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Interactive comment on "Controls on the distribution of cosmogenic ^{10}Be across shore platforms" *by* Martin D. Hurst et al.

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Response to review

We would like to thank Dr. Alan Trenhaile for his positive and constructive comments. Below are our responses to all of these comments including details of any changes we have made to the manuscript guided by the reviewer's suggestions. We have numbered the reviewer comments and they are coloured black, while our responses are coloured blue, and italicised where we are quoting directly from the revised manuscript.

1. Cosmogenic dating was initially greeted by rock coast workers, as a quasi-panacea, a long awaited solution to the question, that had arisen over more than

a century, regarding the age of shore platforms, and especially whether they are primarily contemporary (Holocene) or inherited (from previous interglacials when sea level was similar to today's) landforms. Related to this question and of more immediate practical concern was its apparent ability to provide reliable data on rates of cliff recession over lengthy periods during the Holocene, and to test predictive models and better predict the effects of climate change, and especially rising sea level. There have been a few useful ^{10}Be dating applications. They include the work of Choi et al. (2012), who suggested that the seaward portions of shore platforms in Korea are up to about 150 thousand years old, and that the modern platform is cutting into its interglacial predecessor. Conversely, Regard et al., (2012) opined that in northern France, the mean rate of cliff retreat since the mid-Holocene has been 11–13 cm yr^{-1}, which would have been sufficient to create 'contemporary' intertidal shore platforms hundreds of metres in width. Despite these valuable contributions, I would contend that cosmogenic nuclide analysis, whether for dating landforms or quantifying their rates of erosion has failed, as yet, to revolutionize the study of rock coasts.

The two studies discussed by the reviewer above (plus another nice paper by Rogers et al. (2012)) have done an excellent job in demonstrating that there is significant potential for cosmogenic radionuclides (CRNs) to yield evidence for long-term processes and rates in rocky coast settings. As the reviewer points out, measurement of cosmogenic radionuclides has not been able to "revolutionise the study of rock coasts", nor would we expect it to. Rather, they provide an additional tool in the coastal geomorphologist's repertoire to help understand the rates and processes by which cliffed coasts and shore platforms have evolved in the past, and notably, over timescales longer than those at which observational data has been collected. We were motivated by reviewer's own conclusions when reviewing climate change impacts on rocky coasts that "… we must… acquire more precise and longer records of erosion rates and other expressions of process efficacy and their relationship to prevailing morphogenic conditions" (Trenhaile, 2014, p. 15). It remains to be seen whether cosmogenic radionuclides can improve the precision of erosion rate estimates, but it certainly has the potential to provide longer records (over centennial to millennial timescales) in erosive environments in which there is no alternative evidence of a previous state.

2. Given this, the present paper, which discusses and models the effect of several of the factors and assumptions that constrain the use of cosmogenic analysis on rock coasts, represents a welcome addition to the literature and one which will, no doubt, improve our ability to understand the longterm development of rock coasts. Nevertheless, this paper once again points out the inherent limitations of cosmogenic analysis on rocky coasts for which we have little longterm data on such factors as downwearing and backwearing rates (erosion in the vertical and horizontal planes, respectively) and historical and short-term (storm and calm condition) variations in sediment thickness, type, and extent.

   We are pleased that the reviewer finds our work to be "a welcome addition to the literature" and we hope that it can "improve our ability to understand the long-term development of rock coasts" through the application of CRNs in such environments. We felt that it was a critical step to further explore assumptions that may be required in order for future studies to interpret concentrations of CRNs in terms of process rates on shore platforms so that sampling strategies might be better informed to test these assumptions. This is particularly important given the expense of making CRN measurements that may limit the number of samples that can be acquired in a single study. As an example our results suggest that there is the potential to estimate rates of block removal on stepped platforms through high density sampling and this would be an exciting avenue for future work. We have not made any modifications to the paper based on these opening statements as we feel the context and our aims are already set out clearly in the manuscript, if the reviewer had any specific modifications to our introductory discussion in mind then we would welcome further comment.

3. My main criticism of this paper is the almost complete neglect of downwearing by wearing processes, including by tidal wetting and drying and salt weathering.

