Reply to Comment on "Crustal strength in central Tibet determined from Holocene shoreline deflection around Siling Co"

Xuhua Shi[a, b,*], Eric Kirby[c], Kevin P. Furlong[a]

[a] Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA

[b] Earth Observatory of Singapore, Nanyang Technological University, Singapore 639798, Singapore

[c] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA

* Corresponding author: xshi@ntu.edu.sg

In their comment, England and Walker (2016) consider a subset of shoreline observations presented in Shi et al. (2015) to argue the position that the shoreline is essentially horizontal (4593.9 ± 0.75 m at one standard deviation or 4593.9 ± 1.5 m at two standard deviations). Then they follow their previous analysis (England et al., 2013) to make the case that the absence of deflection of shorelines from the horizontal places a lower bound on the elastic strength of the crust and the viscosity of the deep crust. Although we do not disagree with their previous model to assess crustal strength, we argue that it has been misapplied in this case. We appreciate the opportunity to clarify and amplify our contention that one must consider the full distribution of data. Particularly, observations from the "tails" of the histogram of shoreline elevation are critical to the determination of crustal strength and cannot be discounted simply because they fall outside a chosen range from the mean. We argue that analyzing the variation in shoreline elevation as a mean (± std. dev.) (or any other similar statistical measure) is inappropriate when the data sampling is by nature biased, and a single observation from a key location may be as important as a suite of observations that dominate in determining a mean elevation. Therefore, we hold to the conclusions in our paper (Shi et al., 2015) that the range of shoreline elevations represents deflection of ~2-5 m during crustal rebound, and that this deflection provides an estimate of the elastic strength of the crust consistent with the elastic thickness (T_e) of ~ 20-30 km in central Tibet.

The full range of our observed shoreline elevations is, in fact, ~ 4-5 m (Fig. 1); based on the location of our observation sites, this range occurs over a length scale of ~ 30 km from the lake margin to its center. For example, the elevation of a beach ridge along the highstand complex at Site 93 (Fig. 2a) at the lake margin sits today at 4591.8±0.1 m, suggesting the paleo-mean water level was at, or immediately below, this elevation. In contrast, a shoreline spit near the lake center at Site 36 (Fig. 2a) is today at 4595.8±0.1 m in elevation. The depositional setting of this spit would have been below wave base, implying that paleo-mean water level would have been at least ~ 0.5-1 m above this elevation. Thus, the deflection of these two sites from the paleo-horizontal datum represented by the mean water level is ~ 4 m, or perhaps up to 5 m, when the geomorphic and depositional context of the shoreline features are considered.

The subset of data utilized by England and Walker (2016) was assigned a nominal quality rank (A) that corresponds to the highest degree of confidence in the shoreline correlation to the Lingtong highstand (Shi et al., 2015); this subset of data has an elevation range of 3 m (Fig. 1). Although we agree (and, indeed, previously argued) that the “A” quality sites provide the best estimates of shoreline elevation, the lower quality data, i.e. those from the tails of elevation histogram in Fig. 1, cannot be discounted so readily in the analysis. Our extensive mapping, surveying, and site characterization all suggest that even these lower confidence sites represent the same shoreline level (Shi et al., 2015). We also recognize that in using shorelines, such as those around Siling Co, to estimate the flexural response to lake withdrawal, not all observations provide comparably key data. In particular, the position of the observed shoreline relative to the load becomes very important. In the simplest case of a circular lake where all observations were made along its shoreline, equidistant from the center of the load, all shorelines would rebound the same amount and hence remain horizontal, irrespective of flexural rigidity. Similarly, for a very long, but relatively narrow lake, all shorelines along the long axis of the lake would rebound by a similar amount and remain horizontal. As the shape of the lake becomes more irregular, the rebound will vary along the margin, but with a relatively complex interplay among lake (i.e. load) geometry, elastic thickness, and flexural response (Shi et al., 2015).

