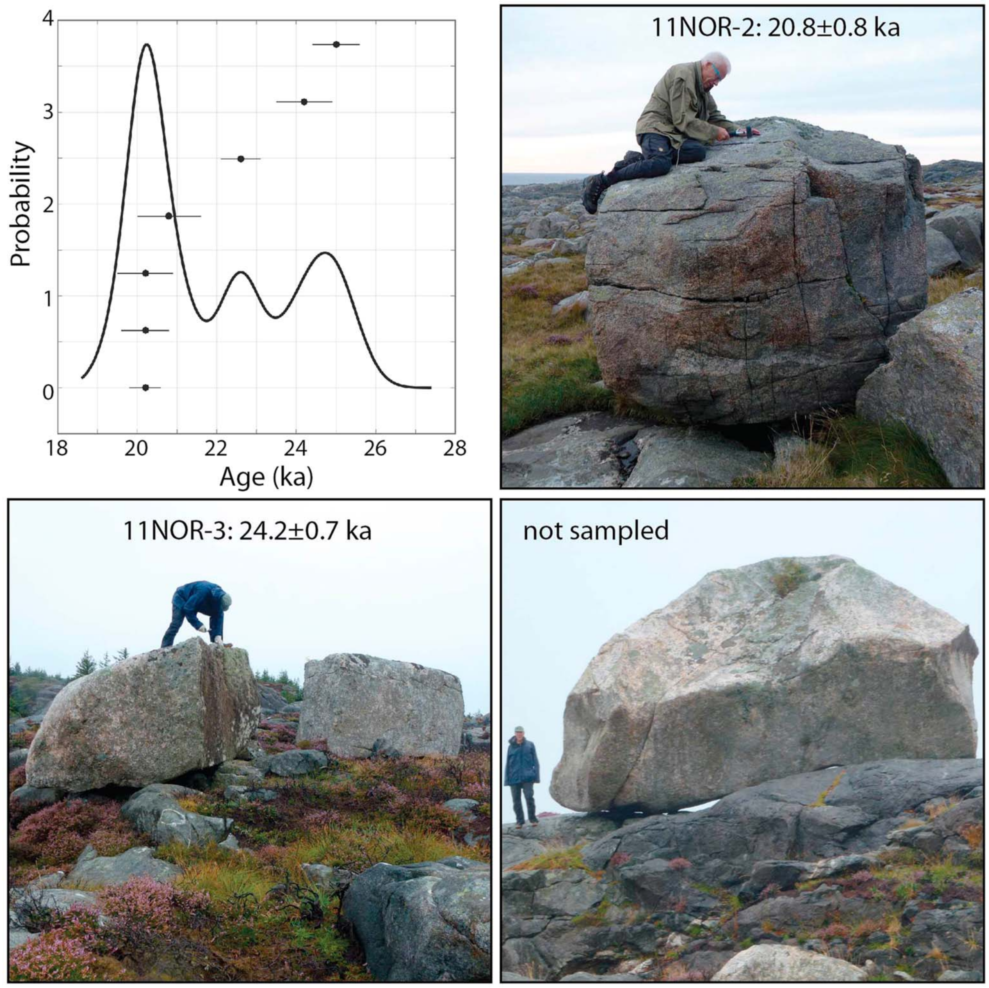

Figure 2. Normal kernel density plot for the seven Utsira boulder samples (black line), as well as individual exposure ages (upper left). Error bars on exposure ages are shown at the 1 sigma level. The prominent right skew of the plot is interpreted to be a manifestation of ^{10}Be inheritance due to insufficient glacial erosion during the LGM. Also shown are examples of erratic boulders on Utsira.

youngest samples). The ^{10}Be age of a single bedrock sample, from the northeastern portion of the island, of 40.8 ± 0.9 ka supports the influence of inheritance on the distribution of ^{10}Be ages.

The anomalously old age of the bedrock sample reveals that upon LGM deglaciation, a significant inventory of ^{10}Be in the bedrock surfaces remained from the exposure period(s) prior to the last ice sheet advance (LGM) across the island. Thus, any erratic boulders plucked from the upper few meters of bedrock surfaces during the LGM would likely exhibit ^{10}Be ages that would be clearly older than the mean ^{10}Be age of the entire distribution. Furthermore, because the boulders seem to be locally sourced, the inheritance in some of the erratic boulder samples is easy to accept. Although there is no relationship between boulder dimension and ^{10}Be age, some of the boulders we dated are large (up to 4 × 3 × 6 m), and larger ones exist (up to ~5 × 8 × 6 m), revealing that the ice sheet is capable of plucking very large boulders during the LGM (Figure 2).

