Preliminary Field Report

Liquefaction and deformation near Lake Iliamna may be evidence of recent earthquakes on the Lake Clark Fault

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ABSTRACT

Earthquake history in the Lake Iliamna region is poorly studied, and the potential for future earthquakes is unknown. Strong shaking in the Lake Iliamna region is a potential threat to communities and infrastructure, including facilities that may be constructed as part of the proposed Pebble Mine. We have found preliminary evidence of post glacial earthquake activity along Lake Iliamna, in the form of deformed sediment and warped paleo-shorelines. Our techniques included aerial imagery analysis, precision GPS field surveys, and outcrop investigation. The deformed sediment – a series of liquefaction features in beach-bluffs – most likely resulted from repeated episodes of strong shaking sometime in the period since glaciers retreated from the lake around 12,600 years ago. Variation in the elevation of surveyed shorelines formed after glacial retreat shows probable tectonic deformation—caused either by earthquakes or slower movement along a fault—since that time. Both lines of evidence are consistent with earthquakes on the Lake Clark Fault southwest of its mapped limit near Lake Clark, or by activity on some other unmapped fault. There are other possible sources of sediment deformation besides earthquakes, but none match the particular features we observed. Further investigation is needed to characterize earthquake potential in the area.

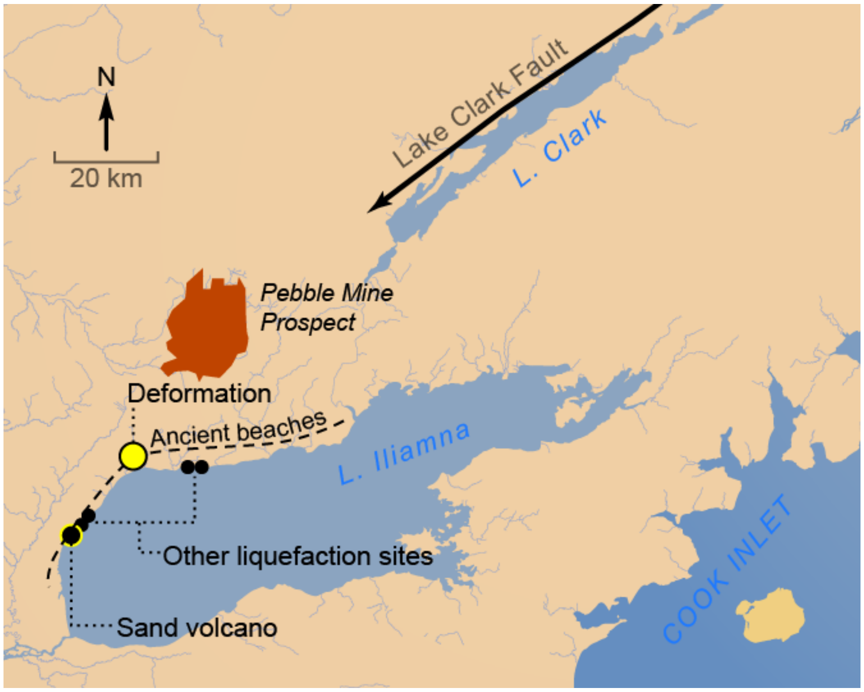

Figure 1. Map of the region, and locations of field sites. These sites lie southwest of the mapped trace of the Lake Clark Fault, on the far side of the proposed Pebble Mine.

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LIQUEFACTION FEATURES

Sediment exposed in bluffs along Lake Iliamna showed evidence of a liquefaction-caused sand volcano, along with additional liquefaction features representing at least one more event—consistent with recurring strong shaking in the area. The extensive "sand volcano" deposits, including liquefied source sediment, sand dikes, sills, and surface deposits, were revealed along 20 meters of lakeshore bluff (Fig. 2.) Liquefaction features similar to this large sand volcano are rare, and are typically associated with strong earthquake shaking (e.g. Martin & Bourgeois, 2012; Waller, 1966). Additional liquefaction of lake sediments spread over multiple kilometers of Lake Iliamna coastline may also have been earthquake-caused.

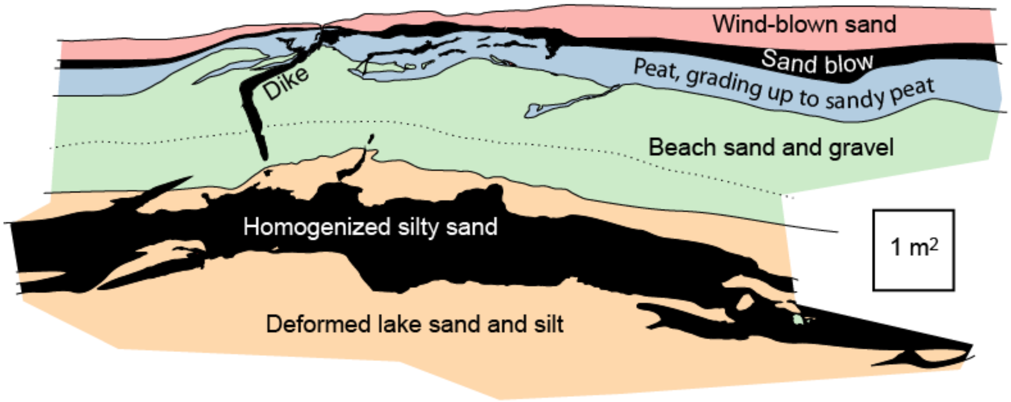

Figure 2. Sketch of a sand volcano deposit: Saturated lake-bottom sediment liquefied and injected upward through sand, gravel, and peat deposits then erupted onto the surface. Sand poured out onto the surface as a "sand blow" that covered sandy peat for tens of meters in either direction. The large dike (labeled) extends roughly perpendicular into the outcrop, and includes complex branching that was removed during outcrop cleaning. The upper part of the peat unit is rich in sand that is similar to the overlying aeolian deposit, suggesting that the marsh was already beginning to be overrun by dunes when the sand blow occurred.

The features of the sand volcano are not consistent with any source of deformation other than an earthquake (See Appendix A for detailed discussion). As part of our investigation, we assessed shoreline sediments for cryoturbation (ice-process deformation), deformation from glacial overriding, landslide or wave induced liquefaction, and other possible sources of sediment deformation.

The sand volcano occurred late in the stratigraphic sequence recorded in the Lake Iliamna bluffs – after lake level subsided, and peat formed (Fig. 3). Most of the overlying sediment is dune sand that is part of an active dune system. Pending radiocarbon dating and tephra identification (in progress), our interpretation is that this deposit is mid to late Holocene in age, likely within the past few thousand years.

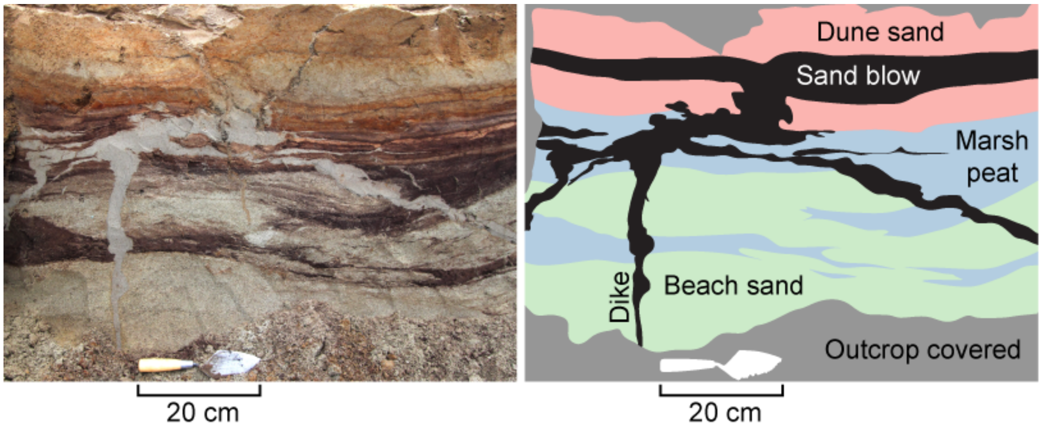

Figure 3: Photo of upper part of a sand volcano. This site sits about 5 meters south (left) of the site shown in Fig. 2. Sand forced upward from below penetrated beach deposits and peat to erupt onto wind-blown sand atop the peat. The surficial sand blow deposit is continuous to the north all the way to the larger feature shown in Fig. 2.

