The genesis of an inter-field marine sandwave and the associated anti-asymmetry migration of neighboring crests

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[1] A series of high resolution multibeam echo sounding surveys near San Francisco, CA suggests the occasional migration of marine sandwave crests in the direction opposite to that indicated by the shape asymmetry of the individual sandwaves, in contrast to all previous observations of the relationship between bedform shape asymmetry and migration. The anti-asymmetry migration occurs over approximately the same time period that a new sand wave crest is formed within the large and relatively stable field. The new sandwave crest appears approximately midway between two larger crests, in the vicinity of structural defects in a nearly two-dimensional portion of the field. The sandwaves in the vicinity of the new crest are found to have migrated away from the new crest regardless of their shape asymmetry. Later a large section of the new crest disappears, and the neighboring sandwaves migrated back toward the vacated crest location. This migration occurs for sandwaves up to at least ten wavelengths away from the new crest. **Citation:** Hanes, D. M. (2012), The genesis of an inter-field marine sandwave and the associated anti-asymmetry migration of neighboring crests, *Geophys. Res. Lett.*, *39*, L04402, doi:10.1029/2011GL050641.

1. Introduction

[2] Sandwaves are large bedforms typically found in shallow marine environments with sand beds and large tidal currents. They were first described by *Luders* [1929, 1936] and *Van Veen* [1935], and have received considerable attention by the research community beginning in the late 1970's and continuing until the present. *Allen* [1980, 1982a, 1982b, 1982c] provided conceptual models for the origin, internal structure, and shape of sandwaves, with the basic mechanism described as secondary circulation cells induced by the interactions between the flow, water surface, and sloped seabed. More recently detailed linear stability theory and/or process-based numerical simulations [e.g., *Hulscher et al.*, 1993; *Nemeth et al.*, 2002; *Besio et al.*, 2004, 2008; *Sterlini et al.*, 2009] have been applied to explain the existence, characteristics, and migration of sandwaves.

[3] The sandwaves of the Golden Gate are located southwest of the Golden Gate Bridge near San Francisco, CA (Figure 1), and are shown as shaded relief bathymetry in Figure 2. Sandwaves in this region were first described by *Gibson* [1951]. The sandwaves were measured using single beam echo sounding and side scan sonar by *Rubin and McCulloch* [1980], and later stunningly visualized from multi-beam echo soundings (MBES) by *Barnard et al.* [2006]. *Barnard et al.* [2006] reported a large field of about 40 large sandwaves in depths ranging from approximately 30 to 90 meters and covering an area of approximately 8 square km. The height and wavelength of these features ranged from 4 to 10 meters, and 30 to 220 meters, respectively. Subsequent to the MBES survey described by *Barnard et al.* [2006] additional MBES surveys were conducted in October, 2005, February, 2007, and April, 2008.

[4] *Barnard et al.* [2006] reported that the Golden Gate sandwaves were highly dynamic, exhibiting crest migration along a central axis of a few meters on tidal time scales, and a seaward net migration of approximately 7 meters over one year. At that time it appeared from two surveys conducted a year apart from each other that the field of sandwaves was "marching" out to sea, up the slope of the ebb tidal delta. However, as shown by *Sterlini et al.* [2009] and in Figure 3, subsequent surveys indicate that the migration along the same central axis varies from year to year, and is in the opposite direction between the Oct 2005 and Feb 2007 surveys. This occurs in spite of the consistent seaward shape asymmetry of the sandwaves at the times of the surveys. Sandwaves [e.g., *Allen*, 1982c; *Langhorne*, 1982; *Knaapen*, 2005] and all other known asymmetric bedforms migrate in the direction pointed toward by the steeper face, making these observations both anomalous and intriguing.