The ~1500–2000 year (9–11%) difference between the mean ^{10}Be age of 20.3 ± 0.3 ka (the four youngest boulders on Utsira) and the basal radiocarbon age from the Troll core site of ~18,140–18,760 cal yr B.P. is difficult to explain. The radiocarbon age is from very near the basal contact with till, making it difficult to argue that the sediments postdate the deglaciation at the Troll site by more than decades to a few centuries. One possibility is that the foraminifera (mixed benthics) that were dated contained some younger tests due to bioturbation; however, the effect on the radiocarbon age would likely be small. Similarly, if the 405 year reservoir correction that was used is too small, then the resulting radiocarbon age would be younger, making

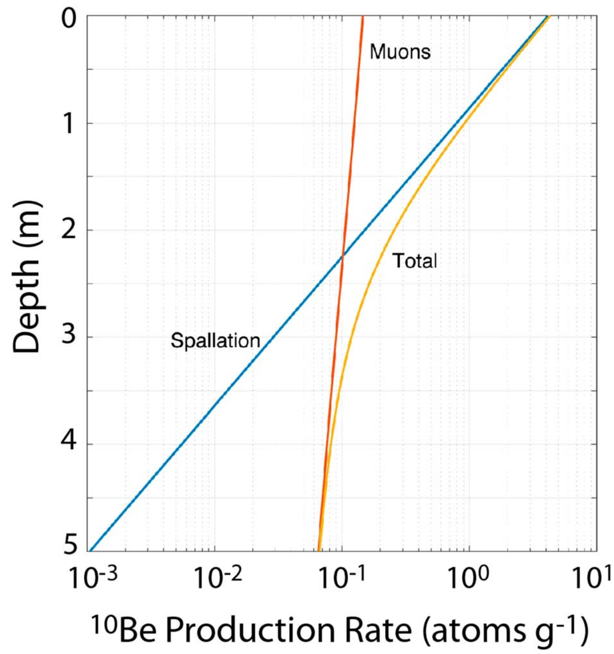

Figure 3. Relationship between ^{10}Be production via spallation (blue) and muons (red) versus depth at Utsira ($\rho = 2.65$ g cm^{-3}). Production by spallation and muons has been scaled based on the mean elevation of samples from Utsira; the fraction of total (yellow) ^{10}Be production by muons is 3.4% at the surface.

the age discrepancy yet larger. If the reservoir correction was too high, which seems unlikely, the radiocarbon age could only become a couple centuries older. H.P. Sejrup (oral communication, 2016) has obtained basal radiocarbon ages from additional cores that are consistent with the Troll core. Furthermore, the age of deglaciation at the Troll site is supported by a suite radiocarbon ages from basal marine sediments above till in isolation basins on Karmøy (14 km east of Utsira) that are 18.0 cal ka B.P. [*Svean*, 2016]. Based on the above, it is reasonable that Utsira became ice free between 18.5 and 18 ka.

We thus now explore the possibility that the age discrepancy between the ^{10}Be and radiocarbon ages could lie in the ^{10}Be dating method. Although inheritance may explain the older outliers among the age population, the cluster of four ages that are virtually identical is not easily explained by neutron-produced ^{10}Be inheritance [*Heyman et al*., 2011]. An additional factor could be that the ^{10}Be production rate that *Svendsen et al*. [2015] used is too low, resulting in ^{10}Be ages that are too high. However, the ^{10}Be production rate used of 4.15 ± 0.15 atoms g^{-1} yr^{-1} (along with Lm scaling of *Balco et al*. [2008]) is from a local production rate calibration experiment with a robust age control [*Goehring et al*., 2012a, 2012b]. Furthermore, this value is higher than other recently derived ^{10}Be production rates [e.g., *Balco et al*., 2009; *Putnam et al*., 2010; *Briner et al*., 2012; *Young et al*., 2013; *Stroeven et al*., 2015]. Thus, realistic alternative ^{10}Be production rates would result in an increase in the age discrepancy with the Troll core radiocarbon chronology.

Another consideration relates to the influence on ^{10}Be production due to potential effects from ice age atmospheric compression and katabatic winds for sites adjacent to ice sheets. Because Utsira is at low elevation, atmospheric compression effects during the early portion of postglacial exposure (when the ice sheet was still nearby) would be negligible [*Staiger et al*., 2007]. On the other hand, the effect of katabatic winds could lead to higher rates of ^{10}Be production hence ^{10}Be ages older than their true exposure durations. *Staiger et al*. [2007] estimate that this effect could be >2% in Antarctica, but it is difficult to model. These effects are likely too small to satisfactorily account for the 9–11% age difference, as are other factors mentioned above.