   We acknowledge this criticism and its importance, and are not suggesting that these processes are not important mechanisms of downwear on shore platforms. Previous studies that have tried to quantify cliff retreat rates have relied on the assumption of steady-state retreat whereby a constant shore platform morphology is translated landward through time. In this study we have applied a dynamic morphological evolution model, guided by the reviewer's own work (e.g. Trenhaile, 2000), that is capable of generating the sorts of behaviour we wished to explore (e.g. shore platforms that widen with time). We have thus gone further than any previous studies of cosmogenic radionuclides in coastal settings when considering the morphological evolution of the coast. All numerical models are abstractions of the real world at some level but our experiments allow us to explore a number of interesting behaviours such as both continuous and discontinuous distribution of erosion (gradual downwear vs block removal). Such a model, at first order, broadly recreates the patterns of downwear observed from short-term monitoring data, with downwear decreasing with decreasing elevation on the shore platform (see also response to reviewer comment #5).

4. The paper notes that models have indicated that shore platforms and cliffs trend towards a morphological steady state. There are certainly many examples of steady states in model predictions with constant sea level, although when one considers the effect of changing relative sea level, simulated longterm platform development is more complex (see for example: Trenhaile, A. S. 2001: Modeling the Quaternary evolution of shore platforms and erosional continental shelves . Earth Surface Processes and Landforms 26, pp. 1103-28, and Trenhaile, A. S. 2014. Modelling the effect of Pliocene-Quaternary changes in sea level on stable and tectonically active land masses. Earth Surface Processes and Landforms 39, 1221-35).

In this paper we do not explore the history of shore platform development throughout the quaternary but rather focus on the development of shore platforms during the Holocene (more specifically, the last 7-8 thousand years, the time over which eustatic sea level has been relatively stable). Where shore platforms are inherited features formed perhaps during a previous interglacial period, subsequent exposure would result in CRN concentrations substantially higher than those from contemporary platforms, as demonstrated by Choi et al. (2012). We have clarified this in the introduction by adding a more detailed description of the findings of Choi et al. (2012) and by clarifying that we are only concerned in this study with Holocene platforms stating:

"Some shore platforms may have formed during the Holocene and thus be entirely contemporaneous features, whilst others, particularly wide platforms in resistant lithologies, have been interpreted as inherited features, formed during previous sea level high stands and reoccupied during the Holocene (e.g. Blanco Chao et al., 2003). Evidence for the antiquity of shore platforms may be revealed by CRNs. For example, Choi et al. (2012) measured ^{10}Be concentrations in shore platforms cut into resistant lithologies on the Korean coast. High concentrations were consistent with modelled ages extending back as far as 142 ka, and importantly, these ages did not correct for weathering and erosion and thus should be considered as minimum ages. Thus Choi et al. (2012) conclude that these platforms are at least partially inherited features, originated in the Pleistocene."

"In this study we quantified the sensitivity of platform CRN concentrations to topographic shielding, various processes of platform erosion/downwear, the presence/absence of beach cover, and transience in shore profile evolution. In doing so we consider only the development of shore platforms during the Holocene, over the timescale during which eustatic sea level has been relatively stable (7 ka to present). We addressed this with a numerical model coupling cross-shore coastal evolution and ^{10}Be production to explore the potential for quantifying

coastal retreat rates from ^{10}Be concentration measurements."

5. The paper quotes our work (Porter et al., 2010) in eastern Canada (on page 15 of the manuscript), but essentially ignores the relevant conclusions that relate to spatial variations across the intertidal zone. This paper showed, based on laboratory experiments lasting several years and about 2000 rock samples, together with about 200 transverse micro-erosion metre stations in the field, that, while weathering downwearing rates (isolated in the laboratory experiments) tend to be a maximum in the upper intertidal zone, there is no clear pattern in the field, possibly because of the effect of other erosional mechanisms with different elevational efficiencies.

