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RIPPLE, RIPPLE MARK, AND RIPPLE STRUCTURE

Definition

Ripples, ripple marks, or *ripple structures* can be defined as small-scale, flow-transverse ridges of silt or sand produced by fluid shear at the boundary between moving water or air and an erodible sediment bed. Principal ripple types are *current ripples*, formed by unidirectional water flows, *wave ripples*, generated by oscillatory wave action, and *wind ripples*, formed by eolian currents (see *Deserts*). Large-scale equivalents of ripples are *dunes* (see *Surface Forms*).

Basic concepts

Ripple marks are quasi-triangular in vertical cross-section parallel to flow direction (Figures R6(A),(C–E)) or wave propagation (Figure R6b). Current ripples are asymmetric, with gentle upstream face (*stoss side*) and steep downstream face (*lee side*) approaching or at angle-of-repose. Individual current ripples can be up to 60 cm long and 6 cm high, but the mean length and height of a field of current ripples are usually <20 cm and <2 cm, respectively. Wave ripples are symmetric or slightly asymmetric in cross-section (Figure R6(B)). They can be 200 cm long and 23 cm high, but typical dimensions are an order of magnitude less.

The geometry of ripples is expressed by the *vertical form index* (or *ripple index*), L/H, the *symmetry index*, L_S/L_L, and the *plan form* (Figure R6). Most common vertical form indices are 8–9 for current ripples and 3–8 for wave ripples, although lower indices and indices up to 20 are no exception for both types. The mean symmetry index for a field of current ripples is mostly >2.5, and dissimilar from typical indices of <2.5 for wave ripples. However, co-existence of oscillatory and unidirectional currents may produce *combined-flow ripples*, whose symmetry index overlaps with current ripples, and thus complicates genetic process reconstruction. Weak cross-sectional asymmetry can also be produced by intrinsic resultant mass transport of water in the direction of wave propagation, mostly in shallow water. Current ripples comprise four common styles of plan form: *incipient*, characterized by mm-high solitary ripples or ripple patches on a flat bed; *straight-crested*, with straight, continuous crest lines (Figure R6(C)); *sinuous-crested*, with sinuous, continuous crestlines (Figure R6(D)); and *linguoid*, with discontinuous, tongue-shaped crestlines (Figure R6(C)). Although wave ripples can have three-dimensional plan form, particularly in the presence of unidirectional currents, wave interference, or under high waves, straight crests with diagnostic bifurcation and abrupt termination of crest lines are most common.

Flow over current ripples separates at the brinkpoint in an upper *zone of free flow* and a *zone of backflow* with *separation eddy* in the lee of the ripple (Figure R6(A)). These zones are divided by a *zone of mixing*, a shear layer along which Kelvin-Helmholtz vortices generate high instantaneous shear. In the ripple trough, the shear layer gradually trends downward until the main flow becomes *reattached* to the bed. Current ripples migrate in the flow direction by erosion of the stoss side and deposition on the lee side. The migration rate is inversely proportional to ripple size and proportional to local sediment transport rate, which varies with the degree of sheltering by adjacent ripples. Depositional processes associated with ripple migration comprise suspension settling through the zone of mixing and recurrent avalanching of bed load material from the brinkpoint onto the lee slope (Figure R6(A)). Each avalanche-settling cycle produces a *cross lamina*. Sets of cross-laminae are diagnostic of migrating current ripples. Preservation of cross-lamination is enhanced by net deposition in flows that are oversaturated with sediment and produce *climbing ripple cross-lamination* (see C*ross-Stratification*).