3. The Deep Accumulation of ^{10}Be at Utsira

The production of ^{10}Be within a bedrock or boulder surface is dependent on two primary mechanisms, spallation by neutrons as discussed above and by two flavors of muons (fast and negative, or slow, muons). In contrast to spallation by neutrons, production by muons extends deep into the Earth's surface on account of fewer nuclear interactions, and therefore, the attenuation of muons occurs over a longer mass-depth scale (on the order 1500 g cm^{-2} and 4000 g cm^{-2} for slow and fast muons, respectively) [e.g., *Heisinger et al*., 2002a, 2002b; *Phillips et al*., 2016] than neutrons (~160 g cm^{-2}) [*Gosse and Phillips*, 2001]. In general, the production of ^{10}Be by muons at the surface is only a small fraction of the total production, but at depths greater than ~2.5 m (Figure 3), production by muons exceeds production by spallation and becomes the dominant

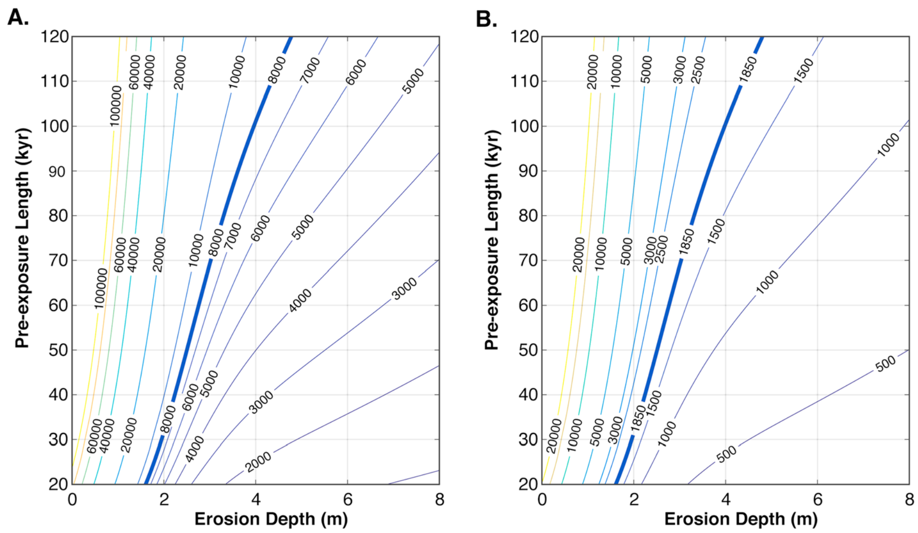

Figure 4. (a) Contours of modeled inherited ^{10}Be concentration (atom g^{-1}) at Utsira for a range of preexposure lengths and theoretical source depths of glacially plucked boulders during the LGM. (b) As in Figure 4a except inherited ^{10}Be concentrations are converted to equivalent exposure age (years). The bold contours represent the solution outlined in the text.

production mechanism. In most settings, the accumulation of ^{10}Be by muons is of negligible importance due to its small contribution to total ^{10}Be production. Overall, ^{10}Be production by muons is low (<0.1 g^{-1} yr^{-1}), but over long time periods (more than tens of thousands of years) ^{10}Be can accumulate at significant depths to measurable levels given current analytical capabilities. Because of the low elevation of Utsira, the relative contribution to total ^{10}Be production by muons using the latest ^{10}Be production cross sections [*Phillips et al.*, 2016] is 3.4% at the surface (Figure 3), which is higher than it would be at a higher elevation site because neutron-produced ^{10}Be production increases more rapidly with altitude. The samples from Utsira are thus more prone to inheritance from deep production by muons than are higher elevation sites.

To explore the possible influence of inheritance in the erratics from Utsira, we model the buildup of ^{10}Be in Utsira bedrock. We modify the canonical equation describing ^{10}Be accumulation [*Lal*, 1991] to model the accumulation of ^{10}Be during a continuous period of exposure prior to the LGM (t_{pre}), removal of a depth of rock (z) via plucking during the LGM (and attendant loss of ^{10}Be), and accumulation of ^{10}Be following ice retreat (t_{post}) [*Applegate et al.*, 2010]:

$$N_{10} = \frac{P_{10}(z)}{\lambda_{10}}\left[1 - e^{-\lambda_{10}t_{\text{post}}}\left(1 - e^{-\lambda_{10}t_{\text{pre}}}\right)e^{-z\rho/\Lambda} + \left(1 - e^{-\lambda_{10}t_{\text{post}}}\right)\right]$$

We use this equation to derive a range of solutions of pre-LGM exposure duration versus glacial erosion (in this case plucking) depth (Figure 4). Note that we use the sea level high-latitude spallation production rate from *Borchers et al*. [2016] and scaling of *Lal* [1991] recast in terms of air pressure [*Stone*, 2000].