Additionally, we found smaller-scale liquefaction evidence in multiple widely-spaced locations, including at least one event that must have preceded the major event described above. The predating event was several meters below the base of the sand volcano's origin, in the same lake sediment (Figure 4). These features were clearly caused by liquefaction, rather than cryoturbation or glacial processes. Other sources of liquefaction, including landslides and waves cannot be completely eliminated, but are unlikely to explain all of these features (see Appendix A for detailed discussion of alternative hypotheses).

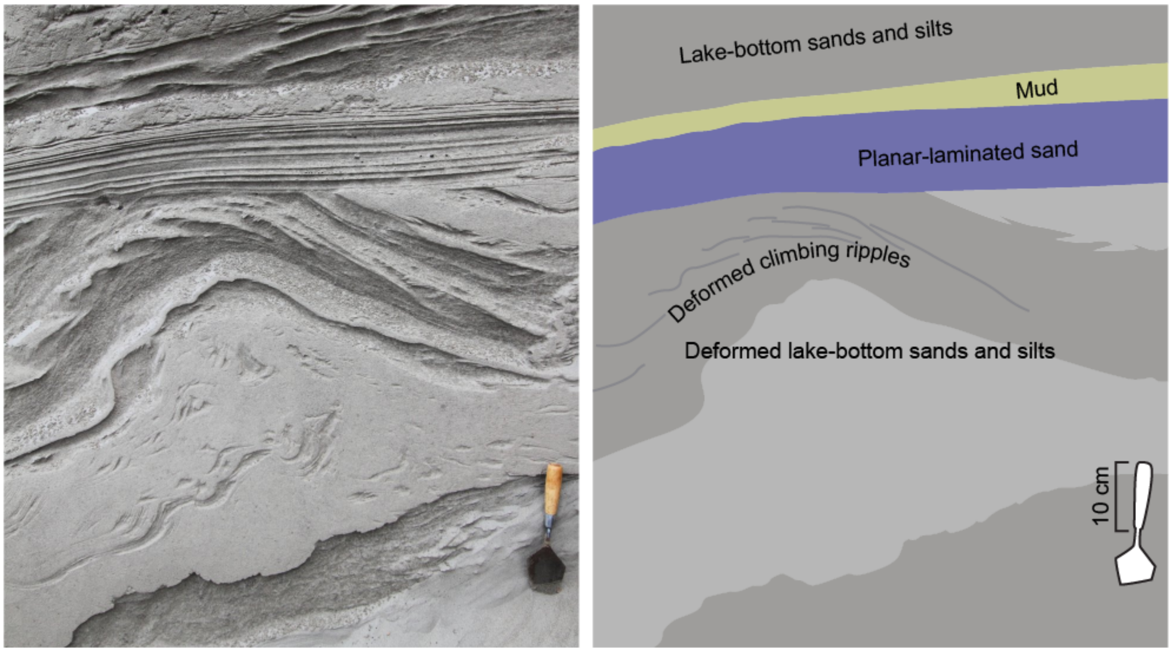

Figure 4: Deformed lake sediments are truncated by a minor unconformity several meters below the sand volcano. If this deformation is liquefaction induced by earthquake shaking, the planar-laminated sand capped by mud that overlies the deformation may record a lake tsunami resulting from the same earthquake.

In total, these features are consistent with recurring strong shaking in the area along some unmapped fault—either an extension of the Lake Clark Fault, or an unknown structure.

PALEO-SHORE DEFORMATION

Elevation variations along once-horizontal lake shorelines are a possible indication of tectonic deformation—caused either by earthquakes or slower movement along a fault. Our survey along Lake Iliamna traces a series of ancient beaches found high above the current beach (Fig. 5). These beaches formed earlier in the history of Lake Iliamna, after glaciers retreated about 12,600 C^{14} years ago (Stilwell and Kaufman, 1996, Detterman and Reed, 1973). As the outlet of the lake gradually cut downward, new shorelines formed below the oldest, highest shore. We surveyed the elevation of these shorelines by GPS, focusing on the highest shore, because it is the least ambiguous to correlate, and has had the most time to record deformation (Fig. 6). Though an earlier reconnaissance of these shores found no evidence of tilting or deformation (Kaufman and Stilwell, 1995), our data show that at least the highest shore is no longer horizontal (similar work: e.g. Pedoja et al., 2006; Kelsey, 1990).

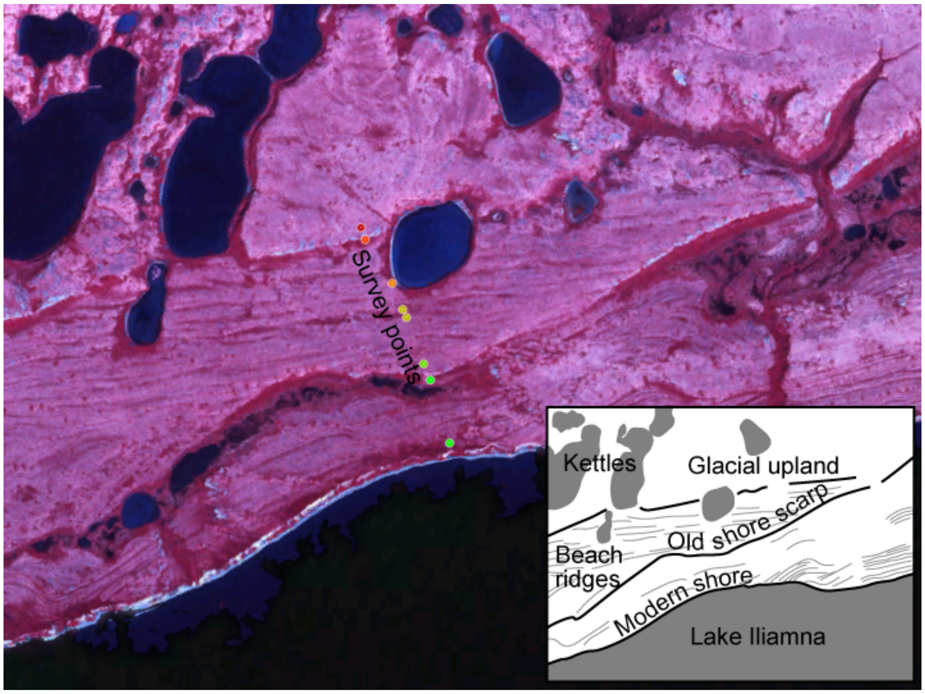

Figure 5: False-color infrared photo of the shoreline of Lake Iliamna. Ancient beaches stranded as the lake level declined over time leave beach ridges and long scarps running roughly parallel to the modern shore. In glacial uplands, and extending across the uppermost scarp and beach ridges, are glacial kettle lakes, showing that the upper shore formed when fragments of glacial ice still lay stranded in moraine and outwash. Interpreted map shown at lower right.