2. Observations

[5] A feature-scale 1024 m by 1024 m region identified by the box in Figure 2 is shown as shaded relief for surveys conducted in October, 2005, February, 2007, and April, 2008 in Figures 4, 5, and 6, respectively. The large-scale background bathymetry has been removed and the orientation has been rotated in order to better visualize the individual sandwaves. The lines marking crest locations were determined by finding local maxima in the feature-scale relief, and fitting a smooth polynomial function to these points. The sandwave field appears relatively stable over these observations although there are some notable morphological changes, particularly in the 2007 survey. Crest number 1, on the leading (ocean-side) edge of the field, is the largest sandwave in the entire field, and it appears to be quite stable. The sandwaves adjacent to crest number 1 show more variability in time. Particularly notable is the formation of a new, long crest in the 2007 survey, denoted by the letters "NU" and "NL" between crests 2 and 3 in Figure 5. The crests labeled 3 through 12 persist in each survey, but migrate somewhat (less than a wavelength) over time. The crests to the right of number 7 are shorter and less regular than 3 through 7, perhaps because of an intruding tongue-like feature that might be due to a rock outcropping.

[6] The new crest in the 2007 survey forms in a region near several defects in the field. In the 2005 survey, crest

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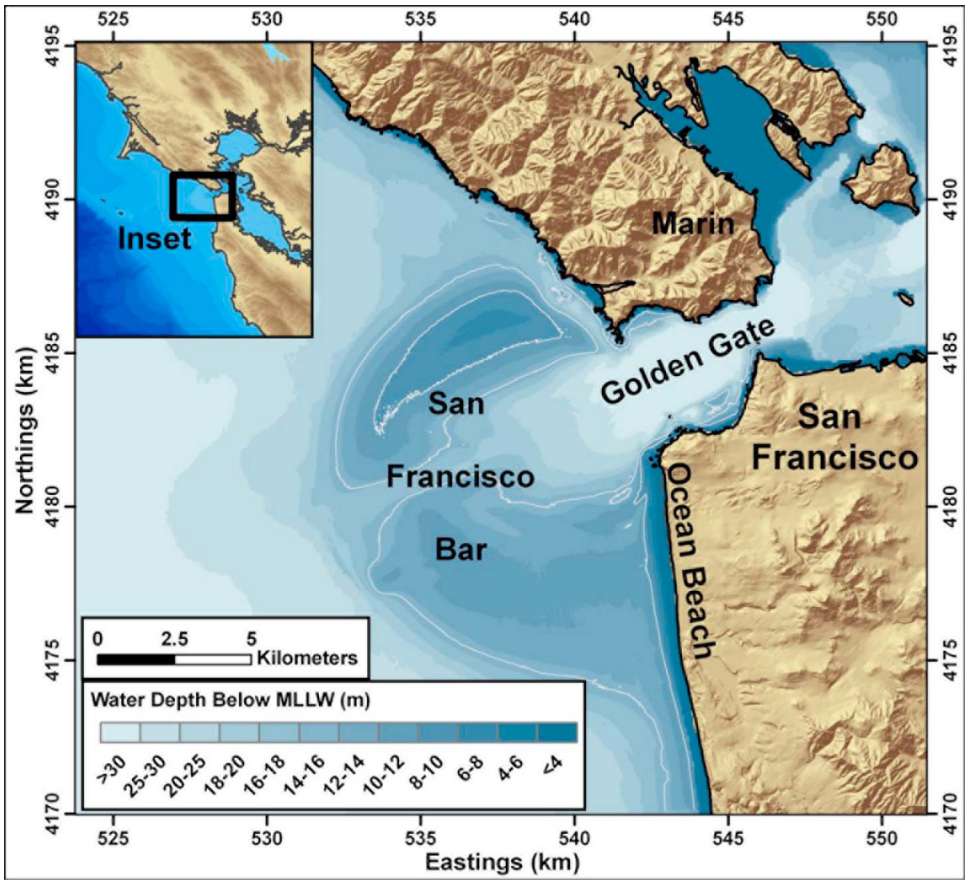

Figure 1. Location of the Golden Gate Sandwaves (from *Hansen and Barnard* [2010]).