Next, we use the age of deglaciation at Troll as a proxy for the deglaciation of Utsira, as discussed above. Using 18.5 ka for a deglaciation age of Utsira, we calculate the inherited ^{10}Be concentration in the 20.3 ka erratics upon LGM ice retreat from the island. This value is ~8000 ^{10}Be atoms g^{-1}, which equates to ~1850 year in apparent age (Figure 4). Utsira likely deglaciated shortly after deglaciation of the Troll site, and thus, we treat this as a minimum estimate of inheritance. In any case, we use this inheritance value to calculate plausible plucking depths for a range of preexposure durations. For example, if Utsira remained exposed between the deglaciation following marine oxygen isotope stage (MIS) 6 (140 ka) and the onset of the LGM advance (30 ka), then the preexposure duration would be 110 kyr. Combined with our estimate of inheritance, this would yield plucking depths of ~4.3 m for the 20.3 ka erratic boulders. This ice sheet occupation of Utsira is reasonable given current knowledge of the history of the Scandinavia Ice Sheet, although it is unknown whether ice reached the island during MIS 4 [*Mangerud et al.*, 2011]. Thus, the measured surfaces of the 20.3 ka erratic boulders may have been plucked from depths on the order of ~4 m below the pre-LGM surface.

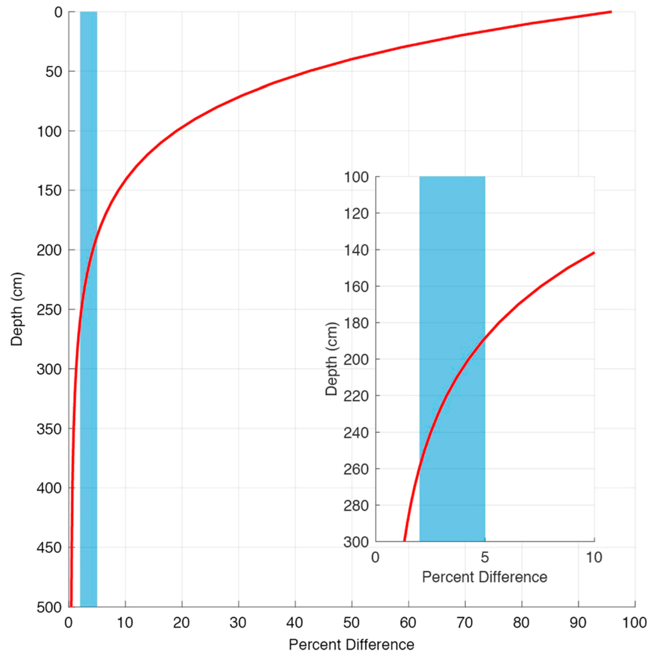

Figure 5. Plot showing constraints for depths where uniform inheritance can be found in Utsira erratics. Red curve shows the difference in ^{10}Be concentration between the top and bottom of a 2.4 m diameter boulder (the average boulder diameter of the sampled Utsira erratics). For example, a 2.4 m diameter boulder plucked from the surface has a measureable difference (95.9%) between the ^{10}Be concentration measured at the top versus the bottom of the block. On the other hand, a 2.4 m diameter boulder plucked from 4 m depth would not have a measureable difference (0.65%) in ^{10}Be concentration between the top and bottom of the block. The typical range in ^{10}Be measurement uncertainties (2–5%) is shown in blue shading, thus setting limits on the minimum depth of plucking of a 2.4 m boulder where one would find "uniform" inheritance.

An erratic boulder with inheritance usually presents itself as an outlier, significantly older than the mean of others in a sample population. At Utsira, on the other hand, we wonder how a cluster of four ^{10}Be ages of erratic boulders, each with a different history of erosion, transportation, and deposition, contains the same amount of inheritance (if the assumed deglaciation age of 18.5 or 18 ka is correct). We interpret this possible "uniform inheritance" as an indication of a near-constant background level of inherited ^{10}Be that exists throughout these boulders. At depths below the neutron-produced ^{10}Be zone (~2.5 m), the change in ^{10}Be concentration as a function of depth is small, and for 2.4 m diameter blocks, is negligible given current detection limits of 2–5% as shown in Figure 5. Near the surface, in the neutron-produced ^{10}Be zone, there is a measureable difference between the top and bottom of a theoretically plucked 2.4 m thick boulder. On the other hand, below about 2.5 m, the percent difference in ^{10}Be concentration between the bottom and top of a plucked boulder becomes lower than current typical analytical precision. We therefore argue that the 20.3 ka Utsira erratics may contain uniform inheritance, in which case their source must be from deeper than 2.5 m below the pre-LGM surface of Utsira. This depth is compatible with estimated plucking depths of ~4 m based on the above calculations. We note that it does not matter which side of the boulder is sampled, as each side will contain statistically similar inheritance levels. In addition, the distribution of erratic ages also supports lower plucking depths: Three of the ^{10}Be ages from Utsira predate 20.3 ka by 2–4 kyr. This could be explained by their origin from shallower depths below the pre-LGM surface, from within the neutron-produced ^{10}Be zone (Figure 4).