   We are grateful to the reviewer for highlighting their findings, and apologise that we did not do justice to this excellent piece of work that explores weathering and erosion processes on shore platforms both in the field and through controlled experiments. The lack of a “clear pattern in the field” meant that we were not able to use the data from their study to parameterise our model, however the model does reproduce the general trend they observed, that downwearing tends to be highest in the upper intertidal zone, declining offshore. Our intention in this study has been to explore the general case, parsimoniously, to better understand the sensitivity of CRN concentrations to factors such as the potential for non-uniform distribution of downwearing, and our analyses are by no means exhaustive. Future work that measure CRN concentrations at specific sites where there are good observational datasets will be a logical and important next step.

   That said, there is a distinct scaling issue between their experiments which take place over at most a 6 year period, and the centennial to millennial timeframe over which we are required to model coastal evolution in order to explore the controls on the build-up of ^{10}Be. We do not feel it would be appropriate to take the results of a single site and extrapolate over several millennia for the purposes of this study, although site specific investigation using CRNs would be well advised to place their findings in the context of such observations. Nevertheless, Stephenson et al. (2012) found that rates of platform erosion averaged over a 32 year period were not significantly different from the two year record initially analysed at the same sites, concluding that low magnitude, high frequency events drive platform lowering at that site. It is not yet clear whether such short-term downwear rates can be extrapolated at other sites, in other lithologies, for different tidal regimes and different erosion processes. Ongoing work with micro erosion metres, combined with our growing ability to derive high resolution 3D surface models with LiDAR and photogrammetry will help to address this matter further and we would welcome such research.

Given all this, we have not carried out any additional experiments in light of the reviewer's criticism. If the reviewer has any specific requirements he would like to see then we would welcome them. Rather, we have expanded our discussion of these issues in the paper to highlight that there is still plenty to be done as detailed below.

At the end of the introduction we have added:

"In this study we quantified the sensitivity of platform CRN concentrations to topographic shielding, various processes of platform erosion/downwear, the presence/absence of beach cover, and transience in shore profile evolution. Our intention is to explore the general case parsimoniously to better understand controls on ^{10}Be concentrations, rather than to make accurate predictions for any specific field site."

In justifying the development of a dynamic morphological model we now state:

"Moreover, micro-erosion meter measurements of platform downwear suggest that downwear is not uniform across the shore profile, but tends to be faster in the upper intertidal zone and decline with depth (Porter et al., 2010), and to explore the influence of such a distribution on ^{10}Be concentrations, a dynamic morphological model was required."

In the discussion we have expanded our brief mention of downwear measurements to say:

"Accounting for the distribution of downwear would be aided by data on the distribution of downwear rates from micro-erosion-meter measurements (e.g. Robinson, 1977; Porter et al., 2010) and there is evidence that rates measured over the short term (1-2 years) are consistent with rates measured over three decades (Stephenson et al., 2010, 2012). Nevertheless, it is still not clear whether it is appropriate to extrapolate these rates over centennial to millennial timescales required to accumulate measureable concentrations of ^{10}Be, nor is it yet clear whether this result is consistent across different shore platforms around the world. Future studies that measure the distribution of CRN concentrations (both across the shore platform and at depth) at sites with long records of observed downwearing rates would be an important next step in this line of enquiry."

6. Whether there are weathering patterns or not, mean rates of downwearing recorded by numerous workers in different environments and on different types of rock, which generally range from almost 0 up to a few millimeters per year (and hence significant lowering per millennium), surely have an important effect on predicted erosion rates. The reliance on models of platform development (whether parallel or declining slope retreat) to represent rates of surface lowering (as opposed to field measurements and micro-erosion metre data) remains an inherent weakness in attempts to apply cosmogenic techniques to rocky coasts.

   The reviewer has highlighted an interesting issue in the application of cosmogenic radionuclides to rocky coasts that will need to be addressed in future studies, namely the disconnect between short-term observations and long-term platform evolution, as we have already mentioned above. Our exploration of the sensitivity of CRN concentrations is not site specific and thus the use of spot measurements from a particular location, extrapolated back throughout most of the Holocene does not seem appropriate. It strikes us that, despite the findings of Stephenson et al (2010; 2012) that rates observed over a few years are similar to those over a few decades for two field sites, the extrapolation of short-term measurements (3 decades at best) of shore platform erosion over millennial timescales is also inherently weak. Future work measuring ^{10}Be concentrations at sites with good long-term field records of surface lowering would be an excellent future extension of the application of CRNs to rock coasts, and we have called for this in the paper (see our response to reviewer comment #5). Moreover, our growing capacity to observe changes in platform morphology in a distributed way using terrestrial LiDAR and photogrammetry in order to identify individual erosion events will lead to better understanding of the efficacy and distribution of platform downwear processes, and we commend the reviewer for pioneering these sorts of investigations.