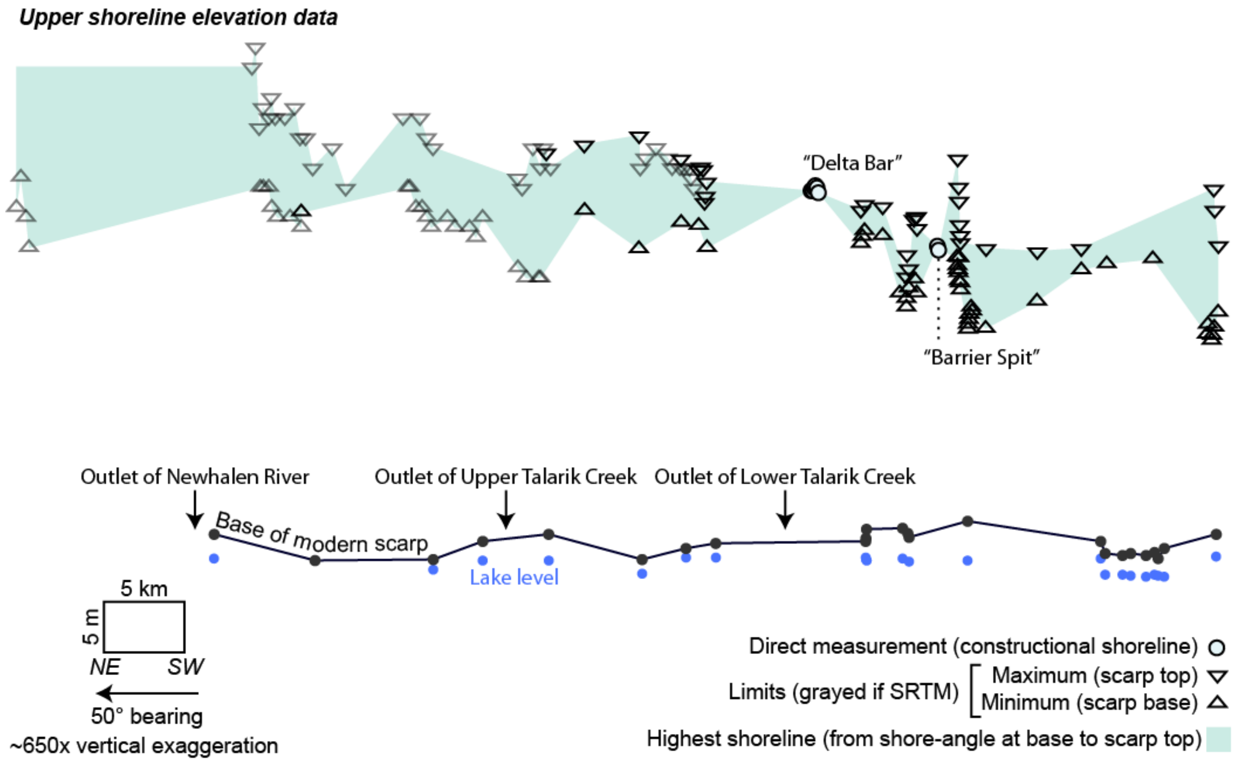

Figure 6: Surveyed elevations and SRTM elevation data tracing the highest shoreline above Lake Iliamna. The precise location of the highest, oldest shore can't be determined at most points, but it must lie between the highest erosional scarp base (shore angle) and the lowest surface unmodified by any shore action (scarp top). At two points (open circles) the upper shore was preserved, forming a beach ridge.

Tectonic deformation of an otherwise horizontal shoreline in an area just west of Lower Talarik Creek can explain the variation in elevation of the uppermost shoreline along Lake Iliamna (Fig. 7). Between about the village of Iliamna and Lower Talarik Creek, there is little change in the elevation of the highest, oldest beach, but just west of Lower Talarik Creek the elevation of the shore drops by about 6 meters. This lower elevation then extends further west all the way to the end of the lake. Our data cannot be explained with no deformation or with isostatic tilting (Fig. 8), presuming that specific unlikely special conditions do not explain away key data points (noted in Fig. 7). For discussion of alternative explanations for our survey results, see Appendix B.

This apparent deformation is spread over about 6 kilometers. If it is a result of motion on a fault, the fault does not break the surface, but is buried at some depth.

If this deformation is related to movement on the Lake Clark fault, it would indicate that the fault extends southwest beyond its mapped extent near Lake Clark (Haeussler and Saltus, 2004) at least to Lake Iliamna, and passes within a few kilometers of the Pebble prospect. Additionally this would imply that the Lake Clark Fault is active. If so, this would provide a straightforward explanation for the evidence of liquefaction we observed only a few kilometers from this inferred fault trace. However, it is also possible this deformation results from tectonic activity on a previously unidentified fault, and the timing of offset on the terraces may not correlate with the liquefaction events.