Based on the above calculations, it seems possible that the 20.3 ka erratics contain a uniform amount of inheritance and that they therefore misrepresent the true timing of deglaciation of Utsira. This conclusion is supported by data from the adjacent island of Karmøy (Figure 1). Here *Svendsen et al*. [2015] provide ^{10}Be ages for three erratic boulders (20.1 ± 0.4, 20.4 ± 0.6, and 22.3 ± 0.7 ka) and one glacially sculpted bedrock surface (97.8 ± 1.9 ka) from the southwestern part of the island, a similar age pattern as on Utsira. Unlike Utsira, the ubiquitous gneissic lithologies of both the bedrock and the boulders make it more difficult to assess whether the boulders are locally derived or not. In any case, adjacent to this site are *Svean*'s [2016] basal radiocarbon ages of 18.0 cal ka B.P. mentioned above. Taken together, it appears that both Utsira and southwestern Karmøy (1) are possibly part of a landscape deglaciated between ~18.5 and ~18 ka, (2) are exposed subaerially for much longer than they are covered by ice, (3) are not eroded deeply when covered by ice, (4) exhibit varying amounts of glacial erosion that yield different amounts of inheritance in bedrock surfaces, and (5) contain a background level of inheritance that yields ^{10}Be ages ~2000 years older than the true timing of deglaciation.

There remain many unknowns, and the calculations based on the Utsira erratics are poorly constrained. If Utsira deglaciated hundreds of years after the Troll site (e.g., closer to the timing of deglaciation of southern

Karmøy at ~18 ka), then the inherited component would be higher, and therefore, erosion depths may be slightly lower (but still below the 2.5 m uniform inheritance cutoff). Similarly, if the preexposure duration were shorter, perhaps, if Utsira were occupied by ice for some portion of MIS 4, then the given amount of inheritance would yield lower erosion depths. On the other hand, if the preexposure duration was longer, for example, if the history of prior exposure predates MIS 6, then the boulders must have been plucked from deeper levels. This is plausible given the limited amount of erosion of bedrock on both Utsira and Karmøy during the LGM yielding such high exposure ages; the same would likely be true during previous glacial occupations of these sites, and therefore, inheritance could build up from one glacial cycle to the next.

4. Conclusions

Our calculations reveal the likelihood that deep uniform inheritance as a result of ^{10}Be production by muons affects the ^{10}Be ages of large erratic boulders on Utsira. The island rests in an ice sheet distal location, and the bedrock surfaces have probably been subaerially exposed through much of the Middle and Late Quaternary; most likely, Utsira was only ice covered during the maximum phases of major glaciations. Thus, long exposure durations combined with light glacial erosion during brief glacial occupations has led to the accumulation of significant (detectable) ^{10}Be even at many meters depth in the bedrock surfaces.

There are many settings around the globe that are similar to Utsira—that is, sites that experience long periods of exposure between brief, maximum ice sheet advances. In fact, this is probably the case for almost all peripheral areas of former ice sheets, for example, southern Laurentide and Cordilleran ice sheets [*Balco and Rovey*, 2010] and the Eurasian Ice Sheet [*Svendsen et al*., 2004]. Although our discussion also applies to mountain summits and northern ice sheet borders, frozen-bedded conditions there result in much more significant inheritance problems [e.g., *Bierman et al*., 1999; *Briner et al*., 2005]. Along southern, erosive ice sheet margins, previous research has indeed revealed inheritance in glacially eroded bedrock [e.g., *Briner and Swanson*, 1998], and *Colgan et al*. [2002] cautioned future users of cosmogenic nuclide exposure dating of bedrock about inheritance limitations in lightly eroded glacial terrains. We suggest this caution be extended to dating erratic boulders as well. Chronologies derived from moraine boulders and erratics resting on or near bedrock (and potentially sourced from that bedrock) [e.g., *Balco et al*., 2002; *Ullman et al*., 2015] could be afflicted by a minor amount of uniform ^{10}Be inheritance that, in turn, could influence ^{10}Be chronologies of the timing of LGM ice extent. Boulders that are recycled from thick moraine deposits or that are sourced from more deeply scoured regions up ice flow would be less likely to contain inheritance. Nevertheless, even at low-elevation, warm-based ice marginal sites that experience abrasion and plucking, glacial removal of the neutron-produced ^{10}Be zone (upper 2.5 m) may not be sufficient to rid surfaces of detectable inheritance. Thus, existing and future chronologies could be influenced by hundreds to a few thousands of years of difficult-to-detect levels of inheritance.