One advantage of Siling Co in this regard, over other lakes in Tibet (e.g., Nam Co and Zhari Namco), is that its shape is relatively irregular and, importantly, there is a peninsula in the south that would have been an island during lake highstands (Fig. 2). This transect allows us to make observations from very near the center of the load (where rebound is expected to be greatest) and link those observations to the more abundant circumferential shorelines. Although there are relatively few of these “island” data (due to the relatively sparse and biased formation and preservation of the shoreline features in such a location), and thus they have only a minimal influence on the mean elevation of the shorelines, they nonetheless provide critical observations. These particularly important sites do come with caveats. As they were isolated island sites when the lake was at highstand, the shoreline features are more localized and they are not built on shallowly sloping lake margins. This fact leads to a higher fraction of these sites being assigned a lower quality ranking as they may not be unambiguously tied to the continuous shorelines that ring the lake. Moreover, the limited numbers of these sites and their higher elevations make them tend to appear in the tails of the histograms (Fig. 1). Therefore, if one excludes even some of these key sites (either explicitly or by considering only the mean of all sites), one inherently excludes the data that would most likely record differential rebound. The expectation is that if only circumferential sites are included then the range of observed shoreline elevations will be smaller. Therefore, although the “island” and peninsula sites are of somewhat lower quality, we contend that they do need to be included in the analysis of crustal strength. Since a large fraction of these sites are not “A” quality, they were not included in England and Walker (2016)’s analysis of our data, leading to a biased observation of a reduced magnitude of the shoreline deflection.

In our original paper (Shi et al., 2015; Fig 5), we provided a series of analyses that utilized all of the data to assess the best fitting T_e for the observations. Another way to consider this is to compare the observed distribution of shoreline elevations (Fig. 1) with those expected (at the same locations) from various flexural model assumptions. The results of those analyses are shown in Fig. 2. Here we see that as T_e increases, the breadth of the observed range of shoreline elevations becomes narrower. In agreement with the site-by-site analyses we conducted in Shi et al. (2015), we see under this simpler analysis that T_e of 20 km yields an expected range of observations of 4-5 meters, similar to the observed range. As T_e exceeds 30 km, the expected range becomes less than 3 meters. This analysis also illustrates that the island/peninsula sites provide most of the observations that define the high elevation side of the distribution, particularly for the case of a thinner elastic thickness (Fig. 2).

England and Walker (2016) also presented an analysis of viscosity values that could produce a near horizontal set of shorelines. Although we do not think this is necessarily relevant, given our contention that variations in shoreline elevation do exist at Siling Co, we can provide some additional insight into the lake level history that is different from their assumption of an instant lake emptying from the Lingtong highstand at 4 ka. We have obtained new age estimates from beach ridge complexes below the Lingtong highstand that require lake recession to have occurred over a protracted interval from ~ 4-1 ka (Shi et al., manuscript in preparation for submittal), with several potentially significant hiatuses during that interval. Because lake unloading from the Lingtong highstand is progressive, and importantly, not instantaneous, the rate and spatial distribution of lake unloading will likely change the relevant time duration of lower crustal relaxation and may consequently affect inferences of crustal viscosity.

Finally, we wish to draw attention to a recent study using InSAR observations of crustal deformation induced by the rapid lake-level rise of Siling Co over the past forty decades. This result implies a viscosity of $1\text{-}3\times10^{18}$ Pa s in the lower crust (Doin et al., 2015), which is reasonably consistent with our viscosity estimates of $\leq 1\text{-}2\times10^{19}$ Pa s (Shi et al., 2015). Whether similar signals are present around other Tibetan lakes remains to be determined. Regardless, it seems clear that the continued search for constraints on the rheology of Tibetan crust will require extensive sampling of surface deformation across a range of timescales. Assessment of shoreline deflection at other sites across the plateau could be an important component of this search, but will require careful evaluation of local site conditions (i.e. mean water depth) and detailed chronology to refine correlations among sites. In all cases, the signal of shoreline deflection is likely to be small, but, as this exchange illustrates, consideration of the extremal values in the distribution is essential to determinations of crustal strength.

