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Reply

Reply to comments by Matthias Kuhle on "Qu

We welcome Kuhle (2008) comment on our paper (Seong et al., 2007[2]) and the opportunity to discuss our recent research on the Quaternary glacial history of the Himalayan–Tibetan orogen, which includes Owen et al. (2002, 2003, 2005, 2006), Finkel et al. (2003), Lehmkuhl and Owen (2005), and Owen and Benn (2005). In these studies, we apply well-established geomorphic and sedimentological techniques to map the former extent of glaciation and to establish, in many cases, the equilibrium-line altitudes (ELAs) of former glaciers. Furthermore, we date glacial and associated landforms using optically stimulated luminescence (OSL) and terrestrial cosmogenic radionuclide (TCN) methods to define the timing of glaciation to place a temporal framework on our glacier and ELA reconstructions.

Our recent research shows a complex pattern of glaciation, influenced by strong climatic gradients throughout the region. In general, we find that in regions of greater aridity, the extent of glaciation has become increasingly restricted throughout the Late Quaternary leading to the preservation of old (>100 ka) glacial landforms. In contrast, in regions that are very strongly influenced by the monsoon ($>1600\,\mathrm{mm\,a^{-1}}$), the preservation potential of pre-Lateglacial moraine successions is generally extremely poor. This is likely because Lateglacial and Holocene glacier advances may have been more extensive than in early glaciations and hence may have destroyed any landform or sedimentary evidence of earlier glaciations. In essence, there are striking regional contrasts, even across a mountain range, in both the timing and extent of glaciation throughout a region and the whole orogen.

In Kuhle's (2008) comment, he begins by suggesting that OSL and TCN dating are erroneous in the studies undertaken in the Himalaya and Tibet because these dating methods "*have not been calibrated in particular for strong radiation in high altitude up to now and which, moreover, sensitively depend on the vague estimation of weathering rates and dislocation, and the astrophysical metric of which cannot even be said to have been reliably clarified yet*". While both these dating methods have many uncertainties associated with them, what he implies is simply incorrect. In the case of OSL dating, the higher radiation at high altitudes contributes a little to the cosmic dose rate, which accounts for at most 10% of the total dose rate and hence any possible uncertainty is at greatest a fraction of a percent of the OSL age and therefore essentially negligible. Richards (2000) provides a more detailed discussion on dating glacial deposits in the Himalaya using OSL methods and we refer the reader to this paper. Neither weathering nor "dislocation" effect OSL dates. In the case of TCN dating it is difficult to understand the exact nature of the difficulty that Kuhle finds with our results. Clearly, there are uncertainties associated with surface exposure dating, as is true of all geochronological techniques. Even with such a well-established approach as radiocarbon dating, uncertainties must be assessed when considering the reliability of ages. The first problem mentioned by Kuhle is the problem of "strong radiation at high altitude". Presumably, Kuhle is referring here to the increase in cosmic-ray flux as a function of altitude. In fact, cosmogenic nuclide production rates have been calibrated at altitudes ranging from sea level to about 4045 m asl (Balco et al., 2008 and references therein). The altitude dependence, which is actually a dependence on the mass of overlying atmosphere, is understood and the uncertainty introduced by potential changes in atmospheric pressure in the past can be reasonably well estimated (Balco et al., 2008 and references therein). In addition, for our study area in the Central Karakoram, the consistent ages of Lateglacial moraines over an altitudinal range of several kilometers show that the scaling models used are robust for altitudinal corrections to our ages.