As the reviewer points out both here and in his final comment, we do not yet understand the spatial distribution of weathering on shore platforms.

7. The traditional distinction (classification) between sloping and subhorizontal (or to use Sunamura's terminology, type A and B platforms) belies the fact that there is a continuous spectrum of forms with gradients that reflect tidal range and rock hardness (resistance), as well as possibly sediment grain size and the effect of Holocene sea levels higher that today.

   We thank the reviewer for highlighting that such a classification is an over simplification and we agree that these two forms are effectively end-members of a much wider array of shore platform morphologies. Our experiments were intended to explore such intermediate platform morphologies, we do not limit ourselves to type-A and type-B platforms. However the beginning of section 2 may have been misleading on this point. We now begin this section by saying:

   "Cliffed, rocky coasts, are commonly fronted by shore platforms that have previously been classified into two types (Sunamura, 1992). Type-A platforms are characterised by a gently sloping erosional platform surface extending offshore

   beyond maximum low water. Type-B platforms are shallow gradient to sub-horizontal and terminate at their seaward edge at maximum low water through a scarp (Figure 2a). Numerical models of shore platform evolution have successfully recreated both of these end-member morphologies, but have revealed that there are a range of other possible morphologies in between, for example sloping platforms terminating terminating in a scarp (e.g. Trenhaile, 2000; Walkden and Hall, 2005; Matsumoto et al., 2016)."

8. It is not clear to me why, on line 12 or page 4, abrasion is assumed to be dominant with a steady state that assumes platform downwearing is gradual and constant (especially since weathering is not considered). Sediment on shore platforms accumulates preferentially at the cliff foot and in structural depressions on the platform. In the latter case, abrasion rates with vary enormously across the intertidal zone in an essentially random manner. Abrasion towards the rear of the platform is spread over the intertidal surface as the cliff retreats, but constant abrasion assumes constant wave and sea level conditions as well as constant beach types and amounts.

   We thank the reviewer for highlighting the overly simple nature of this explanation. Our assumption is that in the case of steady-state retreat that platform lowering is constant and gradual across the shore platform. Over centennial to millennial timescales we might reasonably expect that the sorts of processes the reviewer describes here will tend to occur uniformly over a platform. Indeed, the existence of generally flat or planar platforms in some settings suggest this must be the case. We now state:

   "A steady state approach assumes platform downwear is gradual and constant across the entire profile, and proportional to the rate of cliff retreat. We are therefore assuming that the combined mechanical and chemical processes that can cause shore platform lowering culminate to constant and gradual downwear in this case."

9. Page 4, line 20, many models do/did not emphasize erosion at the water surface but rather erosion due to wave generated bottom currents (which is only effective in clays and other 'soft' rocks.

   We now state that: *"We developed a simple numerical model for shore profile evolution (the ROck and BOttom COastal Profile [RoBoCoP] Model), broadly similar to those of Sunamura (1992), Anderson et al. (1999) and Trenhaile (2000). These models assume..."*

10. An alternative to the Bruun Rule, which has been criticized by several workers and in any case is not designed for beaches with rigid (shore platform) foundations, is given by: Trenhaile, A. S. 2004. Modeling the accumulation and dynamics of beaches on shore platforms. Marine Geology 206, 55-72.

    We thank the reviewer to drawing our attention to this alternative model for beach profile shape. We note that our model is not employing the criticised "Bruun Rule" that relates rates of shoreline retreat to relative sea level rise, but rather we use a "Bruun Profile" as a description of the shape of the beach profile. We chose a Bruun profile for its computational simplicity. Our goal was not to explicitly replicate beach behaviour but rather to explore the influence that shielding by sediment cover has on the accumulation of ^{10}Be in shore platforms. Thus we took a parsimonious approach to representing beach morphology. We note that Trenhaile (2004) takes a similarly simplistic approach, representing the shoreface as a planar slope of constant gradient, though that gradient varies depending on wave conditions and grain size.

