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Response to Comment on "Absence of Cooling in New Zealand and the Adjacent Ocean During the Younger Dryas Chronozone"

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Applegate *et al*. present the results of a moraine degradation model and suggest that the age of the Waiho Loop may be 1000 years older than the age we presented, thus raising the possibility that the moraine is a Younger Dryas landform. We show that this assessment is misleading on a number of grounds.

We exposure-dated the Waiho Loop moraine in New Zealand and showed that it was deposited well after the Younger Dryas chronozone (*1*). This dating dispels the notion that the Waiho Loop is evidence for a global Younger Dryas cooling event. Applegate *et al*. (*2*) suggest that a diffusion model can be used to explain most of the variability in the exposure ages. We appreciate the opportunity to add field observations and discuss the statistical treatment of the data to show that our original interpretation of the ages is robust.

Two processes contribute most of the scatter seen in exposure age data from moraines and, as stated in (*1*), both of these effects are likely to be in the data from the Waiho Loop. The first process is the exhumation and exposure of boulders from beneath the original surface after the deposition of the moraine. This can take place as a result of slow diffusive processes such as slope wash operating through time or instantaneously by mass movement of a section of the moraine. Exhumation of boulders results in younger than expected exposure ages and shows up as a tail in a probability plot of the ages to the young side of the true age of the moraine. The second process is the exposure of a surface before the boulder is incorporated into the glacier. This commonly results from the inclusion of supraglacial material into the moraine. Previous exposure manifests as a tail in a probability plot of the ages to the old side of the true age of the moraine. Our interpretation of the exposure ages from the Waiho Loop was based on field evidence of the likely impact of these processes and a statistical reduction of the data consistent with those observations.

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The moraine degradation model employed by Applegate *et al*. (*2*) represents the influence of diffusive processes on the exposure age distribution of model boulders. Previous applications of the model, such as in semiarid settings in the southwest of North America, produce reasonable results where the moraine profile is clearly observed to have diffused over time. In contrast, the Waiho Loop moraine has retained most of its original profile with a steep distal face, less steep proximal face, and a narrow crest. Similar preservation is also seen on the older moraines nearby that are more than 16,000 years old (*3*). The exceptional preservation appears to be the product of the dense vegetation cover, a result of the high annual rainfall. Indeed, the vegetation cover is so thick that the moraine surface is actually accumulating a peat cover, not eroding to expose fresh boulders. Neither slopewash nor soil creep was seen to be operating on the narrow crest of the moraine where we sampled. The field evidence indicates that diffusive processes are limited, at odds with the model parameters used by Applegate *et al*. (*2*).

Landslides are the dominant erosive process on the Waiho Loop, and small landslips occur on the lower third of the moraine where rivers undercut its edge. The stretch of the moraine with topography most indicative of this process is the eastern half. Here, the course of the Waiho River has moved through time around the perimeter of the moraine, and the Tatare Stream has breached the moraine (but this stream may follow the course of an original meltwater channel). The eastern stretch of the moraine also hosts the two youngest exposure ages on boulders (WH-08 and WH-09), likely to be the result of landslips ~5000 and ~8000 years ago. Such resurfacing of the moraine is most likely stochastic and not a continual lowering of the whole moraine as modeled by Applegate *et al*. According to figure 1 in (*2*), fewer than 10% of the boulders sampled on a moraine representative of this model would actually reflect the true age of the feature. This represents widespread alteration of the model surface and is not consistent with the evident preservation of the moraine. This highlights the danger of applying a prescriptive model to a landscape feature not studied in the field.

Applegate *et al*. (*2*) also excluded most of the data from their analysis. They included only one-third of the ages in their comparison to their model on the grounds that the relationship between the ^{36}Cl exposure ages and the true age of the moraine is "complex." This is not correct for our data, where the contribution of ^{36}Cl by neutron capture is very small because of the low chloride content. Production is therefore dominated by spallation, as is the case for ^{10}Be. Much of the scatter between the ^{36}Cl ages is due to difficulty in constraining the native chloride contents, which are close to background. The background subtraction, which is significant with regard to the native chloride content, leads therefore to greater uncertainty and the increased potential for the propagation of nonrandom errors. Recalculating the ^{36}Cl ages based on the first set of chloride measurements, which were the most precise, considerably reduces the age scatter between duplicates, and all except one pair agree within 1 SD.

Lastly, it is not possible to ignore the effects of previous exposure. Previous exposure is a considerable problem where there is an obvious contribution of supraglacial material to the moraine. The Franz Josef glacier traverses a long valley with steep sides, and exposed boulders from the valley walls must have fallen onto glacier as rockfall or landslides. This material is likely to be concentrated at the edges of the glacier, and therefore it is not surprising that the oldest exposure ages are those found at the left and right extremes of the moraine (WH-01, WH-02, and WH-10). Additionally, the disagreement between duplicate samples taken at either end of large boulders (WH-06 and WH-07) hints at the possibility of previous exposure at one end of the boulder. Minor cases of previous exposure are difficult to detect because the ages overlap with other ages from the moraine, making it difficult to eliminate them as outliers [for example, see (*4*)]. The probability of previous exposure prevents the assumption by Applegate *et al*. (*2*) that the oldest ages are the most likely to reflect the age of the moraine.

The argument presented by Applegate *et al*. provides only circumstantial evidence that the application of a diffusion model is the best way to interpret the exposure ages from the Waiho Loop. Our observations of the geomorphology of the moraine indicate that an average of the exposure ages after eliminating obvious outliers is probably the best way to interpret the data. However, the reduced χ^2 of the data set is 2.55 for 8 degrees of freedom (with a probability that χ^2 exceeds this value of 1%), indicating that there is additional scatter in the data over and above the statistical uncertainties. This scatter, as argued above, is most likely due to cases of minor prior exposure, stochastic exhumation of boulders early during moraine stabilization, and potential errors in the calibration of production rates for both ^{10}Be and ^{36}Cl. A rigorous statistical prescription for treating this situation has been given by Galbraith (*5*). It entails adding an additional constant random uncertainty to each data point and provides a means of determining the mean and error in the mean as well as the magnitude of this additional uncertainty. The resulting mean value of 10.22 ± 0.38 ka has, as expected, a somewhat larger error than the error-weighted mean given in (*1*), but is statistically indistinguishable from it. This age is more than 3 SDs from the Younger Dryas termination, using production rates that produce consistent Younger Dryas ages for Younger Dryas features at comparable latitudes and altitudes elsewhere. Excluding the younger and older ages that increase the scatter does not materially change the age of the moraine and does not alter the conclusion that the Waiho Loop was not formed at the end of the Younger Dryas chronozone.

References

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