Acknowledgments
Our investigation forms part of the research project Eurasian Ice Sheet and Climate Interaction (EISCLIM) financially supported by The Research Council of Norway (grant 229788/E10). We thank two anonymous reviewers for comments that greatly improved this manuscript. All data for this paper are properly cited and referred to in the reference list.

References

Applegate, P. J., N. M. Urban, B. J. C. Laabs, K. Keller, and R. B. Alley (2010), Modeling the statistical distributions of cosmogenic exposure dates from moraines, *Geosci. Model Dev.*, *3*(1), 293–307, doi:10.5194/gmd-3-293-2010.

Balco, G. (2011), Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990–2010, *Quat. Sci. Rev.*, *30*(1), 3–27.

Balco, G., and C. W. Rovey (2010), Absolute chronology for major Pleistocene advances of the Laurentide Ice Sheet, *Geology*, *38*(9), 795–798, doi:10.1130/G30946.1.

Balco, G., J. O. Stone, S. C. Porter, and M. W. Caffee (2002), Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA, *Quat. Sci. Rev.*, *21*(20), 2127–2135.

Balco, G., J. O. Stone, N. A. Lifton, and T. J. Dunai (2008), A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements, *Quat. Geochronol.*, *3*(3), 174–195, doi:10.1016/j.quageo.2007.12.001.

Balco, G., J. Briner, R. C. Finkel, J. A. Rayburn, J. C. Ridge, and J. M. Schaefer (2009), Regional beryllium-10 production rate calibration for late-glacial northeastern North America, *Quat. Geochronol.*, *4*(2), 93–107, doi:10.1016/j.quageo.2008.09.001.

Bierman, P. R., K. A. Marsella, C. Patterson, P. T. Davis, and M. Caffee (1999), Mid-Pleistocene cosmogenic minimum-age limits for pre-Wisconsinan glacial surfaces in southwestern Minnesota and southern Baffin Island: A multiple nuclide approach, *Geomorphology*, *27*(1), 25–39.

Borchers, B., S. Marrero, G. Balco, M. Caffee, B. Goehring, N. Lifton, K. Nishiizumi, F. Phillips, J. Schaefer, and J. Stone (2016), Geological calibration of spallation production rates in the CRONUS-Earth project, *Quat. Geochronol.*, *31*, 188–198, doi:10.1016/j.quageo.2015.01.009.

Briner, J. P., and T. W. Swanson (1998), Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran ice sheet, *Geology*, *26*(1), 3–6, doi:10.1130/0091-7613(1998)026<0003:UICCTC>2.3.CO;2.

Briner, J. P., G. H. Miller, P. T. Davis, and R. C. Finkel (2005), Cosmogenic exposure dating in arctic glacial landscapes: Implications for the glacial history of northeastern Baffin Island, Arctic Canada, *Can. J. Earth Sci.*, *42*(1), 67–84.

Briner, J. P., N. E. Young, B. M. Goehring, and J. M. Schaefer (2012), Constraining Holocene ^{10}Be production rates in Greenland, *J. Quaternary Sci.*, *27*, 2–6.

Broecker, W. S., and G. H. Denton (1990), The role of ocean-atmosphere reorganizations in glacial cycles, *Quat. Sci. Rev.*, *9*(4), 305–341, doi:10.1016/0277-3791(90)90026-7.

Clark, P. U., A. S. Dyke, J. D. Shakun, A. E. Carlson, J. Clark, B. Wohlfarth, J. X. Mitrovica, S. W. Hostetler, and A. M. McCabe (2009), The Last Glacial Maximum, *Science*, *325*(5941), 710–714, doi:10.1126/science.1172873.

Colgan, P. M., P. R. Bierman, D. M. Mickelson, and M. Caffee (2002), Variation in glacial erosion near the southern margin of the Laurentide Ice Sheet, south-central Wisconsin, USA: Implications for cosmogenic dating of glacial terrains, *Geol. Soc. Am. Bull.*, *114*(12), 1581–1591.

Glover, K. C., T. V. Lowell, G. C. Wiles, D. Pair, P. Applegate, and I. Hajdas (2011), Deglaciation, basin formation and post-glacial climate change from a regional network of sediment core sites in Ohio and eastern Indiana, *Quatern. Res.*, *76*(3), 401–410.

