Reply to Engel, Kindler, and Godefroid's comment on "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming is highly dangerous" *by* J. Hansen et al.

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GENERAL COMMENTS

We appreciate the comments of Engel, Kindler, and Godefroid, but disagree with major components of their arguments.

There is near consensus that the megaboulders on Eleuthera were transported by giant waves around the end of the late last interglacial (end-Eemian; late MIS 5e), and we welcome validation of this conclusion by our colleagues. Our research has also documented a multi-meter rapid upward shift of global sea level during the same late MIS 5e interval (Neumann and Hearty, 1996; Hearty *et al*., 2007; O'Leary *et al.*, 2013). We are currently engaged in a debate on whether a late Eemian tsunami, bank margin collapse, or superstorms (as per Hearty, 1997; Hearty *et al*., 1998) were underlying causes of boulder transport. However, if all the evidence is considered, it is the *connectivity* among the boulder, runup and chevron deposits and structures (Fig. 1), in association with other definitive evidence of extreme oceanic events that constitutes the strength of our position.

Given that waves transported megaboulders on North Eleuthera during the late Eemian and that global sea level rose rapidly several meters at the same time, it *simply does not follow* that hundreds of kilometres of adjacent low-lying platform areas of the Bahamas would completely escape their fury and force, leaving no trace of these giant waves. Engel *et al* make the much less plausible proposition that the neighboring chevron ridges and runup (and the unique sedimentary structures within them) located only a few km from the wave-tossed boulders, were formed by the unrelated and fairly banal processes of wind and rainfall.

Several key points raised again here by Engel *et al.* (eolian origin of the chevrons and "rain-induced fenestrae" (Bain and Kindler, 1994; Kindler and Strasser, 2000)) were rigorously and specifically addressed in Hearty *et al*., 2002, which was not cited in their comment. We defend our position that we did not feel compelled to repeat or re-reference all the nuance discussions on a number of topics given the very broad scope of our ACPD paper.

Superstorms, super winds, and the broad fetch across the North Atlantic would have been a critical combination for the generation of long-period waves required to explain the trilogy of features (boulders, runup, and chevrons) we describe (Fig. 1). A coherent coastal gradient of sedimentological features coincides with distance from the coast and increasing elevation, reflecting the attenuating force and 'reach' of the waves. On rocky, steep coasts, megaboulders were catapulted by giant waves. On older, eastern-facing built up dune ridges, waves ran up to over 30-40 m elevation, leaving meter-thick to thin, repeated sequences of fenestral beds, often associated with scour structures (Hearty et al., 1998). Across kilometres of low-lying flats, chevrons with multi-meter thick, tabular fenestral beds (Fig. 2AB) were formed.

Our modeling results indicate that the presence of cold waters in the North Atlantic creates a blocking high pressure system in that region which coexists with very warm and humid conditions immediately to the south. This generates strong pressure gradients that severely strengthen the prevailing northeasterly winds in the mid-Atlantic and subtropical Atlantic regions. At the same time, however, it yields favorable conditions for the creation of superstorm types of systems, which can develop when a tropical storm is blocked by a high pressure ridge and is eventually swept aloft by the circulation of a mid-latitude baroclinic storm, which is further strengthened by large temperature contrasts. An example of such an event is the 'Perfect Storm' that formed off the coast of Newfoundland around Halloween of 1991, which generated high winds and extremely large waves in the North Atlantic, but also large destructive waves under calm wind conditions much further south in the Bahamas and the Caribbean Sea (https://en.wikipedia.org/wiki/1991_Perfect_Storm).

The end-Eemian is also associated with a massive flux of marine carbonate sediments from the adjacent shelves to the shore by water and wind (Neumann and Hearty, 1996), such that most of the present day Bahamian island topography is a product of this depositional interval. Wind was an important agent in the remobilization the massive flux of marine-generated ooid sediments transported to the islands at this time.