number 2 has a discontinuity defect near the center of Figure 4. The crest labeled A, located in the lower half of Figure 4 between crest 1 and 2, has a clear termination. Also in the 2005 survey, there is a short segment of crest between crests 3 and 4, labeled B. Between 2005 and 2007 there are a number of changes in this region that we associate with the genesis of the new crest. In the 2007 survey sandwave crest 2 is now continuous, and has migrated

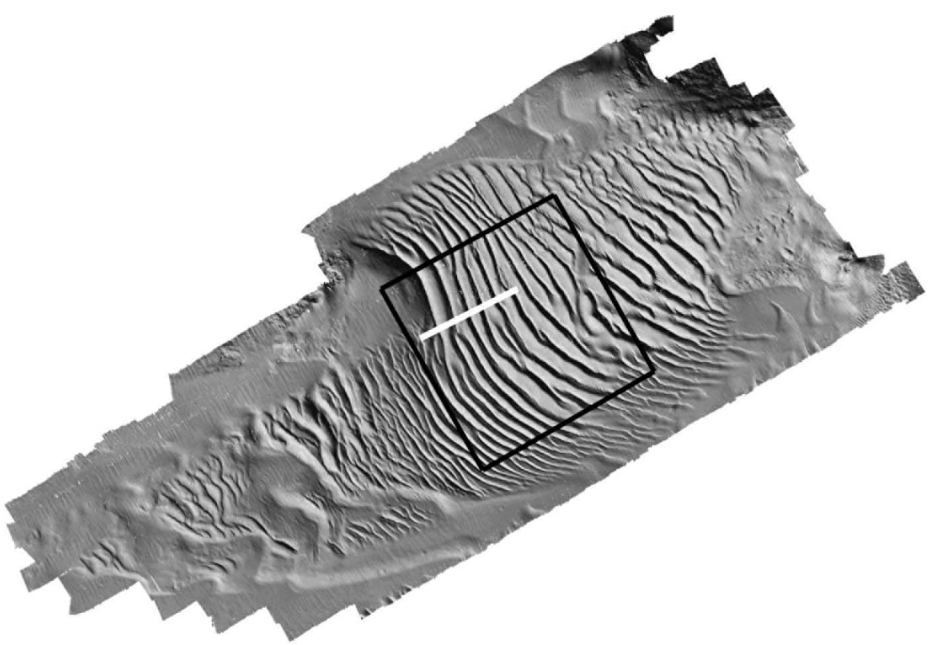

Figure 2. Shaded relief bathymetry of the GGSW measured in April 2008, approximately 2 km by 4 km.

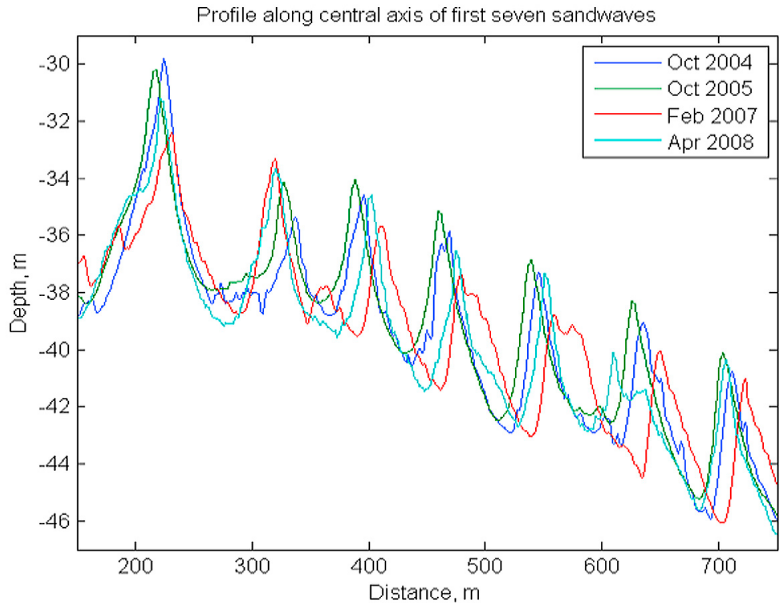

Figure 3. Multiple profiles along centerline of field (white line in Figure 2).