Acknowledgements

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References

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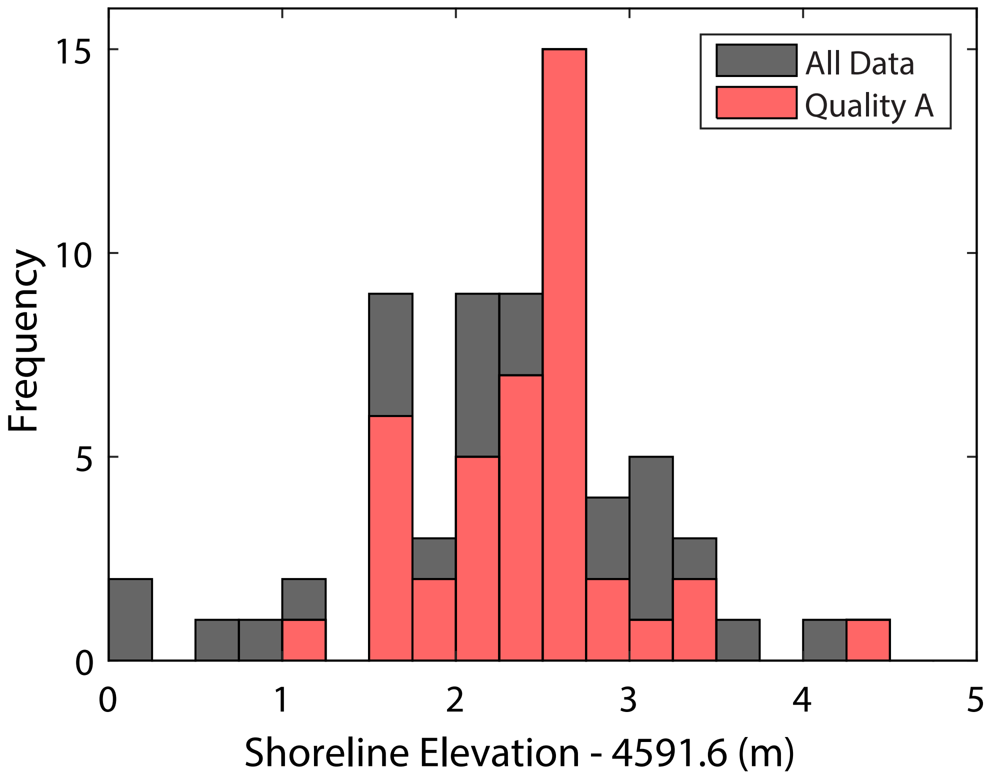
Figure Legends

Fig. 1. The histograms showing the distribution of the observations of shoreline elevations (Shi et al., 2015) at all sites (black bars) and Quality A sites (orange bars) around Siling Co.

Fig. 2. (a) The map showing the locations of surveyed shoreline sites around Siling Co. The thick black-outlined circles denote shorelines in the islands/peninsulas. (b-c) Histograms showing the distribution of the predicted shoreline deflections at ALL surveyed shoreline sites for T_e = 20 km and 30 km, respectively. Red and black bars represent the sites at the island/peninsula and at the paleolake margin, respectively. (d-e) Histograms showing the distribution of the predicted shoreline deflections at shoreline sites ONLY with the highest confidence (Quality A) in the correlation, for T_e = 20 km and 30 km. Color patterns are the same as in panels b and c.



All Data
Quality A
Frequency
Shoreline Elevation - 4591.6 (m)
0
5
10
15
0
1
2
3
4
5