Wind was ever present, but torrential rainfall simply cannot explain the distribution across the Bahamas, gradient, concentration, structure, or thickness of fenestral beds in late Eemian strata. If seasonal rainfall were a *significant* agent in the formation of fenestrae in dunes, such features would be common and observable in all eolian beds, regardless of age. This is clearly not the case. In Engel *et al*'s Fig. 1, storm waves surging on to the upper beach to fore dune interface while sea level was a few meters lower than present 5-6 ka ago could readily explain the presence of fenestrae. Wind ripples forming on storm beach sets would be a normal occurrence. Intertidal beach bubbles are formed on most sandy beaches of the world and are the pervasive and diagnostic sedimentological standard of waves worldwide in fossil beach deposits, while only scanty, obscure, and dubious published reports of rainfall-induced fenestrae are available.

Documentation of a significant volume of evidence collected over past decades points to extremely powerful events associated with the close of the late Eemian. That evidence suggests that the events of the last interglacial are not fully guided by uniformitarianian principles that would readily translate to our present Holocene interglacial.

Parsimony and Occam's Razor. It is far too random and chronologically coincidental to argue that the trilogy of evidence is caused by unrelated processes. If giant, long-period waves lifted 1000-ton boulders onto and over the coastal ridge, then the same waves must have also impacted large areas of the eastern Bahamas, for which there is abundant documentation. A common, synchronous, and non-random set of superstorm-related processes best explains boulder transport by waves, emplacement of runup deposits on older built up ridges, and chevron formation across lower areas of the Bahamas.

SPECIFIC COMMENTS:

RE: Eolian control of chevrons p. C6271.

The presence of a few eolian structures does not make the chevron ridges in the Bahamas parabolic dunes, rather it merely suggests the deposits were sub-aerially exposed and wind blown during periods of relative quiescence. Unlike parabolic dunes, the chevron ridges are dominated by thick, low-angle (<10°), seaward-dipping, oolitic strata (Hearty et al., 1998, Tormey 1999; Fig 2A-C). Foreset beds, diagnostic of migrating parabolic dunes, are absent from many chevron ridges (Fig. 2AB), supporting their formation primarily by waves.

Furthering the distinction, fenestral porosity in low-angle bedding is prevalent *throughout* chevron ridges, occurring in repeated cycles of cm-thick beds that onlap the underlying strata, and often comprise *meter-thick* fenestrae-rich packages that can be followed in outcrop for tens of meters (Fig. 2AB). Finally, the cross-stratification, rhizomorphs, and land snails (living surfaces would also develop on chevrons between storms) cited by Engel et al. as evidence of eolian control have very limited extent in the chevron ridge examined by Kindler and Strasser (2000) on north Eleuthera, occurring only in a few small (1-2 m^2) patches (Fig 2A). Figure 3 provides an excellent photographic example of plant cast and mold traces, covered with onlapping, planar, fenestral beds, and scour wave structures in late Eemian strata at Old Land Road, Great Exuma Island (Hearty et al., 1998).

Given the abundance of sedimentary structures consistent with repeated inundation by waves, and limited eolian structures, particularly lacking the essential foreset beds diagnostic of the core of migrating dunes (Hunter, 1977), it is evident that the chevron ridges are lowland storm-beach ridges, rather than parabolic dunes (Table 1, p. 318 in Hearty et al., 1998; Tormey and Donovan, 2015). When the storm is up, waves dominate and form the thick, tabular, fenestrae-rich beds. When the water recedes, the deposit is sub-aerially exposed to wind and biological processes, only to be inundated by waves during the next storm episode.

RE: Rainfall origin of fenestrae. Top p. 6272.

In addition to the chevron ridges, fenestral porosity has been reported in Eemian eolianites at multiple hilly localities on islands throughout the Bahamas, in some cases up to +43 m (Wanless and Dravis, 1989; Hearty et al., 1998; Tormey and Donovan, 2015). A torrential rainfall origin for the fenestral porosity was suggested (Bain and Kindler, 1994; Kindler and Strasser, 2000) as an alternative to formation by large waves, and directly challenged by Hearty et al. (2002). Further, Tormey (1999) showed that the greatest concentration of fenestrae is found within the lowest angle, backset and topset beds of the Eemian eolianites *and* chevron ridges, but not the high-angle foresets. It is highly unlikely that torrential rain could achieve the sheet-flow conditions necessary to form fenestrae on Atlantic-facing bedding slopes less than 10°, while not appearing in the few steep foresets one does find. It is the forward momentum of wave swash that gives waves the ability to climb hillsides and achieve sheet-flow on low-angle slopes of dry sand, trapping air between the incoming wash and the interstitial water below (Dunham, 1970). In Figure 3, the fenestral beds are clearly lapping up and over older strata (each truncation level is up slope from the previous), reflecting rising water and increasing energy.