slightly to the left. Crest A and the lower part of crest 2 have joined together below the previous discontinuity in crest 2. Crest 3, located to the right of the new crest, has migrated to the right, and its lower portion is now located near where segment B was formerly located in the 2005 survey. A new short segment of a crest similar to B, labeled as C, appears between crests 4 and 5 in the 2007 (and 2008) surveys. In the 2008 survey the central portion of the new crest has

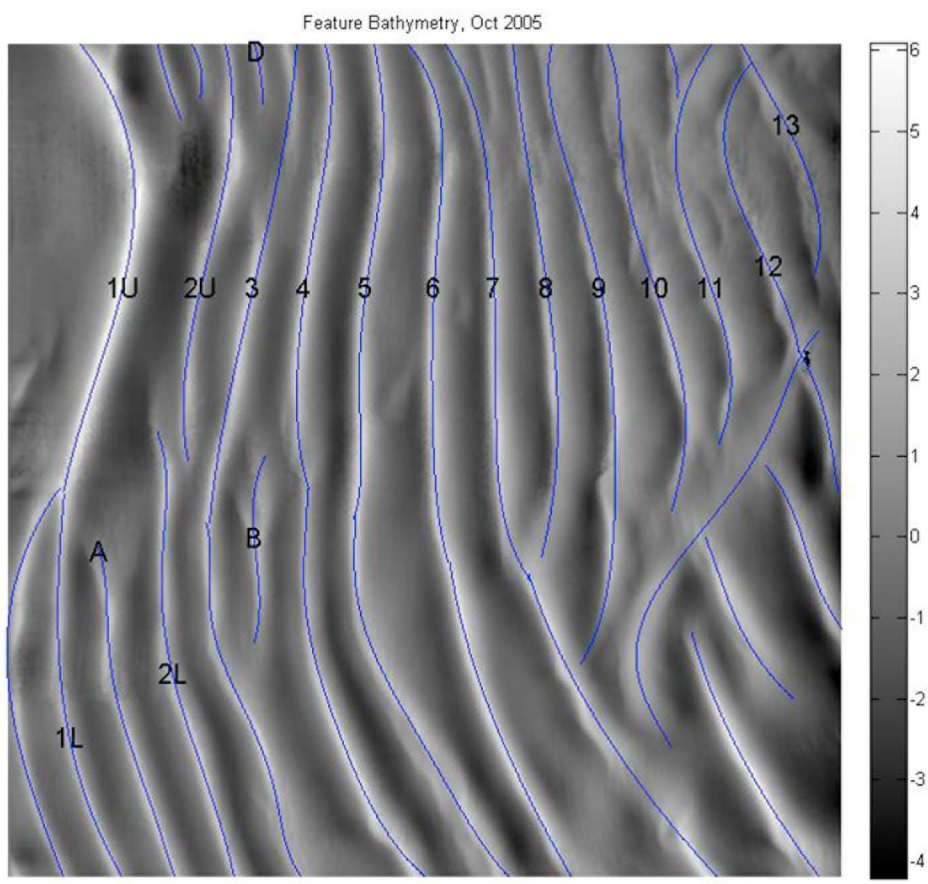

Figure 4. Feature scale bathymetry measured October, 2005 with sandwave crests highlighted.