11. The paper needs some proof-reading. There are other examples that could be given but note 'ditributed' on line 14 of page 10 and on line 15 it should be 'adjacent to the cliff'.

    We apologise for the sloppy presentation despite our endeavours to catch all typological errors, and thank the reviewer for highlighting any such mistakes when

they have occurred. We have corrected the blunders explicitly pointed out by all reviewers, and our redraft has undergone thorough proof reading by all authors.

12. On lines 12 to 13 on page 11 it is claimed that there is no downwearing on top of flat-topped steps. This is wrong - weathering certainly lowers the surface until (and in some cases before) it is eliminated by step retreat.

    This is not a claim since we are referring specifically to the model simulations: "there is no vertical downwear in these simulations". Our simulations exploring block removal processes are exploratory and can be considered end-member scenarios. We sought to understand the influence that block removal processes might have on ^{10}Be concentrations at the surface. Were there some vertical downwear then we would expect the gradients in ^{10}Be concentrations across the flat-topped steps to be lower, i.e. concentrations would not increase as rapidly in an offshore direction. The result presented in this section demonstrates that block removal processes will cause deviations from the expected "hump" shaped distribution, but the general form of the hump still remains, and this is encouraging for potential future applications.

13. Lines 10 to 13 on page 13 emphasize errors due to differences in predicted downwearing rates according to the two evolutionary models. The reality is likely to be worse owing to weathering induced downwearing (with spatial patterns, if any, that we do not yet understand).

    Yes, the point we are trying to make is that the more rapid the rate of downwearing, the more ^{10}Be-laden rock is removed from the platform surface and the lower the subsequent production rate will be; therefore, the lower the CRN concentrations will be. This will lead to an over prediction of cliff retreat rates if not factored in (i.e. if one were to blindly assume steady-state retreat of a planar shore platform). If weathering processes are leading to more rapid downwear then this problem will be amplified. We have stressed in the discussion that measuring

CRN concentrations at sites with good records of downwear will be an important next step in developing our ability to estimate rates of cliff retreat, or platform downwear using CRNs. We have not added to the results section highlighted by the reviewer, but instead build on this issue in the discussion:

"In scenario (ii) cliff retreat rates tended toward a constant rate with the result that the distribution of ^{10}Be was approximately constant through time (Figure 14). The concentrations of ^{10}Be were not consistent with a steady state evolution scenario in which the platform gradient is fixed, which predicted roughly twice the amount of ^{10}Be for a particular position on the platform. The difference can be explained by the dissimilar platform morphology brought about by uneven distribution of platform downwear in the transient model simulations. Greater rates of downwear in the inter-tidal zone lower the platform more rapidly in the near-shore, which removes ^{10}Be-laden rock and results in deeper water in the near-shore (and therefore reduced ^{10}Be production) relative to the steady state model runs that assume constant and uniform downwear. These differences may be exacerbated when taking into account the spatial distribution of other processes such as weathering, the spatial distribution of which is currently poorly understood (Porter et al., 2010)."

References

Anderson, R.S., Densmore, A.L., and Ellis, M.A., 1999, The generation and degradation of marine terraces: Basin Research, v. 11, no. 1, p. 7–19, doi: 10.1046/j.1365-2117.1999.00085.x.

Chao, R.B., Casais, M.C., Cortizas, A.M., Alberti, A.P., and Trenhaile, A.S., 2003, Evolution and inheritance of a rock coast: Western Galicia, Northwestern Spain: Earth Surface Processes and Landforms, v. 28, no. 7, p. 757–775, doi: 10.1002/esp.496.

Choi, K.H., Seong, Y.B., Jung, P.M., and Lee, S.Y., 2012, Using Cosmogenic ^{10}Be Dating to Unravel the Antiquity of a Rocky Shore Platform on the West Coast of Korea: Journal of Coastal Research, v. 282, no. 3, p. 641–657, doi: 10.2112/JCOASTRES-D-11-00087.1.