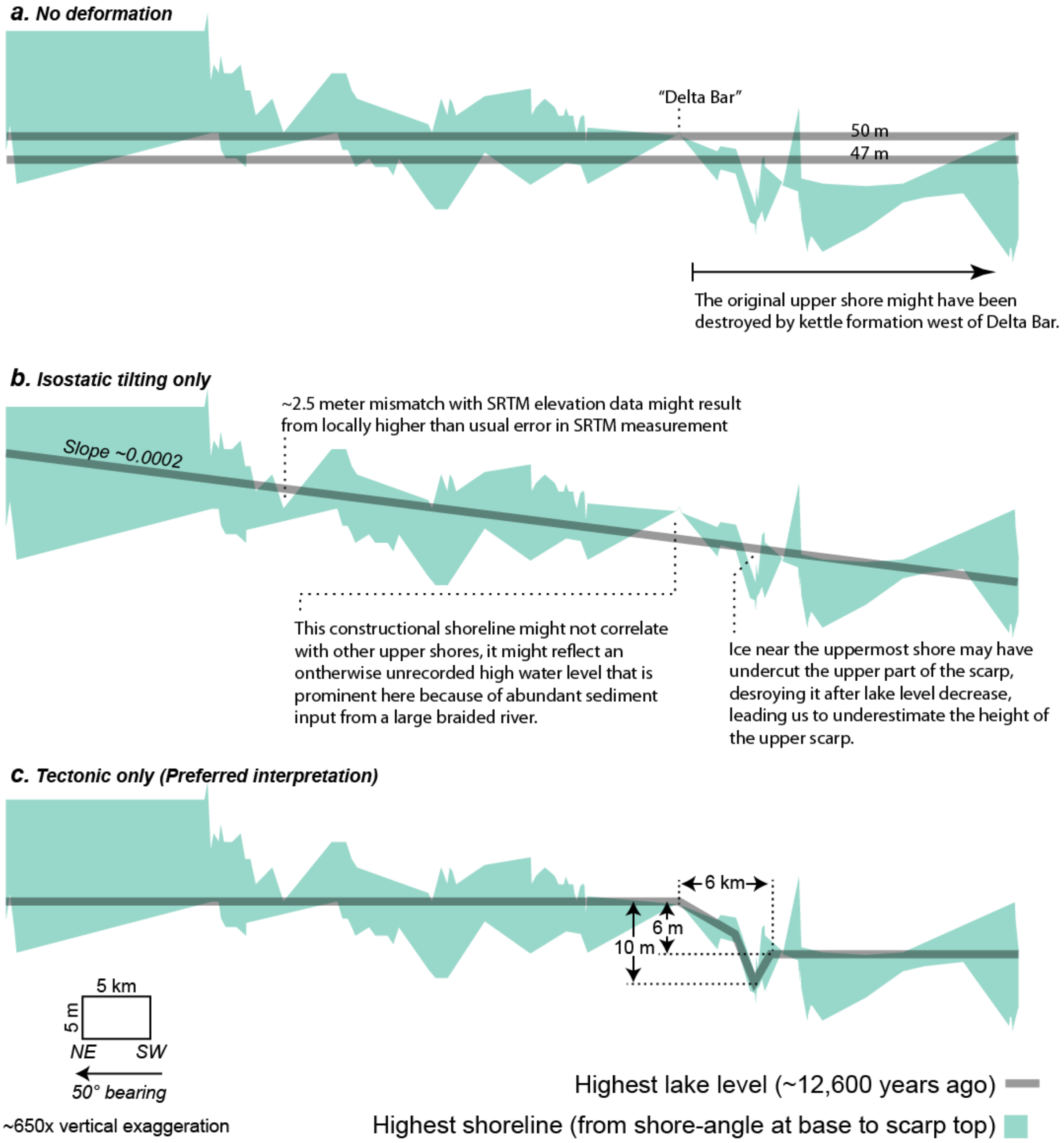

Figure 7: Ancient beaches running parallel to Lake Iliamna vary in elevation along their length. This variation shows the shoreline is no longer horizontal (a), and simple isostatic tilting (b) does not explain a relatively abrupt change in elevation, unless that change is an artifact of measurement irregularities. Localized tectonic deformation explains all of our data (c).

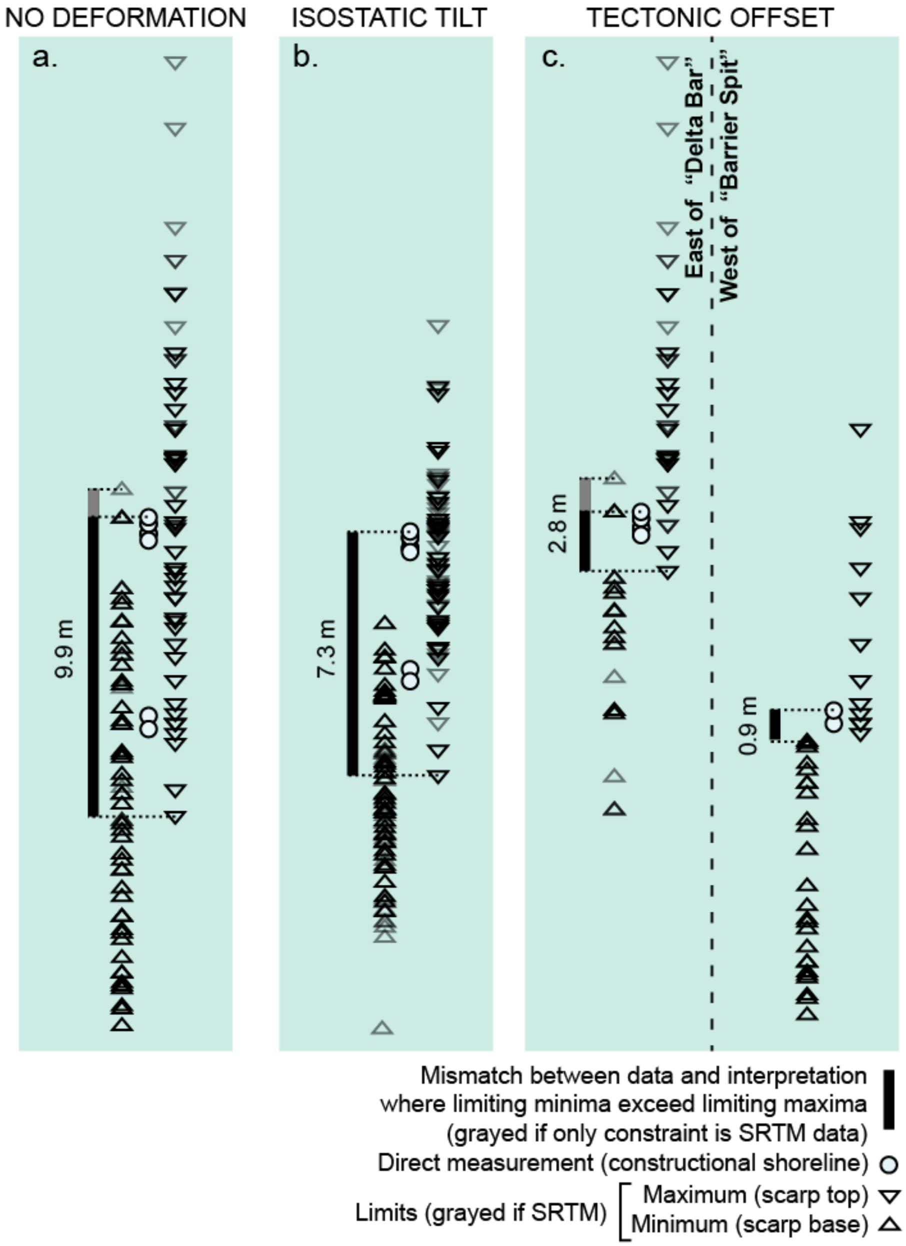

Figure 8: Mismatch between data and interpretations presented in Fig. 7. The mismatch range (black bar) is an overlap between limiting minima and limiting maxima, where scarp bases lie above scarp tops. For the tilting interpretation (b), the residual between a slope of 0.0002 and our data is plotted. Non-deformation (a) and isostatic tilting (b) have over twice the mismatch as for tectonic offset (c). For the tectonic offset hypothesis (c), points between "Delta Bar" and "Barrier Spit" are excluded, however these data can be completely explained assuming a subsided trough (graben) in the area of offset.

CONCLUSIONS

Our preliminary analysis of deformed sediments and abandoned lake terraces along shores of Lake Iliamna suggest a history of strong shaking and tectonic deformation. This deformation and shaking likely occurred within the past few thousand years, or at least since deglaciation of Lake Iliamna 12,600 years ago. Our data are consistent with activity on the Lake Clark Fault, likely on a trace that does not break the surface. Alternately, earthquakes may originate on some other, currently unidentified tectonic structure.

PURPOSE

This research was funded by the Center for Science in Public Participation. A draft was released to the EPA for their July 23, 2012, Watershed Assessment comments deadline. This report was updated for submission to Keystone expert panel in early October 2012.

FURTHER RESEARCH

Our research is ongoing. We will be continuing our analysis and data collection in the coming year. Pending our full paper to be submitted for peer review, additional preliminary analysis and data will be available here:
http://www.groundtruthtrekking.org/pebble-mine-seismology-earthquake-science/

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APPENDICES

Purpose of these Appendices

In response to a request for scientific results relevant to the review of Pebble Limited Partnership's Environmental Baseline Documents, we are releasing these preliminary results. Appendix A presents a detailed discussion of possible origins for liquefaction features. Appendix B presents details of our analysis of elevated shorelines.

Appendix A: Liquefaction evidence and possible interpretations

Overview

We documented an extensive "sand volcano" deposits including liquefied source sediment, sand dikes, sills, and surface deposits, revealed along over 20 meters long section of lakeshore bluff (Fig. 2). Similar liquefaction features as large as this sand volcano are rare outside of a seismic context. They are typically associated with very strong shaking (e.g. Martin & Bourgeois, 2012; Waller, 1966).