Goehring, B. M., Ø. S. Lohne, J. Mangerud, J. I. Svendsen, R. Gyllencreutz, J. Schaefer, and R. Finkel (2012a), Erratum: Late glacial and holocene ^{10}Be production rates for western Norway, *J. Quat. Sci*, *27*(5), 544–544, doi:10.1002/jqs.2548.

Goehring, B. M., Ø. S. Lohne, J. Mangerud, J. I. Svendsen, R. Gyllencreutz, J. Schaefer, and R. Finkel (2012b), Late glacial and holocene 10Be production rates for western Norway, *J. Quat. Sci*, *27*(1), 89–96, doi:10.1002/jqs.1517.

Gosse, J. C., and F. M. Phillips (2001), Terrestrial in situ cosmogenic nuclides: Theory and application, *Quat. Sci. Rev.*, *20*(14), 1475–1560, doi:10.1016/S0277-3791(00)00171-2.

Håkansson, L., J. Briner, H. Alexanderson, A. Aldahan, and G. Possnert (2007), 10 Be ages from central east Greenland constrain the extent of the Greenland ice sheet during the Last Glacial Maximum, *Quat. Sci. Rev.*, *26*(19), 2316–2321.

Hays, J. D., J. Imbrie, N. J. Shackleton, and others (1976), *Variations in the Earth's Orbit: Pacemaker of the Ice Ages*, Association for the Advancement of Science, American.

Heisinger, B., D. Lal, A. J. Jull, P. Kubik, S. Ivy-Ochs, S. Neumaier, K. Knie, V. Lazarev, and E. Nolte (2002a), Production of selected cosmogenic radionuclides by muons: 1. Fast muons, *Earth Planet. Sci. Lett.*, *200*(3–4), 345–355, doi:10.1016/S0012-821X(02)00640-4.

Heisinger, B., D. Lal, A. J. T. Jull, P. Kubik, S. Ivy-Ochs, K. Knie, and E. Nolte (2002b), Production of selected cosmogenic radionuclides by muons: 2. Capture of negative muons, *Earth Planet. Sci. Lett.*, *200*(3–4), 357–369, doi:10.1016/S0012-821X(02)00641-6.

Heyman, J., A. P. Stroeven, J. M. Harbor, and M. W. Caffee (2011), Too young or too old: Evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages, *Earth Planet. Sci. Lett.*, *302*(1–2), 71–80, doi:10.1016/j.epsl.2010.11.040.

Houmark-Nielsen, M., H. Linge, D. Fabel, C. Schnabel, S. Xu, K. M. Wilcken, and S. Binnie (2012), Cosmogenic surface exposure dating the last deglaciation in Denmark: Discrepancies with independent age constraints suggest delayed periglacial landform stabilisation, *Quat. Geochronol.*, *13*, 1–17, doi:10.1016/j.quageo.2012.08.006.

Hughes, A. L. C., R. Gyllencreutz, Ø. S. Lohne, J. Mangerud, and J. I. Svendsen (2016), The last Eurasian ice sheets—A chronological database and time-slice reconstruction, DATED-1, *Boreas*, *45*(1), 1–45, doi:10.1111/bor.12142.

Lal, D. (1991), Cosmic ray labeling of erosion surfaces: In situ nuclide production rates and erosion models, *Earth Planet. Sci. Lett.*, *104*(2), 424–439, doi:10.1016/0012-821X(91)90220-C.

Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records, *Paleoceanography*, *20*, PA1003, n/a–n/a, doi:10.1029/2004PA001071.

Lowell, T. V. (1995), The application of radiocarbon age estimates to the dating of glacial sequences: An example from the Miami sublobe, Ohio, USA, *Quat. Sci. Rev.*, *14*(1), 85–99.

Mangerud, J., R. Gyllencreutz, Ø. Lohne, and J. I. Svendsen (2011), Glacial history of Norway, in *Glaciations—Extent and Chronology: Developments in Quaternary Science*, vol. 15, Amsterdam, the Netherlands, 2011, edited by J. Ehlers, P. L. Gibbard, and P. D. Hughes, pp. 279–298, Elsevier, Amsterdam, isbn:978-0-444-53447-7.

Martinson, D. G., N. G. Pisias, J. D. Hays, J. Imbrie, T. C. Moore, and N. J. Shackleton (1987), Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy, *Quatern. Res.*, *27*(1), 1–29, doi:10.1016/0033-5894(87)90046-9.

Nesje, A., S. O. Dahl, H. Linge, C. K. Ballantyne, D. McCarroll, E. J. Brook, G. M. Raisbeck, and F. Yiou (2007), The surface geometry of the Last Glacial Maximum ice sheet in the Andøya-Skånland region, northern Norway, constrained by surface exposure dating and clay mineralogy, *Boreas*, *36*(3), 227–239, doi:10.1111/j.1502-3885.2007.tb01247.x.