Weathering rates, next mentioned, are definitely a source of uncertainty in calculating surface exposure ages and can significantly alter surface exposure age estimates. These were addressed in Seong et al. (2007), and the effect of erosion on the quoted surface exposure ages was estimated as a function of the exposure time in this paper and in several previous papers (e.g. Owen et al., 2002, 2003, 2005, 2006; Finkel et al., 2003). Kuhle is also concerned that dislocation might invalidate the TCN ages. The exact process of concern here is not clear, but Kuhle is presumably referring either to inheritance or to boulder movement after emplacement. We find little evidence for inheritance in the dynamic high-mountain environments under

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[2] Kuhle's (2008) comment references Seong & Owen et al. (2007), which we infer is a reference to Seong et al. (2007).

observation, where fresh rock is continuously being supplied to glacier surfaces by rock falls and avalanching. The effects of toppling and rock splitting, while possible, were minimized by sampling large boulders that have little chance of toppling. Where evidence for toppling is present it is mentioned. Such effects were further examined and estimated by collecting multiple samples from the sample surface. This approach is discussed in detail in most papers that include TCN ages, and specifically our work in the Himalaya and Tibet (e.g. Owen et al., 2002, 2003, 2005, 2006; Finkel et al., 2003).

We presume that by "the astrophysical metric" Kuhle (2008) refers to changes in cosmic-ray flux over time. Such changes are dominantly caused by changes in the Earth's magnetic field intensity. TCN age calculations model these changes and the different scaling models result in age estimates, which differ by the order of 5–25% for this region (Owen et al., in press).

Using both OSL and TCN dating methods, essentially independent techniques, on the same landforms allows us to test these dating issues. Of note is our work in Hunza Valley that found consistent moraine ages determined in two separate studies using luminescence dating (Derbyshire et al., 1984; Spencer and Owen, 2004) and in a study using TCN methods (Owen et al., 2002). Similarly, Finkel et al. (2003) confirmed the luminescence ages of Richards et al. (2000) using TCN methods on moraines in the Khumbu Himal south of Everest. These studies provide confidence in the numerical dating methods. In summary, the uncertainty in these methods results in errors on the order of 5–25% of the age of the sediment or landform that is being dated. They allow us to determine the ages of moraines on millennial timescales for Lateglacial and Holocene glacial successions and on Milankovitch timescales for older moraines in the Himalayan–Tibetan orogen.

In his comment, Kuhle (2008) recognizes the striking differences in the extent of glaciation (and ELA depression [ΔELA]) between the Central Karakoram (Seong et al., 2007) and the Hunza Valley, which lies ~50 km to the NW (Owen et al., 2002; Spencer and Owen, 2004). In the Hunza Valley, Benn and Owen (2005) calculated a global Last Glacial Maximum (gLGM) ΔELA of <200 m (not <100 m as highlighted by Kuhle, 2008), while in the Central Karakoram, the ΔELA for the Lateglacial was ~550 m, inferring a similar or possibly larger gLGM ΔELA (Seong et al., in press). Furthermore, sharp contrasts exist to the east of the Central Karakoram where during the early part of the last glacial cycle extensive valley glaciers advanced down the Nubra Valley to the Shyok, ~100 km from their present positions (Owen et al., 2007), while 50 km to the south, on the southern slopes of the Ladakh Range, glaciers only advanced a few kilometers from their present positions (Owen et al., 2006). These studies illustrate the significant regional climate gradients that exist, as well as demonstrating the influence of other factors, such as the hypsometry of the glacial basins, in controlling glaciation in the Himalaya and Tibet. Furthermore, significant local variation in ELAs occurs in the Himalaya, reflecting numerous factors, including microclimatology, snow blow (supply) area, supraglacial debris cover, avalanche potential and bedrock exposure. Benn and Lehmkuhl (2000) illustrate this complexity in the Khumbu Himal where they show, for example, that the Chhukung Glacier, which has a snout at ~5200 m asl, is some 200 m above the ELA of the adjacent Ama Dablam Glacier. All these factors point out the complexity of reconstructing former ELAs in the tropics and high mountains. These issues are discussed in detail in Harrison (2005). The papers of Benn et al. (2005) and Owen and Benn (2005) specifically highlight the potential for strong regional gradients and differences in ELAs.