Additionally, we identified liquefaction of lake sediments at six other sites spread over multiple kilometers of Lake Iliamna coastline. The bluff outcrops along Lake Iliamna's shore also expose glaciotectonic sediment deformation and cryoturbation, which we positively identified throughout the area. There is some potential for confusion between liquefaction and these other modes of deformation. However at the sites we identified cryoturbation could be eliminated because they formed underwater, and were deep below the subaerial soil by the time they emerged. Also, glaciotectonic deformation could be eliminated because each site lacked a consistent sense of shear, and was characterized by fluid flow structures rather than localized failure of sediment under high confining pressure. This does not imply the liquefaction is co-seismic. For example, it might arise as a result of rapid sedimentation, stress from storm waves or lake tsunamis, mass movement, impact from lake ice in shallow water, or stresses induced during glacial advance (Figure 9). Therefore, even though many liquefaction features we observed are consistent with strong earthquake shaking, further documentation of the nature and context for deformation is needed to definitively eliminate other possibilities, especially in the cases other than the sand volcano.

Figure 9: Sediment deformed by liquefaction at a bluff about 25 km northeast of the sand volcano. In this case it is difficult to constrain the cause of liquefaction. Some sediment in this area may have been overrun during a glacial advance, so it is possible, for example, that it liquefied as glacial ice asymmetrically loaded the sediment surface.

Physical structure of the Sand Volcano

The sand volcano occurred late in the stratigraphic sequence recorded in the Lake Iliamna bluffs. The apparent source was sandy lake sediments often dominated by climbing ripples, which transition upward into gravel beach deposits, capped by peat. We interpreted this sequence to record upward shallowing from lake-bottom turbidites to wave transported beach sediments, ultimately capped by peat when lake-level dropped below the beach top. A thin layer of organic-rich aeolian sand overlies the peat, just below the sand-blow deposit (Fig. 3). The sediments overlying the sand blow are dune sands that are part of an active dune system. The deposit is loosely consolidated, lacks glaciotectonic deformation structures, and is overlain by no major unconformities, so we believe it post-dates the Iliamna Stade glaciation 12,600 years ago (Stilwell & Kaufman 1996). Given this, it is likely that the deposit is mid to late Holocene in age. We are submitting samples of peat (extracted from below the sand volcano) and buried alder root (extracted from above it) for radiocarbon dating to better constrain the timing of this event.

For the purpose of this discussion, we refer to the entire structure including deformed source sediment, dike, and surface deposit as a "sand volcano" while we call the surface deposit itself a "sand blow."

Source sediment: The apparent source was a thick deposit of extensively deformed lacustrine sediments, at least 2 meters under the paleo ground surface. At the top of this deposit is a large sill of homogenized, silty sand. The sill hosts silty rip-up clasts which range in size from less than centimeter to tens of centimeters in size. The rip-ups are predominantly from the lake-bottom deposits (Fig. 10). We also identified two rip-ups of beach sediment, which probably sunk through the liquefied sediment. Feathery, branching elutriation structures and granule-sized silty clay rip-ups are common in the largest body of homogenized sediment.

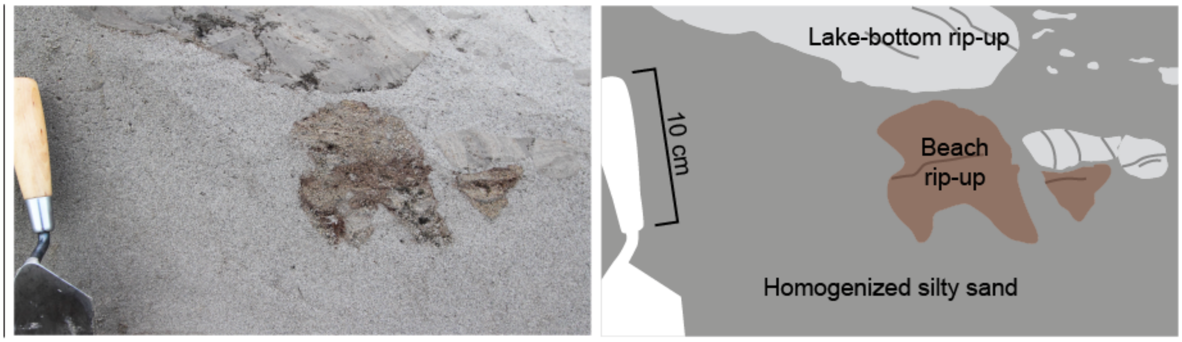

Figure 10: Rip-ups suspended in homogenized sediment. The beach rip-ups originated about 2 meters higher in the overlying unit, while the lake-bottom rip-ups are remnants of the original sediment homogenized by liquefaction. Granule-sized rip-ups too small to see in this photo are common throughout the homogenized sand.

Injection features: Extending up from the source sediment are tabular dikes that branch and form sills in peat near the paleo-surface, 2-3 meters above the source (Fig. 2, 3). The dikes include elutriation structures, and are discontinuous due to connections outside the plane of the cleaned outcrop.

Sand blow: A laterally continuous sand blow deposit atop peat and aeolian sands extends 15 meters or more north from the top of the primary dike. At the furthest exposure from the vent, the sand blow is at its thickest – over 50 cm thick. This deposit is distinct from the aeolian sands it underlies in that it is finer and siltier, and it includes granule-sized silty clay rip-ups. It is grayer (less oxidized) than the aeolian sand where it is thick enough to have not been fully weathered at the surface.

We did not expose the full extent of either the large buried sill (labeled "Homogenized silty sand" in Figure 2), or the surface blow. The horizontal extent of the homogenized sill was greater than 10 meters, and that of the surface blow was greater than 20 meters.

Possible Origins

Artesian Springs

Artesian springs require strong hydraulic pressure to be applied through the source sediment, forcing water to the surface. The sand volcano originates in a large lacustrine sand deposit. We did not find the bottom of the lake sands, but they extends downwards for at least 5 meters, and are horizontally continuous for hundreds of meters. These permeable sands allows the lateral movement of water, and would not lead to a localized artesian spring.

Additionally there is little relief to develop an artesian head. The uplands above the site are only

20 meters higher, are generally flat inland for many kilometers. And despite undercutting of this deposit by about 13 meters, there is no modern bluff-base spring.

Compaction Induced Dewatering

Syndepositional or Near-term Postdepositional Dewatering

The liquefaction that produced this feature clearly post-dated source deposition by centuries to millennia. The injection features (dikes, sills) cut through younger lacustrine and beach strata, a peat layer, and into aeolian sands. The deposition of up to 50 cm of peat alone likely represents 1000 years or more. Absent a mechanism for cracking the ground surface (such as mass movement), dewatering would be expected to take the form of tubular dikes (Neuman-Mahlkau 1976, Burne 1970). In contrast, the dikes we observed are tabular in shape

Long-term Postdepositional Compaction-Induced Dewatering

Long-term compaction-induced dewatering also seems unlikely. The sediment would need to have remained saturated and uncompacted for a long period of time, sufficient for the deposition of more lacustrine sediments and beach sediment over it, followed by the development of a peat bog or lagoon. For a compaction-induced dewatering even to have occurred at that point, presumably a major stimulus would have needed to agitated the sediment.

Also, during the long period of time between source deposition and sand-volcano formation, the deposit would have experienced shaking from multiple distant earthquakes, likely including more than one subduction-zone earthquake. If the deposit had been unconsolidated to the point where it was vulnerable to liquefaction without any impulse, it would presumably have liquefied under the influence of one of these earthquakes.

Normal Lake Processes

Presumably, the area was at various times battered by storm waves from Lake Iliamna, while the lake was at a variety of different elevations. Alfaro et al (2002) identifies clastic dikes, once considered to be of seismic origin, as resulting from storm waves, on the basis of an examination of nearby tempestites. Obermeier (1990) notes an abundance of small liquefaction features described as coseismic in the literature, quite likely resulted from normal shoreline processes.