Fig. 1

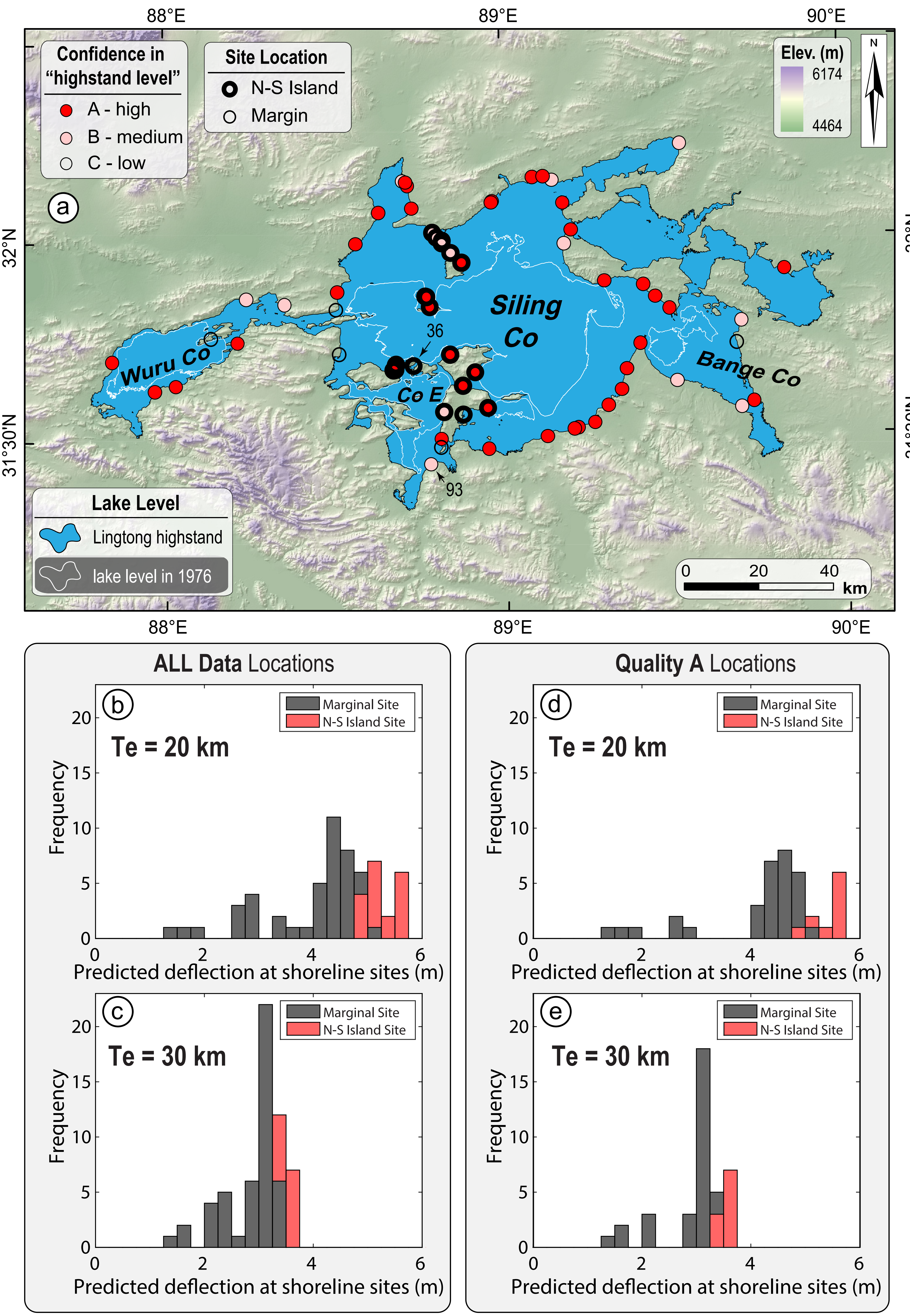

88°E
89°E
90°E
32°N
31°30'N
Confidence in "highstand level"
A - high
B - medium
C - low
Site Location
N-S Island
Margin
Elev. (m)
6174
4464
N
a
Siling Co
Wuru Co
Co E
Bange Co
36
93
Lake Level
Lingtong highstand
lake level in 1976
0
20
40
km
ALL Data Locations
Quality A Locations
b
c
d
e
Te = 20 km
Te = 30 km
Marginal Site
N-S Island Site
Frequency
Predicted deflection at shoreline sites (m)

Fig. 2