Flow over wave ripples comprises three stages: (1) During passage of a water wave crest, flow separation occurs over the ripple crest and a separation eddy and avalanche deposit are produced; (2) During subsequent decelerating flow in the wave cycle, the eddy rises, and may take suspended sediment with it; (3) During passage of the water wave trough (with reversed flow direction), the suspended sediment moves over the ripple crest, a new separation eddy develops and avalanching occurs on the opposite ripple face. Wave ripple cross-lamination produced by net deposition from successive waves

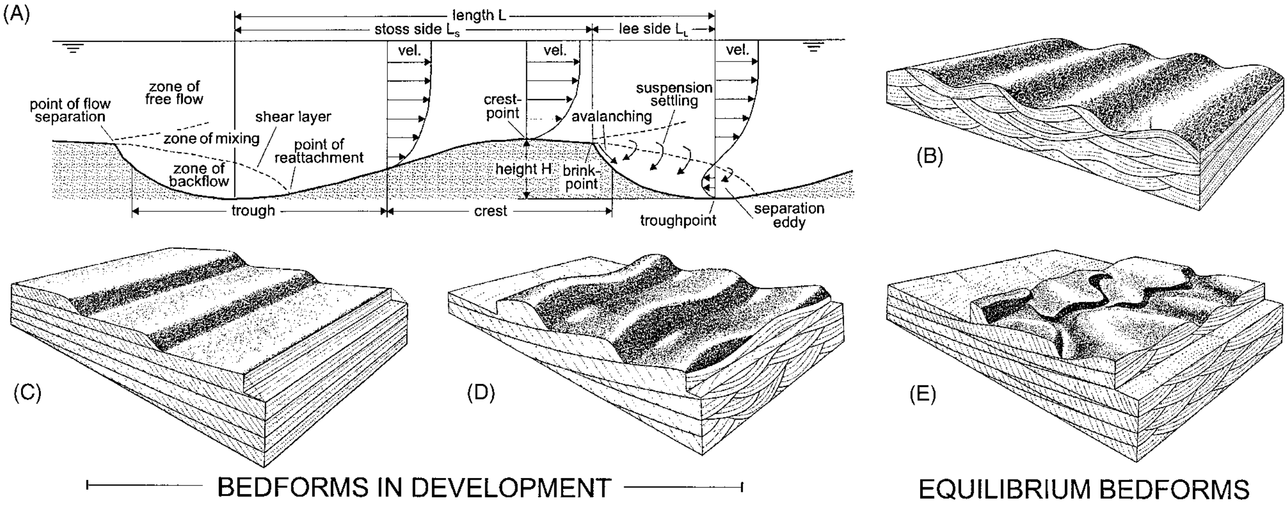

Figure R6 (A) Ripple marks in vertical profile parallel to flow. Terminology is based on Allen (1968) and Reineck and Singh (1980). Note that avalanching and suspension settling generate cross-lamination depicted in (C)–(E). vel. = flow velocity. Water depth note to scale. (B) Plan form and internal structure of symmetrical wave ripples with rounded crests. Wave ripple crests can also be pointed. Wave propagation direction is perpendicular to cret lines. Note bundle-wise arrangement of cross-laminae. (C) Straight-crested, (D) Sinuous-crested, and (E) Linguoid current ripples, with characteristic cross-lamination. Flow is from left to right. Note that current ripples evolve from straight-crested via sinuous-crested to linguoid, independent of flow velocity. Ripples in (C) and (D) are therefore developing, and (E) shows equilibrium forms. Figures (B)–(E) after Reineck and Singh (1980).

is characterized by bundles of oppositely inclined laminae (Figure R6(B)). For combined-flow ripples, the dominant inclination of cross-laminae is parallel to the unidirectional flow component.

Historical development

Ripple marks have been described extensively since the beginning of modern observational geology. Sorby (1859), Darwin (1884), Hunt (1904), Kindle (1917) and Bucher (1919) established the foundations for modern ripple analysis. Allen (1968), Potter and Pettijohn (1977), Reineck and Singh (1980) and Allen (1984) summarized further benchmark papers, which include studies on ripples in recent and ancient sediments, ripples in experimental flumes, and the theory of ripple formation and stability. In the last two decades, ripple marks have been used primarily in facies analysis. Yet, innovative work continued in experimental flumes and through mathematical modeling (e.g., Miller and Komar, 1980; Diem, 1985; Arnott and Southard, 1990; Gyr and Schmid, 1989; Nelson and Smith, 1989; Best, 1992; Baas, 1994, 1999; Werner and Kocurek, 1999; Baas *et al.*, 2000). Best (1996) and Raudkivi (1997) presented excellent reviews of recent current-ripple literature.