Most importantly, the character of fenestral bedding in both the Eemian chevron ridges and run-up deposits changes with increasing elevation and distance from shore, as does the abundance and geometry of fenestral pores: 1) at low elevations and in proximal locations, the chevron ridges are dominated by thick, continuous, tabular, fenestrae-rich beds (Fig. 2AB); 2) at moderate elevations and further inland, fenestrae are concentrated in discrete packages within eolianites, often associated with scour (Fig. 3) and rip-up clasts; and 3) in the highest and most distal eolian ridges, only rare, thin, discontinuous fenestrae beds can be found (Fig. 2C; Tormey and Donovan, 2015). This spatial transition would is unlikely if torrential rain was falling relatively equally across an area during a storm; rather, this is exactly the pattern waves would produce as waves attenuate with greater distance and elevation inland.

Finally, in outcrop and thin section, cyclic changes in the geometry of individual fenestral pores have been observed (Tormey and Donovan, 2015). At several locations, fenestrae tend to be larger and more elongated at the base of individual lamina, becoming smaller and more equant upward. This is typically repeated over several centimetres, suggesting repeated inundation and basal compaction by pulses of water, rather than singular sheet flows.

Overall, the trilogy of features we describe in ACPD, along with the addition of massive sediment flux from the shelf to the shore and extensive dune building all point to a highly disrupted climatic transition during the late Eemian and the entry into the following sub-glacial condition of MIS 5d (e.g., Oppo et al., 2006).

RE: Local tsunami due to submarine mass failure, p. 6274.

Reply: It is possible that bank margin collapse did occur in North Eleuthera that may or many not have been temporally coincident with boulder deposition. It is also plausible that if collapse of the over-steepened shelf margin occurred around the time of boulder deposition, it may have been stimulated by the impact of large super storm waves. Regardless, a local point source of the tsunami from bank margin collapse at North Eleuthera would disperse tsunami waves outward, which would strike other margins of the Bahamas, Caribbean, and Bermuda at a variety of angles radiating from this point source. Our research throughout the Bahamas has revealed no evidence of such a point-source event. It is also important to note to the contrary, that the bank-protected northern coast of Bermuda and protected coasts of Great Exuma Island, Bahamas (e.g., Fig. 3) expose runup beds similar in timing and structure to those described above, yet are oriented away from the Bahamas and shielded from any point source tsunami emanating from North Eleuthera.

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FIGURES

Figure 1. Conceptual model or 'trilogy' (after Fig. 10, Hearty et al., 1998) showing the formation and deposition of chevron ridges landward of former tidal passes, runup deposits on older built up ridges, and giant boulders landward of high cliffs, respectively, upon impact by giant waves from a northeasterly source.