Ottesen, D., C. R. Stokes, R. Bøe, L. Rise, O. Longva, T. Thorsnes, O. Olesen, T. Bugge, A. Lepland, and O. B. Hestvik (2016), Landform assemblages and sedimentary processes along the Norwegian Channel Ice Stream, *Sediment. Geol.*, *338*, 115–137, doi:10.1016/j.sedgeo.2016.01.024.

Phillips, F. M., et al. (2016), The CRONUS-Earth Project: A synthesis, *Quat. Geochronol.*, *31*, 119–154, doi:10.1016/j.quageo.2015.09.006.

Putnam, A. E., J. M. Schaefer, D. J. A. Barrell, M. Vandergoes, G. H. Denton, M. R. Kaplan, R. C. Finkel, R. Schwartz, B. M. Goehring, and S. E. Kelley (2010), In situ cosmogenic 10 Be production-rate calibration from the Southern Alps, New Zealand, *Quat. Geochronol.*, *5*(4), 392–40.

Rinterknecht, V. R., et al. (2006), The Last Deglaciation of the Southeastern Sector of the Scandinavian Ice Sheet, *Science*, *311*(5766), 1449–1452, doi:10.1126/science.1120702.

Sejrup, H. P., et al. (2003), Configuration, history and impact of the Norwegian Channel Ice Stream, *Boreas*, *32*(1), 18–36, doi:10.1080/03009480310001029.

Sejrup, H. P., A. Nygård, A. M. Hall, and H. Haflidason (2009), Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK, *Quat. Sci. Rev.*, *28*(3–4), 370–380, doi:10.1016/j.quascirev.2008.10.019.

Sejrup, H. P., C. D. Clark, and B. O. Hjelstuen (2016), Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea, *Geology*, *44*(5), 355–358, doi:10.1130/G37652.1.

Shackleton, N. J. (2000), The 100,000-year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity, *Science*, *289*(5486), 1897–1902, doi:10.1126/science.289.5486.1897.

Staiger, J., J. Gosse, R. Toracinta, B. Oglesby, J. Fastook, and J. V. Johnson (2007), Atmospheric scaling of cosmogenic nuclide production: Climate effect, *J. Geophys. Res.*, *112*, n/a–n/a, doi:10.1029/2005JB003811.

Stone, J. O. (2000), Air pressure and cosmogenic isotope production, *J. Geophys. Res.*, *105*(B10), 23,753–23,759.

Stroeven, A. P., D. Fabel, M. Margold, J. J. Clague, and S. Xu (2014), Investigating absolute chronologies of glacial advances in the NW sector of the Cordilleran Ice Sheet with terrestrial in situ cosmogenic nuclides, *Quat. Sci. Rev.*, *92*, 429–443, doi:10.1016/j.quascirev.2013.09.026.

Stroeven, A. P., J. Heyman, D. Fabel, S. Björck, M. W. Caffee, O. Fredin, and J. M. Harbor (2015), A new Scandinavian reference ^{10}Be production rate, *Quat. Geochronol.*, *29*, 104–115, doi:10.1016/j.quageo.2015.06.011.

Svean, A. (2016), Glasiasjonshistorie og strandforskyvning I Boknafjordsområdet i Rogaland, Master degree thesis, Dept. of Earth Science, University of Bergen.

Svendsen, J. I., H. Alexanderson, V. I. Astakhov, I. Demidov, J. A. Dowdeswell, S. Funder, V. Gataullin, M. Henriksen, C. Hjort, and M. Houmark-Nielsen (2004), Late Quaternary ice sheet history of northern Eurasia, *Quat. Sci. Rev.*, *23*(11), 1229–1271.

Svendsen, J. I., J. P. Briner, J. Mangerud, and N. E. Young (2015), Early break-up of the Norwegian channel ice stream during the Last Glacial Maximum, *Quat. Sci. Rev.*, *107*, 231–242.

Ullman, D. J., A. E. Carlson, A. N. LeGrande, F. S. Anslow, A. K. Moore, M. Caffee, K. M. Syverson, and J. M. Licciardi (2015), Southern Laurentide ice-sheet retreat synchronous with rising boreal summer insolation, *Geology*, *43*(1), 23–26.

Undås, I. (1948), Trekk fra Utsiras natur og den siste Skageraksbre, *Stavangers Museums Årbok*, 5, *Geology*, *43*(1), 23–26, doi:10.1002/2016GL070100/pdf.

Young, N. E., J. M. Schaefer, J. P. Briner, and B. M. Goehring (2013), A ^{10}Be production-rate calibration for the Arctic, *J. Quaternary Sci.*, *28*(5), 515–526, doi:10.1002/jqs.2642.