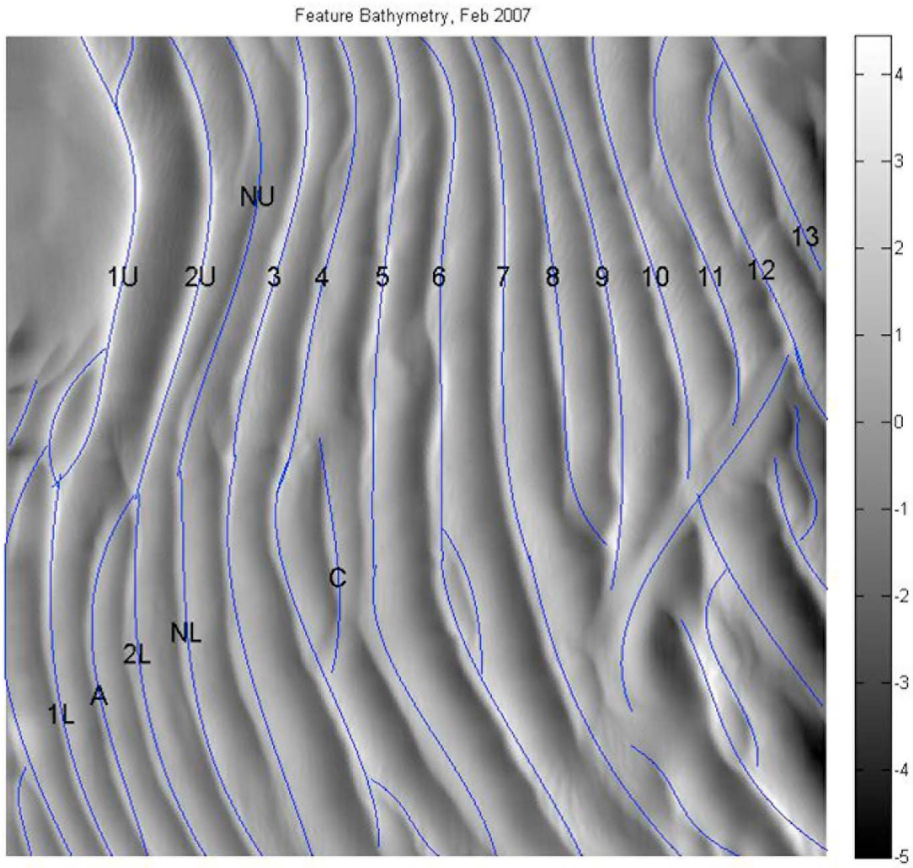

Figure 5. Feature scale bathymetry measured February, 2007 with sandwave crests highlighted.

disappeared, although the lower portion (NL) is still present. Segment A has once again separated from the lower part of crest two, and section NL has nearly merged with crest two.

[7] By tracking the various crest locations through the three surveys a clear pattern emerges. Figure 7 maps the crest locations for the first 10 crests for the three surveys. Crests 4 through 10 tend to migrate to the right between the 2005 and 2007 surveys, and then back to the left between the 2007 and 2008 surveys. The displacement of the crests near the centerline (where the numbers 1 through 10 are plotted in Figure 4–6) is plotted in Figure 8 as a function of distance from the first crest. In between the 2005 and 2007 surveys, when the new crest formed, the rightward displacement of crests located on the right side of the new crest decreased with distance away from the new crest. In contrast, between the 2007 and 2008 surveys, the leftward displacement of the neighboring crests increased with distance from the first crest.

[8] The migration of sand wave crests between the surveys is summarized as follows: The overall trend between 2005 and 2007, during which period the new crest developed, is for crests to the left of the new crest to either remain in place or migrate slightly toward the left, while crests to the right of the new crest migrated more substantially toward the right. During the period of 2007 to 2008 the upper portion of the new crest disappeared, and the corresponding upper portions of the other crests migrated back toward the left, sometimes ending up to the left of where the crests were initially in the 2005 survey.

3. Discussion and Hypotheses

[9] The primary findings reported here are the genesis of an intra-field sandwave and the associated migration of sandwaves in a direction opposite to the crest shape asymmetry. The genesis of an intra-field bedform is common, and its occurrence as described above near the location of several "defects" is entirely consistent with the suggestions of *Huntley et al.* [2008] for sorted bedforms. The interactions between individual bedforms and the associated field-scale evolution are also consistent with the wide range of bedform interactions described by *Werner and Kocurek* [1999] and *Kocurek et al.* [2010] for fluvial and aeolian systems. Given the limited temporal resolution of the surveys, it cannot be determined whether the genesis of the new crest preceded the migration of neighboring sandwaves, or visa-versa. Thus it is possible that the formation of a new crest contributed directly to the migration of neighboring sandwaves, or it is also possible that the migration of the existing sandwaves opened up space with was subsequently filled by the new crest. The mechanism for the generation of the new crest is not well known. The prevailing models for sand wave growth do not invoke flow separation, but flow separation dynamics are the most likely explanation for the growth of the new sand wave crest. Given the regions mixed semi-