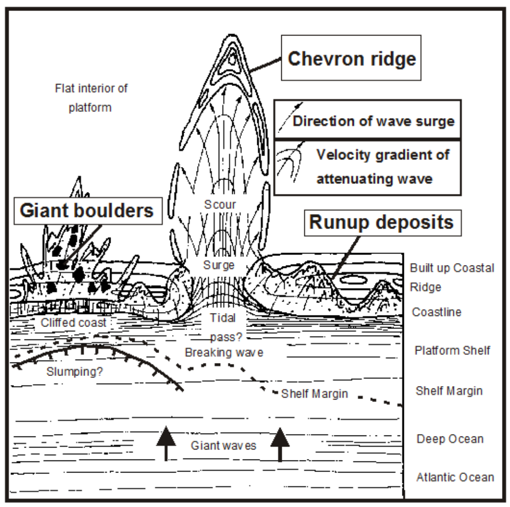

Figure 2: Cross-section diagrams (Tormey, 1999) of Eemian chevron and dune deposits on north Eleuthera (2AB 10 km west of megaboulders) showing geometry of bedding, fenestral porosity (lines of blue dots), and fossil roots (vertical wavy lines). A) Chevron ridge exposure at Licrish Hill characterized by rising sequences of thick, tabular fenestral beds. B) Chevron ridge exposure at Airport Junction characterized by a rising succession of thick, tabular fenestral beds. C) Eolian ridge exposure at a higher elevation road cutting at Annie Bight (6 km south of megaboulders) characterized by dominantly backset and topset bedding with scattered, thin, wispy fenestrae beds.

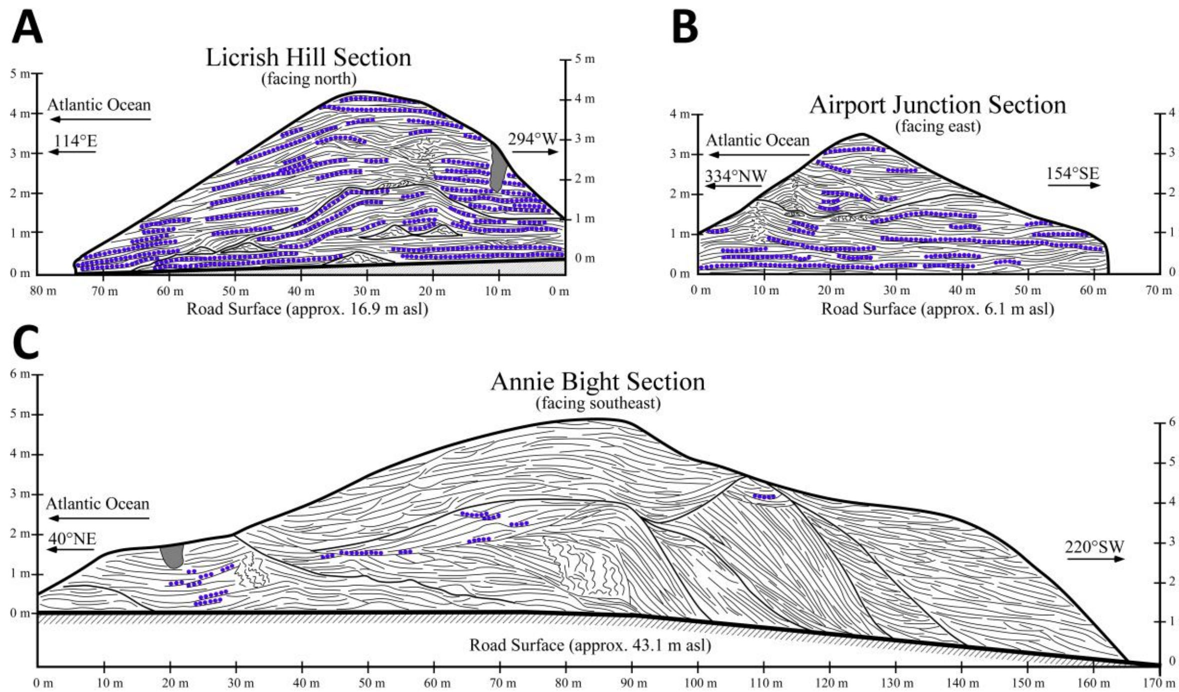

Figure 3. Photograph of runup deposits in a road cutting above +23 m (1 m scale in photo) on Old Land Road, Great Exuma Island, situated deep in Exuma Sound about 200 km south of North Eleuthera. The older built-up eolianite forms the lower half of the image, while multiple "packages" of planar, fenestrae-filled beach sets comprise the upper half. The upper progression of sedimentary packages (labelled a-e) clearly shows an onlapping, rising sequence of beds, indicating increasing wave energy. Further, the individual laminae of scour structures (arrows and inset image) display the same onlapping, upward climbing succession. It would be impossible to achieve such bedding if rain-saturated sediments were flowing downhill on low angle slopes under the influence of gravity, particularly near the crest of a ridge.