The sand volcano feature clearly cuts the soil profile (peat) and appears to be of a scale larger than is to be expected from wave-induced liquefaction (Obermier et al, 1990). The peat layer may have formed in a backshore lagoon environment, or further inland. The presence of the peat layer, the lack of lake sediments atop it, and the overlying aeolian sands indicate that this was probably above beach-level for some time before the liquefaction event, and thus not vulnerable to wave impact or other lake processes like ice-shove.

The source unit would have been subjected to long periods of substantial wave impact when it was immediately overlain by a beach. However, liquefaction does not appear to have occurred during this time. There are no identified sand blow deposits or older injections. It is unlikely that sediments susceptible to liquefaction in protected, backshore environment would not have liquefied while they underlay an active beach.

The other lake process to consider is ice loading. Lake Iliamna supports large seasonal accumulations of ice. Lake-processes can lead to large mounds of ice debris in nearshore waters and along the beach. This origin has the same fundamental weakness as wave-induced liquefaction: it does not explain how the susceptible sediments survived unliquefied when they were buried beneath the nearshore and beach environments, and therefore subjected to their maximum ice loading.

Landslides

"… tabular, sand-filled fissures that widen downward and connect to a sand unit that extends horizontally for tens to hundreds of meters are probably dikes associated with earthquake-induced liquefaction, although the possibility of a non-seismic landslide origin must be considered." - Obermeier et al, 1996

A landslide is the most plausible remaining alternative origin other than earthquake-induced liquefaction.

However, if the bluff sediment was susceptible to large landslides, we would expect to see evidence of such slides along the many kilometers of steep bluffs. The bluff where we documented the sand volcano is dominated by nearshore lacustrine sands and silts, but also include clay-rich moraine deposits, beach deposits, aeolian sands, and soils. Currently, the bluffs stand in steep exposures, often over the angle-of repose. Although sloughing, debris flows, and block spalling are extensive along the bluffs, we did not observe any evidence of large rotational slumps or lateral spreads.

The continuous outcrop extending either side of the sand volcano would be likely to expose evidence of any possible slide cause for the sand volcano. A liquefaction feature like the sand volcano would be expected at the toe of a slide where compression could inject sand upward, or within the slide block where bending and shaking could cause liquefaction. At the headwall of the slide, extension would leave open fissures, rather than fissures that deeper sediment is forced out of. Therefore evidence of a slide cause for the sand volcano should persist in the current bluff. We did not find any normal faulting or offset stratigraphy, which we would expect if this were part of a landslide block. This suggests that, if a landslide were the culprit, it would have to be a very large slide with a subtle surface expression, or some unusual process must have driven venting near the headscarp, and the rest of the slide has eroded away. A lateral spreading landslide is a possible culprit, the other evidence of which has been either been erased by shoreline erosion or entombed by backshore dunes. Sediment venting at the headscarp of a lateral spread is quite plausible. However, lateral spreads themselves result from liquefaction, typically of a seismic origin. Lateral spreading was extensively identified in the 1964 earthquake (Walsh, Combellick & Black, 1995).

While a landslide origin has not been conclusively eliminated, there is no evidence to suggest that interpretation. Further field investigation will include a search of the area for evidence of an associated paleo-landslide, such as normal faulting and disrupted strata.

Earthquake

The sand volcano is consistent with what we would expect from a coseismic liquefaction event (Obermeier 1996, Walsh et al 1995). The depth of the tentatively identified source unit, at 2 meters or more, is consistent with the common depth for seismically generated liquefaction features.

Criteria for Seismically-Induced Liquefaction	
***From* Obermeier, 1996**	**Sand Volcano**
"There is evidence of upward-directed, strong hydraulic force that was applied suddenly and was of short duration."	Upward-thinning injection dikes, injection into the peat layer, and the structureless nature of the sand blow suggest a strong, brief, upward-directed hydraulic force.
"Shape, width, and depth of the feature is consistent with historical observations of seismically induced liquefaction features."	Yes.
"The feature is in a ground-water setting where a suddenly applied, strong hydraulic force of short duration could not be reasonably expected except from earthquake-induced liquefaction."	This is the case, as discussed point-by-point regarding other possible origins.
"Where evidence of age is present, it should support the interpretation that the features formed in one or more discrete, short episodes that individually affected a large area and the episodes were separated by long time periods during which no such features formed."	In a cursory investigation, we identified six other sites with probable liquefaction features along the Lake Iliamna coast. At two sites (including the site discussed here) there were at least two episodes of liquefaction. This evidence shows that the sand volcano is not the sole evidence of liquefaction. However we do not have data to estimate the relative timing or likely causes for other liquefaction sites.

The minimum size earthquake to cause some liquefaction in susceptible sediment is probably M 5.5, although in rare cases it is documented with weaker earthquakes (Obermeier 1996). It is unlikely that a distant earthquake (e.g. on the aleutian subuction zone interface 200 km away) would cause liquefaction of the scale we observed in the sand volcano, though distant earthquakes is a possible cause for some less dramatic liquefaction we documented elsewhere. Any explanation that relies on the sediment being extremely susceptible to liquefaction is implausible because the sediment compacted over centuries and presumably during multiple episodes of shaking from distant earthquakes. Therefor, if this feature is the result of an earthquake, it most likely results from motion on a nearby fault. Its proximity to the terrace deformation we documented is consistent with motion on a buried fault under that deformation being the cause.

Appendix B: Shoreline Terraces and Terrace Deformation

Traces of past lakeshores can put limits on vertical isostatic or tectonic deformation, because those lakeshores were presumably originally horizontal. We focused our surveying on the uppermost shoreline, because it is the most easily identified as a single, originally horizontal, paleo-shoreline. Here we discuss data collection, possible sources of surveying error, and three possible explanations for our results.

Data

The accuracy of our analysis relies both on accurately identifying geomorphic traces of past shores, and on accurately measuring their elevations. We relied on both field observations and aerial and satellite ortho imagery to identify geomorphic features, and measured elevations during field surveys using post-processed Trimble GeoXH GPS data. Our field surveys spanned three expeditions in 2010, 2011, and 2012. We additionally extracted elevations from Shuttle Radar Topography Mission (SRTM) data.

AHAP imagery is publicly available through the USGS (http://earthexplorer.usgs.gov/) and we commissioned ortho-mosaics assembled from this imagery from UAF's mapping office (available upon request.)

Our survey data is available in an online Google Fusion Table (https://www.google.com/fusiontables/DataSource?docid=1_WFU1oQ0VpJLFnRrCcu99i-rss2pxgSIlXy8eg). Data columns include location and elevation info, as well as notes related to our classification of each site.