Lazarus, E.D., McNamara, D.E., Smith, M.D., Gopalakrishnan, S., and Murray, A.B., 2011, Emergent behavior in a coupled economic and coastline model for beach nourishment: Nonlinear Processes in Geophysics, v. 18, no. 6, p. 989–999, doi: 10.5194/npg-18-989-2011.

Matsumoto, H., Dickson, M.E., and Kench, P.S., 2016, An exploratory numerical model of rocky shore profile evolution: Geomorphology, v. 268, p. 98–109, doi: 10.1016/j.geomorph.2016.05.017.

Porter, N.J., Trenhaile, A.S., Prestanski, K., and Kanyaya, J.I., 2010, Patterns of surface downwearing on shore platforms in eastern Canada: Earth Surface Processes and Landforms, v. 35, no. 15, p. 1793–1810, doi: 10.1002/esp.2018.

Regard, V., Dewez, T., Bourlais, D.L., Anderson, R.S., Duperret, A., Costa, S., Leanni, L., Lasseur, E., Pedoja, K., and Maillet, G.M., 2012, Late Holocene seacliff retreat recorded by ^{10}Be profiles across a coastal platform: Theory and example from the English Channel: Quaternary Geochronology, v. 11, p. 87–97, doi: 10.1016/j.quageo.2012.02.027.

Robinson, L.A., 1977, Erosive processes on the shore platform of northeast Yorkshire, England: Marine Geology, v. 23, no. 4, p. 339–361, doi: 10.1016/0025-3227(77)90038-X.

Rogers, H.E., Swanson, T.W., and Stone, J.O., 2012, Long-term shoreline retreat rates on Whidbey Island, Washington, USA: Quaternary Research, v. 78, no. 2, p. 315–322, doi: 10.1016/j.yqres.2012.06.001.

Stephenson, W.J., Kirk, R.M., Hemmingsen, S.A., and Hemmingsen, M.A., 2010, Decadal scale micro erosion rates on shore platforms: Geomorphology, v. 114, no. 1–2, p. 22–29, doi: 10.1016/j.geomorph.2008.10.013.

Stephenson, W.J., Kirk, R.M., Kennedy, D.M., Finlayson, B.L., and Chen, Z., 2012, Long term shore platform surface lowering rates: Revisiting Gill and Lang after 32 years: Marine Geology, v. 299–302, p. 90–95, doi: 10.1016/j.margeo.2012.01.005.

Sunamura, T., 1992, Geomorphology of Rocky Coasts: John Wiley and Sons Ltd.

Trenhaile, A.S., 2014a, Climate change and its impact on rock coasts: Geological Society, London, Memoirs, v. 40, no. 1, p. 7–17, doi: 10.1144/M40.2.

Trenhaile, A.S., 2004, Modeling the accumulation and dynamics of beaches on shore platforms: Marine Geology, v. 206, no. 1–4, p. 55–72, doi: 10.1016/j.margeo.2004.03.013.

Trenhaile, A.S., 2000, Modeling the development of wave-cut shore platforms: Marine Geology, v. 166, no. 1–4, p. 163–178, doi: 10.1016/S0025-3227(00)00013-X.

Trenhaile, A.S., 2001a, Modeling the effect of late Quaternary interglacial sea levels on wave-cut shore platforms: Marine Geology, v. 172, no. 3–4, p. 205–223, doi: 10.1016/S0025-3227(00)00136-5.

Trenhaile, A., 2014b, Modelling the effect of Pliocene-Quaternary changes in sea level on stable and tectonically active land masses: Earth Surface Processes and Landforms, v. 39, no. 9, p. 1221–1235, doi: 10.1002/esp.3574.

Trenhaile, A.S., 2001b, Modelling the quaternary evolution of shore platforms and erosional continental shelves: Earth Surface Processes and Landforms, v. 26, no. 10, p. 1103–1128, doi: 10.1002/esp.255.

Walkden, M.J.A., and Hall, J.W., 2005, A predictive Mesoscale model of the erosion and profile development of soft rock shores: Coastal Engineering, v. 52, no. 6, p. 535–563, doi: 10.1016/j.coastaleng.2005.02.005.