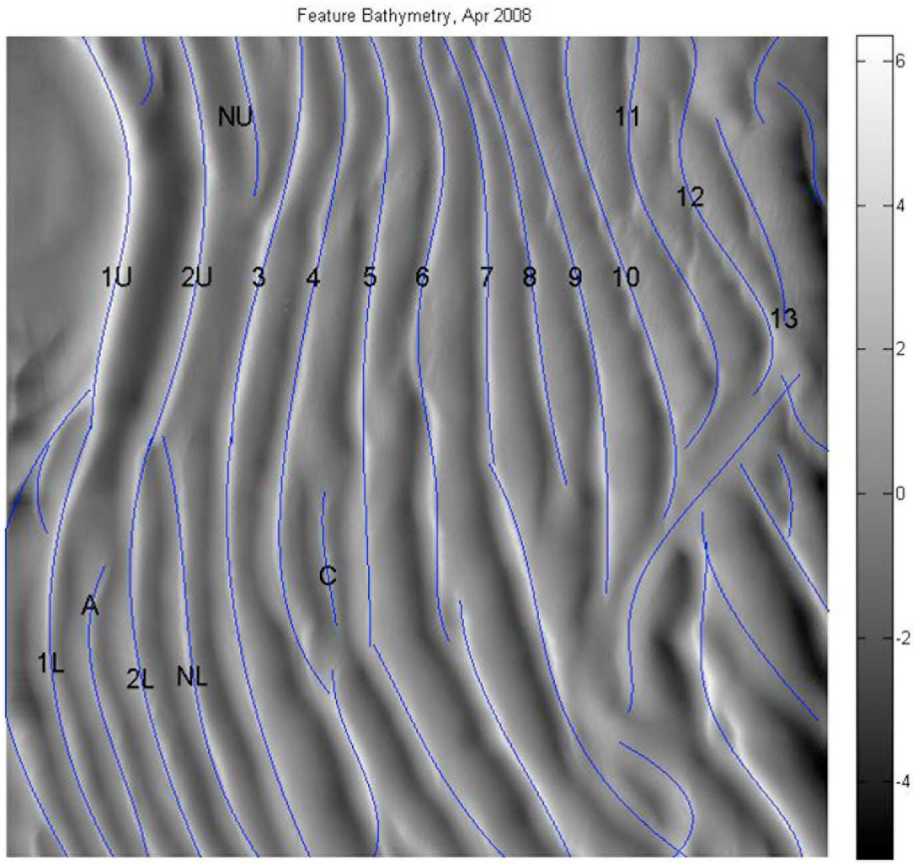

Figure 6. Feature scale bathymetry measured April, 2008 with sandwave crests highlighted.

diurnal tide, it is likely that growth of the new smaller crest approximately midway between the existing larger crests is a result of flow re-attachment during the minor tide cycle. Other explanations are certainly possible too, such as the net longitudinal sediment transport hypothesis to be described below.

[10] Perhaps the most interesting aspect of these measurements is the migration of several bedforms in a direction opposite to that indicated by their shape asymmetry. This observation is believed to be unique, and motivates the generation of several speculative hypotheses that will hopefully be evaluated thoroughly in the future.