SRTM elevation data for Alaska is publicly available from the USGS (http://dds.cr.usgs.gov/srtm/version2_1/SRTM1/Region_07/). We processed this data using QGIS, an open-source GIS, and custom-made Python software. To minimize error, we chose only elevations from blocks of contiguous points at the base or top of scarps (Fig. 11)

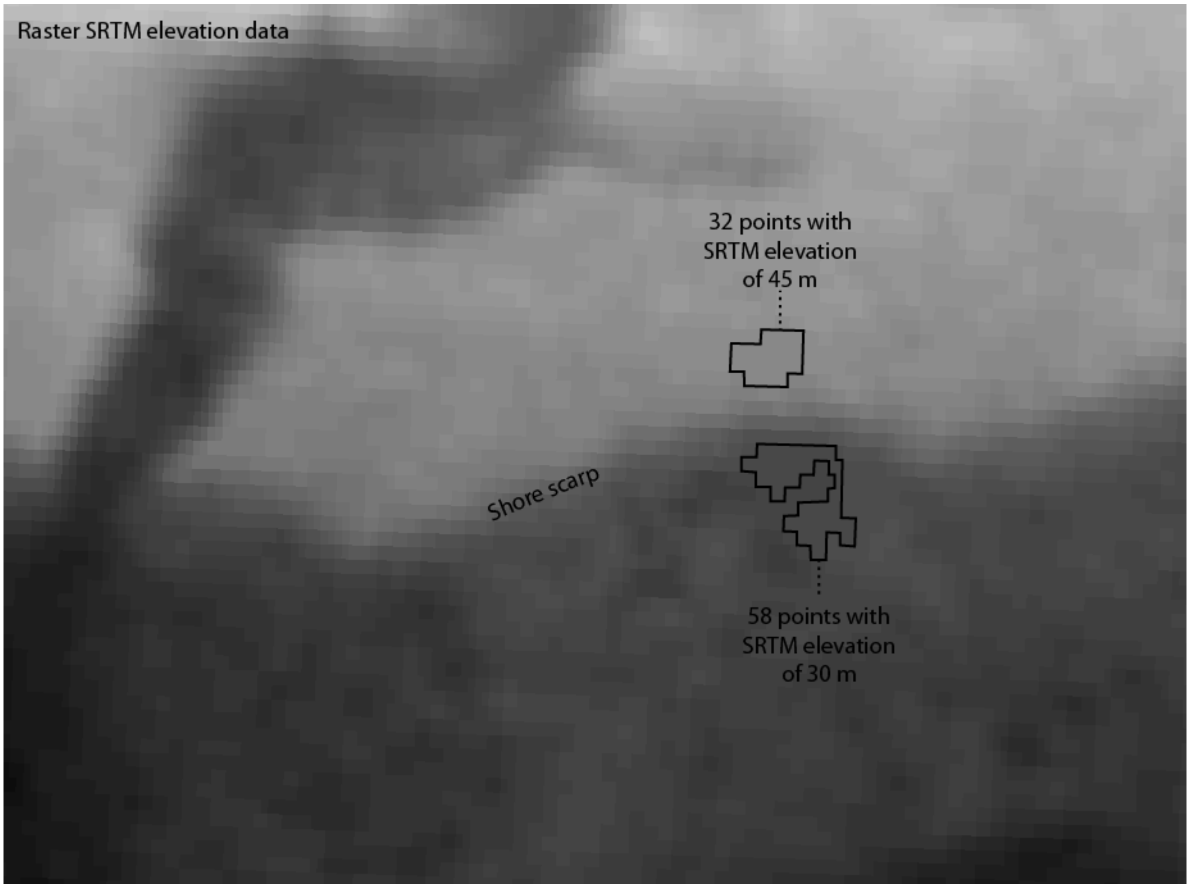

Figure 11: To minimize error, we selected only elevations from blocks of contiguous points all with the same elevation, for example 32 values at the top of the scarp in this crop of SRTM data, and 58 from the bottom. This approach should reduce random error, and also reduce the chances of selecting areas with locally high variation in actual elevation that might be modified by dunes or other processes. We have not quantitatively assessed the error given this selection method, but it is likely substantially less than the 1.8 m 1-σ error for our surveyed points (Fig 13).

Sources of Error (Fig. 12)

Measurement error: Though vertical error for SRTM data in North America as a whole is 7.0 meters (Rodriguez et al., 2006), we found that in areas without tall vegetation in our survey area the 1-σ error was only 1.8 m (Fig. 13). Our survey data generally has precision well under 1 m, as estimated by Trimble post-processing software. In most cases, our elevation data is precise enough that there is greater uncertainty in geomorphic interpretation than there is error in elevation measurements.

Geomorphic uncertainty: We base our interpretation on the estimated elevation of the highest continuous shoreline along Lake Iliamna. We make this estimate by measuring the elevation of geomorphic features, however depending on the particular feature and setting there are various uncertainties in the relationship between our measurement and the actual original lake level.

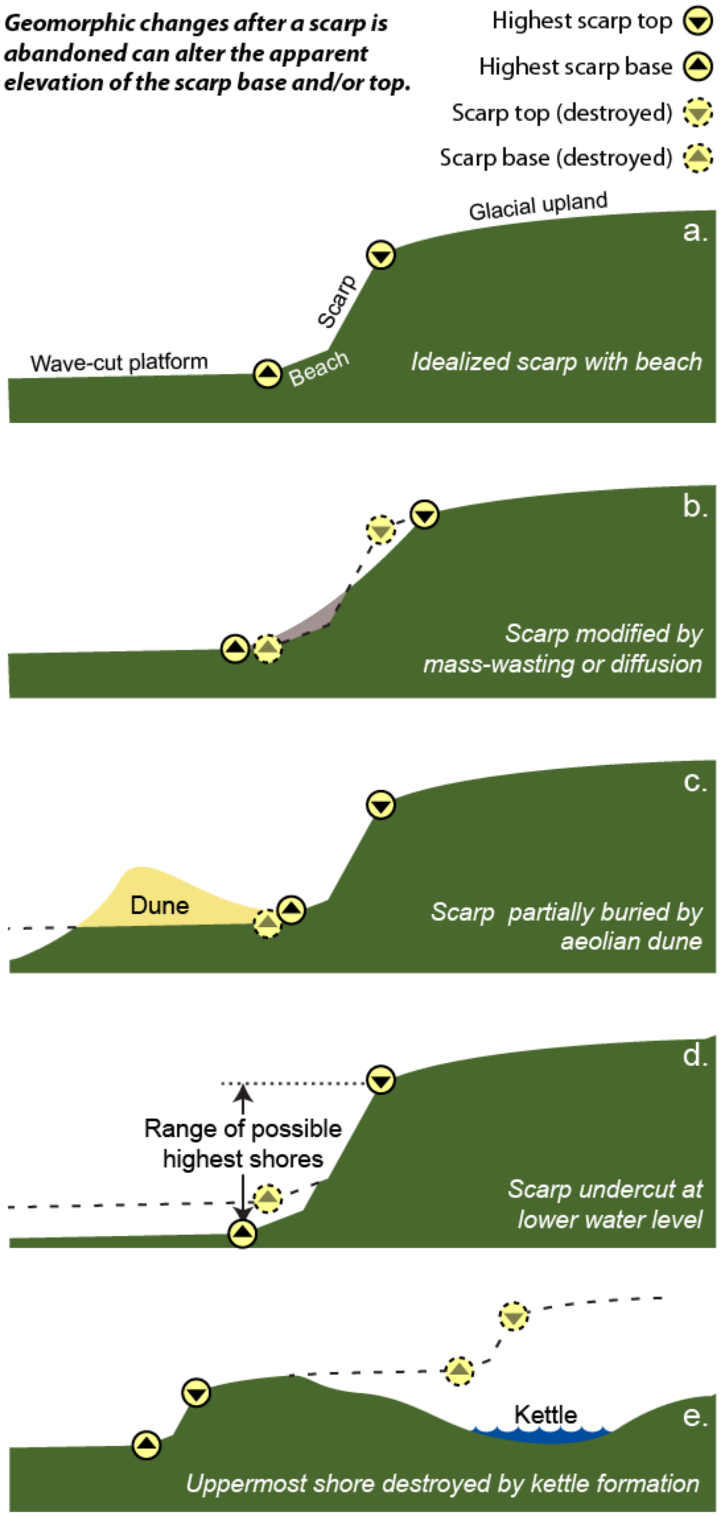

Figure 12: Modification of a scarp following its formation can alter its apparent elevation in a number of ways. Ideally, a scarp extends from a concave break in slope at its base to convexity at its upper limit (a). Diffusion (b) can modify this and make the limits of the scarp much less distinct, but will not change the elevation of the base of the scarp (shore angle) much as long as the wave-cut platform is fairly flat. In some areas dunes built from wind-scoured sand in lower scarps buries the scarp base (c) raising their apparent elevation. However the largest uncertainties occur when a scarp may have been undercut after its formation, either by formation of a lower scarp (d) or by kettle formation as buried ice melts (e).