We agree with Kuhle (2008) that there is a need for regional mapping to fully assess the regional extent of glaciation. Mapping end and lateral moraines, however, as we did in our study of the Central Karakoram (Seong et al., in press), does allow accurate reconstruction of glacial ice volumes for ELA reconstructions. But, without a temporal framework, it is not possible to adequately reconstruct the true extent of glaciation across regions throughout the Himalaya and Tibet at specific times, such as the gLGM. Reconstructions of ice extent across such a region without a temporal control can easily lead to erroneous paleoclimatic interpretations. The Tibet ice sheet proposed by Kuhle (1988, 1995, 2001, 2004, 2006, 2007), for example, is not based on any dated glacial successions; but rather was inferred from ΔELAs based on moraines, which in fact are of different ages (Owen and Benn, 2005). The ΔELA was then erroneously extrapolated across the Tibetan Plateau to argue for an ice sheet at the gLGM. Such reconstructions are extremely tenuous, and generally disregarded by most researchers (e.g. Burbank and Kang, 1991; Rutter, 1995; Lehmkuhl, 1997; Schäfer et al., 2001; Lehmkuhl and Owen, 2005).

Kuhle (2008) highlights, for example, that he had mapped ice extent through the Shigar Valley to Skardu and recognized the till on Karpochi rock (Kuhle, 2001). He failed to note, however, that earlier authors had also mapped these sediments and landforms, including Drew (1873), Cronin (1982) and Owen (1988), and others. None of these authors, however, provide any numerical ages to define the timing of Late Quaternary glaciation. Kuhle (2008) continues by arguing that till, ice-polished surfaces and striations at 1300–2700 m asl above the present river level and ground moraine at Skardu represent gLGM limits. Unfortunately, he does not provide any detailed geomorphic or sedimentological data to show that the ground moraine (the hummocky moraine at Skardu of Seong et al., 2007), erratics and polished ice surfaces that he describes are from the same glacial stage. Furthermore, he does not provide any numerical dating to support a gLGM age for these landforms. Rather, his age assignment is based on the view that since the ΔELA needed to produce these landforms is large ($\geqslant 1000$ m), it must have occurred during the gLGM. Extending this faulty logic, he assigns contemporaneous times to the maximum ΔELAs from distant regions around the Tibetan Plateau. He uses this assignment of contemporaneity, together with rather equivocal field evidence, including exotic boulders and eroded landforms, to hypothesize that an ice sheet existed over Tibet during the last glacial. By doing so, Kuhle (2006, 2008) dismisses the extensive studies by other workers who present glacial geologic evidence that shows that an ice sheet could not have existed on the Tibetan Plateau during at least the last two glacial cycles. This includes the works of Burbank and Kang (1991), Rutter (1995), Lehmkuhl (1997), Schäfer et al. (2001), Owen et al. (2002, 2003, 2005, 2006, 2007) and Finkel et al. (2003). Kuhle (2008) argues that landslides identified by Hewitt (personnel communication to Kuhle) are all Holocene and occur within his proposed LGM limit, which strengthens his proposed LGM age. He does not provide, however, any numerical dating to substantiate this claim for the Holocene ages. Furthermore, assigning Holocene ages to landslides which follow a glacial advance provide only minimum age estimates and therefore do not provide accurate timing of glaciation.

Furthermore, Kuhle (2008) argues that there are "*up to 14 late glacial to historical recessional stages*" in the region. He provides no references, however, to landform descriptions or numerical dating that might substantiate this statement and therefore we cannot assess its validity. We did not recognize 14 distinct moraine sets in the region.

In summary, the extensive recent research undertaken on the Quaternary glacial geology of the Himalayan–Tibetan orogen shows that patterns of former glaciation are complex, with considerable variation in glacier extents and ΔELAs across individual mountain ranges and across the whole orogen. These regional variations have only been recognized by detailed mapping and intensive numerical dating programs. The paleoclimatic significance of these has yet to be fully interpreted.

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