[11] One hypothesis that would explain the observations but eliminate the shape-migration paradox is that between the 2005 and 2007 surveys the sandwaves reversed both their shape asymmetry and their migration direction twice, with the unobserved period resulting in significantly larger migration distances. This behavior would be surprising given that every sand wave observed in four separate surveys had the same shape asymmetry, and the reversed asymmetry has not been observed. However, such behavior is not without precedent and cannot be ruled out given the limitations of the present observations. Even with this hypothesis, it still remains a challenge to explain why the shape and migration direction might have changed during this period between the 2005 and 2007 surveys. Smaller sandwaves and dunes have been observed to reverse their shape asymmetry due to changing hydrodynamics conditions [e.g., *Hawkins and Sebbage*, 1972]. In particular, *Harris* [1991] reported the shape asymmetry reversal of sandwaves due to seasonal changes in the direction of the wind driven current. Similarly, *Besio et al.* [2004] describe that particular combination of tidal constituents M2 and M4 can result in sand wave migration opposite to the direction of the net (residual) tidal current. It is possible that during the winter months there is a hydrodynamic change in the tides or net current direction due to winds, rain, or the dynamics of San Francisco Bay, and that both the sand wave shape and migration direction reverse accordingly.

[12] A second hypothesis is that the net sediment transport direction is opposite or at least has a vector component opposite to the shape asymmetry, allowing the migration of asymmetric bedforms in the direction opposite to that indicated by their shape asymmetry. *Allen* [1982c] postulated that the shape asymmetry of sandwaves is due to the hydrodynamic temporal asymmetry of the tidal currents, without any requirement for flow separation at the crest, with the net sediment transport still in the direction indicated by the shape asymmetry. The Golden Gate sandwaves are located on the edge of a large ebb tidal delta, with the overall km-scale slope being upward-seaward. This small slope should enhance sediment transport in the down-slope (landward) direction. Thus even though the temporal asymmetry in the tidal currents may force a seaward shape asymmetry in the sandwaves, the larger-scale slope enhances sediment transport landward, and perhaps can partially explain the perplexing direction of the net sediment transport and migration direction.