Applications

Ripples and cross-lamination have been used as indicators of stratigraphic younging and to reconstruct (paleo)flow direction or (paleo)wave crest orientation. Moreover, ripples can be used as estimators of local flow properties, notably flow type, flow strength and sediment accumulation rate. Flow strength can be constrained from *bedform stability diagrams* (see *Surface Forms*). Current ripples form at relatively low flow velocities between the threshold for sediment movement and *upper-stage plane bed* (for particles < ~0.12 mm) or *dunes* (for particles ~0.12–0.7 mm). They do not form in cohesive clay and in sand coarser than ~0.7 mm. Wave ripples exist in all silt- and sand-grades, and between maximum oscillatory velocities for the threshold of sediment movement and upper-stage plane bed.

Unidirectional flows occur in many depositional settings, which renders current ripples of limited use in paleoenvironmental reconstruction. Nevertheless, hydraulic conditions are most favorable in sandy rivers, on intertidal flats, and in turbidites. Wave ripples require relatively weak near-bed oscillatory flow, such as on lake beaches, intertidal flats and the marine shoreface. They are therefore better suited for paleoenvironmental analysis than current ripples. Combined-flow ripples have been found on intertidal flats and in other shallow marine and coastal environments.

Ripple marks provide the sediment bed with form roughness. Form roughness is essential for calculating flow resistance, bed shear stress and velocity distribution in sediment transport analysis.

Current investigations and gaps in knowledge

Refinement of existing models and development of new ideas continually improve our knowledge of ripples. Present-day work on current ripples concentrates on the mechanisms controlling their formation (Best, 1992; Raudkivi, 1963; Williams and Kemp, 1971), their rate of development towards equilibrium morphology (Baas, 1999) and the feedback relationships between ripple geometry and flow conditions (e.g., based on "wave instability" theory by Richards, 1980).

A field of current ripples can be generated from a single, artificial, or flow-induced, bed defect if the height of the defect is large enough to induce flow separation at its lee side.

Baas (1994, 1999) demonstrated that current ripples developing on fine- and very fine sand-grade flat beds evolve from incipient, via straight-crested and sinuous-crested, to linguoid equilibrium plan form with constant mean height and length. Contrary to earlier work (e.g., Allen, 1968), the equilibrium dimensions were found to be independent of flow velocity. Velocity governs merely the time needed to reach equilibrium geometry, which may range from several minutes to hundreds of hours. Baas (1993) proposed relationships between sediment size, D, and equilibrium current ripple height, H_e, and length, L_e (*cf*. Raudkivi, 1997):

$$\left.\begin{aligned} H_e &= 3.4 \log D + 18 \\ L_e &= 75.4 \log D + 197 \end{aligned}\right\} \text{(in mm)} \qquad \text{(Eq. 1)}$$

Although the above model has been applied successfully to current ripple dynamics in tidal environments (Oost and Baas, 1994) and used to reconstruct sedimentation rates in turbidites (Baas *et al*., 2000), several gaps in our knowledge remain. First, the role of turbulence in the growth rate of current ripples has never been assessed in detail. Second, aggradation promotes current ripple preservation, but no comprehensive study of its influence on ripple dynamics exists, particularly under conditions of turbulence modulation. This knowledge would strengthen the use of current ripples in (paleo)hydraulic reconstructions, and in the determination of drag coefficients in sediment transport calculations.

The latest studies on wave-induced bedforms concentrate on the sediment entrainment under oscillatory and combined flows, and the dynamics of such flows over wave and combined-flow ripples (e.g., Traykovski *et al*., 1999; Paphitis *et al*., 2001). This work will remain important, considering the complexity of the feedback relationships between flows and bedforms. A better process-based distinction between combined-flow and current ripples is needed, as the use of indices is unsatisfactory. This could be achieved by exploring potential differences in grain fabric of current, wave, and combined-flow ripples.

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Cross-references

Angle of Repose
Bedding and Internal Structures
Bedset and Laminaset
Cross-Stratification
Desert Sedimentary Environments
Flow Resistance
Flume
Paleocurrent Analysis
Sediment Transport by Tides
Sediment Transport by Unidirectional Water Flows
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