At most sites, we surveyed the base and top of a scarp extending up from the uppermost shore. If this highest shore formed during a period of constant lake-level followed by an abrupt decrease in lake level, then this shoreline should represent a single water-level. However, gradually descending beach-ridge plains show that lake level declined steadily from its peak, at least some of the time. The elevation of the base of the upper scarp is highly variable, showing that in some places the scarp remained active as water level decreased, while in other places the scarp was quickly abandoned. As a result, the base of the uppermost scarp can only be viewed as a limiting minimum. Fortunately the top of such scarps provide a limiting maximum – if lake level was ever higher it would have left a trace above this scarp. Thus the height of the scarp covers the range of possible elevations for the paleo lake-level.

The base of scarps can also be obscured or modified by aeolian or mass-wasting processes. This can shift the apparent base of scarp upward. To reduce this error, we generally worked with the first deflection upward from near-horizontal beach plains, minimizing this tendency to overestimate our limiting minimum.

In a number of localities, the uppermost scarp is cross-cut by large kettles, showing that when the lake abandoned this scarp, not all of the glacial ice had melted. In some cases the uppermost scarp could have been completely destroyed by this process, leading us to mis-correlate a lower scarp with the uppermost scarp elsewhere.

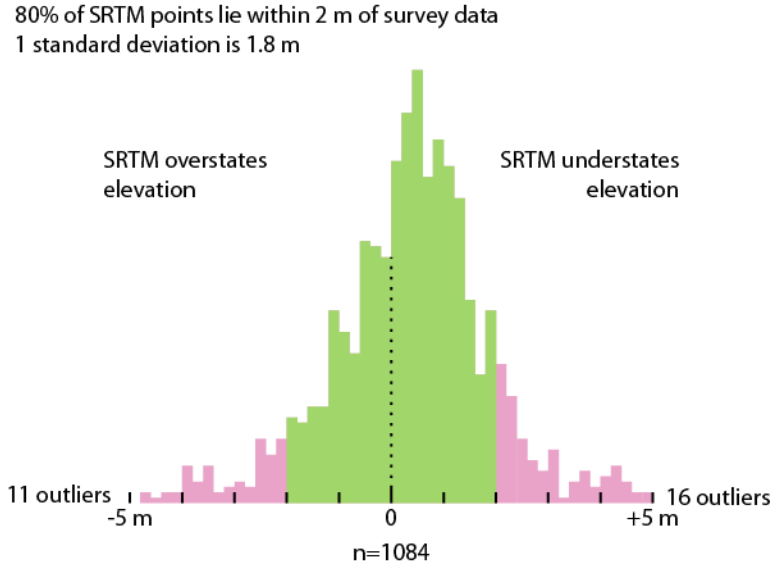

Figure 13: For 1084 of our survey points, SRTM data was approximately normally distributed with a standard deviation of 1.8 m, and a mean of under-estimating surveyed elevation by 0.36 m. SRTM elevations were interpolated to survey points using a Triangular Irregular Network (TIN). We used all survey points where post-processed error was no more than 20 cm, and where the surface was not noted to be either fluvial or aeolian, because these survey points tended to be on local extremes that wouldn't be representative of the SRTM measurement. Our survey points are neither uniform nor random, so local variability in the quality of SRTM data could substantially impact these results. Our approach for extracting scarp base and top elevations chose blocks of consistent data, hopefully minimizing the error revealed here (Fig. 10).

Possible Explanations for variation in terrace elevation

Three simple scenarios might explain the apparent elevation of the uppermost shoreline along Lake Iliamna.

1. **No deformation has occurred (Fig. 7a, 8a)**. Lake level has dropped consistently. Apparent deformation is due to interpretation errors.

2. **Postglacial crustal rebound (Fig. 7b, 8b).** The landscape has tilted, as a result of differential rebound in the crust after glacial retreat.
3. **Tectonic deformation (Fig. 7c, 8c).** A blind fault has vertically offset the surface west of Lower Talarik Creek.

Of the three scenarios, only tectonic deformation can explain all of our survey results. However, it also is possible that isostatic tilting in combination with a specific series of geomorphic misinterpretations explains the apparent deformation (Fig. 7b). Some combination of isostatic tilting and tectonic deformation is also a possibility, but given that tectonic deformation with no tilting is sufficient to explain nearly all the data, we did not explore this more complex scenario.

No deformation (Fig. 7a, 8a)**:** Our survey data is not well explained by a no-tilting hypothesis. We consider two scenarios – an uppermost water level at 47 meters, and at 50 meters. An upper water level of about 47 meters above MSL corresponds to much of the scarp base east of Lower Talarik Creek. However, this elevation falls over 2 meters below a clear constructional shoreline ("Delta Bar"), and falls above the top of the uppermost scarp in many places west of Lower Talarik Creek.

If the shoreline were at 50 meters, putting it in line with Delta Bar, it would fall even farther above the western scarps, but this scenario might be viable if the shorelines we surveyed to the west are a shoreline from a later (and therefore lower) time.

The presence of a higher shore is unlikely. No higher shore is apparent in imagery despite excellent visibility in an area with little vegetation other than tundra. Evidence of a higher shore could conceivably have been erased if that shore were built completely atop ice, and collapsed into kettles after lake level decreased. However, kettle forms are absent in a number of stretches of this apparently lower shore, including one nearly 5-km long section of rolling glacial upland.

This no-deformation hypothesis was advanced by Kaufman and Stillwel, 1996.

Isostatic tilting (Fig 7b, 8b)**:** We explored the possibility of tilting resulting from isostatic rebound. A consistent tilting slope of about 0.0002 (1 meter elevation change per 5 km distance) best explains the overall trend of our data, in this particular projection plane. Shoreline elevations are lower to the west, nearer the edge of the former extent of Iliamna Glacer. This is consistent with isostatic rebound, which would likely decrease toward the limit of glaciation.

This simple isostatic rebound scenario does a poor job of explaining variation in paleo-shoreline elevation observed just west of Lower Talarik Creek. Two locations where we surveyed constructional upper shores would imply a far steeper tilt than 0.0002. The slope is locally higher still, and would be even less consistent with the overall trend of only slightly lower elevation to the west.

Figure 7b depicts a scenario where each observation that fails to fit the isostatic tilting hypothesis is explained by a series of site-specific error or misinterpretations. A low scarp-top observed west of the Newhalen River in SRTM data is assumed to be bad SRTM data. A constructional shore west of Lower Talarik Creek is assumed to be unrelated to scarp formation, and thus noncorrelative. And a low point further west is assumed to be the result of mis-correlation due to undermining of the upper shore by melting kettle ice.

Barring this particular unlikely combination of errors and misinterpretations, isostatic tilting does not explain the shoreline elevation data.

***Tectonic deformation (Fig 7c, 8c)*:** All the survey data can be explained if the highest shoreline is offset by tectonic motion along a blind fault.   The vertical offset would be roughly 6 meters, with a local depression nearby, where the shoreline drops to 10 meters below its level further east. This depression could be a buried graben following the main fault trace.