Preservation of transient flow conditions in wave ripple defects

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Symmetric sand ripples formed by shallow water waves are one of the most commonly observed patterns in modern environments and in sedimentary rocks. Because the size and spacing of oscillatory flow sand ripples scale with wave conditions and water depth, ripples preserved in sedimentary rocks are important paleoenvironmental indicators used to infer ancient wave conditions. Previous studies of oscillatory flow bedforms have focused on the development of ripple fields under constant wave forcing or on the transient adjustment of one-dimensional wave ripple profiles to changing flow conditions. However, modern and ancient ripple fields often contain bifurcating ridge crests, short secondary crests formed within major ripple troughs, and other two-dimensional defects -- deviations from straight, evenly spaced ripples. Understanding the formation and evolution of these ripple defects could provide insight to transient wave conditions.

We performed a series of experiments in a field-scale laboratory wave tank to characterize the response of a rippled bed to changes in oscillatory flow. In each experiment, we subjected a level sand bed seeded with small perturbations to constant wave forcing to establish an equilibrium ripple field. We then imposed an abrupt change in wave conditions that would produce a different ripple spacing. Taking shadows in time-lapse images as a proxy for bed elevation, we computed the two-dimensional Fourier power spectrum of the sand bed over the course of each experiment to determine ripple spacing and spectral entropy, a measure of the variability of ripple crest orientation and spacing. We also made qualitative observations of dominant defect types over time. Ripples formed from the initially planar bed were straight crested, evenly spaced, and largely devoid of ripple defects. After wave conditions changed, the ripple bed developed unevenly spaced crests with a variety of defect geometries.

Different types of defects developed to accommodate increases in ripple spacing and decreases in ripple spacing, and some defect types emerged only to accommodate a particular magnitude of change in spacing. In experiments with increases in ripple spacing, cup-like depressions formed on ripple crests and propagated outward to divide existing crests in two and increase ripple spacing. In experiments with minor decreases in ripple spacing, ridge crests became hourglass-shaped, and secondary crests formed within widened trough segments. These secondary crests eventually merged with sinuous or fragmented crests to decrease ripple spacing. In experiments with larger decreases in ripple spacing, secondary crests formed parallel to existing ripple crests then migrated laterally towards the trough to decrease ripple spacing. In some experiments with only small increases or decreases in ripple spacing, defects did not form and the ripple field adjusted by lateral migration of unbroken ripple crests.

As ripple fields reached a new equilibrium spacing, the abundance of defects declined and ripple crests became straighter and more evenly spaced. Yet, some defect types persisted even after the ripple bed attained an average spacing equilibrated to new wave conditions. Crest terminations and tuning fork-shaped bifurcations in ripple crests became the dominant defect type after the main adjustment of ripple fields to either an increase or decrease in spacing. These defects propagated across the bed in the direction of the flow as edge dislocations until the end of our experiments.

Based on these observations, we constructed a regime diagram relating specific ripple defect geometries quantitatively to the sign and magnitude change in ripple spacing and the cumulative sediment transport following the change in wave conditions. These results provide a basis for interpreting different defect types and deciphering the magnitudes and timescales of changing water flow preserved in modern coastal environments and the rock record.

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