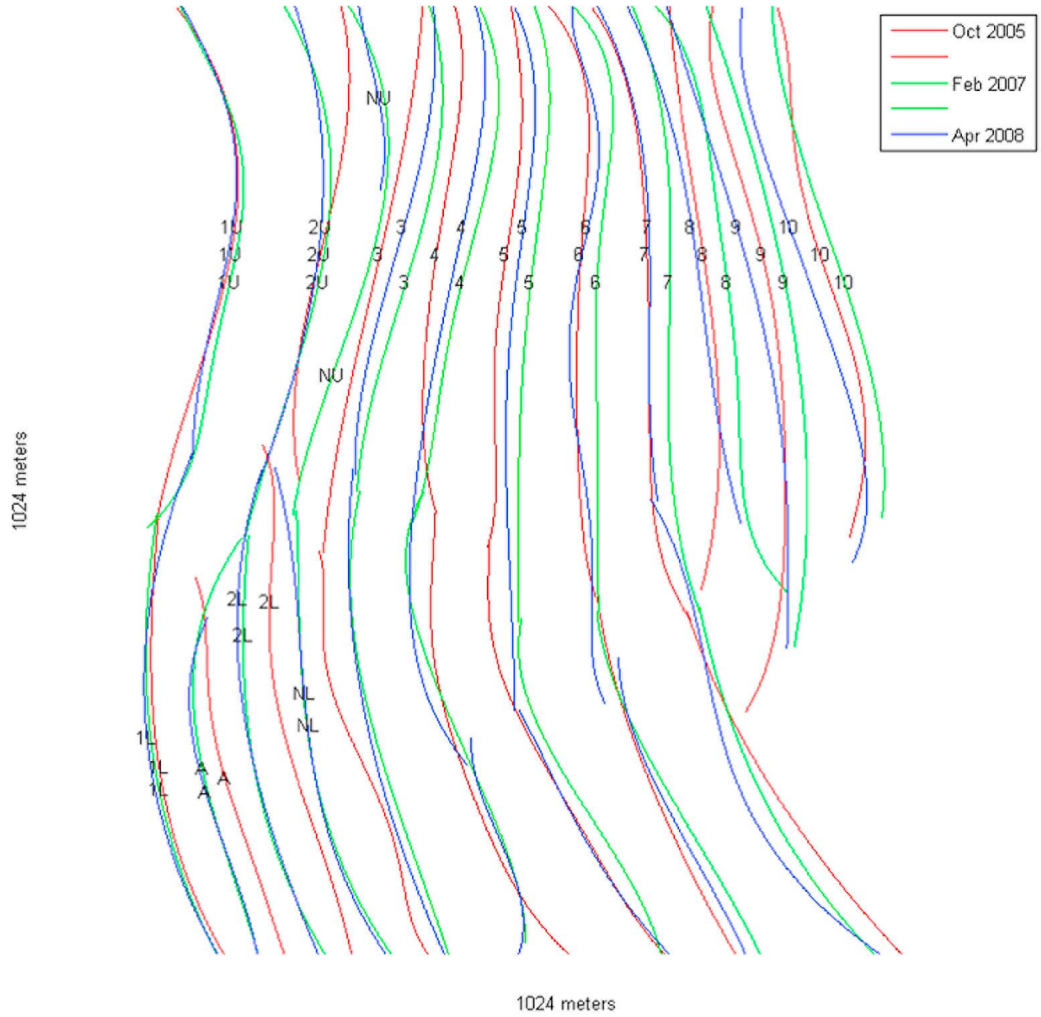

Figure 7. Crest locations for the three surveys.

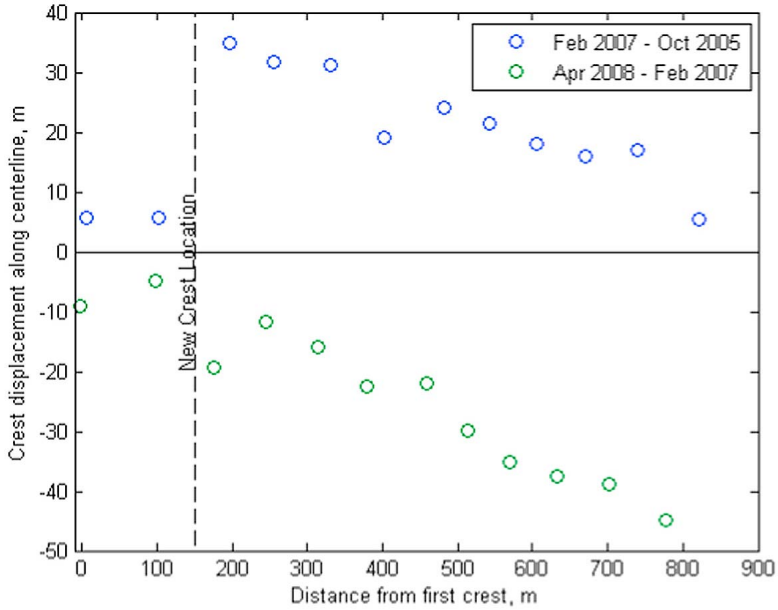

Figure 8. Displacement of crests along the centerline as a function of crest distance from the first crest.

[13] A third hypothesis is that the tidally driven sediment transport is nearly balanced to give zero net transverse sediment transport, such that the net sediment transport is actually longitudinal, and that the appearance and disappearance of crests such as described above is due to longitudinal evolution of the bedform. In this case, the cross-sectional shape of the bedforms might still be asymmetrical due to the tidal forcing, but the erosion and accretion that results in the net migration might be due to gradients in longitudinal sediment transport.

[14] These three hypotheses could be evaluated through future field observations and numerical modeling investigations, and undoubtedly they will be modified or replaced altogether. But at this point it remains a mystery precisely how the sandwaves migrate in one direction while maintaining an asymmetric shape normally indicative of oppositely directed migration. It is clear from these observations that the shape of these bedforms is not a reliable indicator of their long-term migration direction. Rather, it appears that these bedforms are fairly stable over yearly to decadal time scales (and perhaps longer) despite their strong shape asymmetry.

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