Study Area

- The **late Miocene outcrops of the Fish Creek-Vallecito (FCV) Basin in the Anza-Borrego Desert State Park** of south-central California (Fig. 5). The deposits in the basin capture the full **rift and fill sequence of the paleo Gulf of California**.
- The unit of interest is the **Lycium Member** (**100-300 m-thick, 6.3-5.3 Ma**; Dorsey et al., 2011), composed of **medium-to-coarse sand-rich beds (5-200+ cm thick)**
- Interpreted as **locally-sourced slope turbidites** (Winker, 1987).
- The **paleodepositional setting** is thought to have been along a **steep, narrow, high-relief margin**. Depths at deposition have been estimated at between 150-500 m (Dorsey et al., 2011).
- Setting should provide a **higher likelihood of occurrence and preservation** of potentially supercritical flows

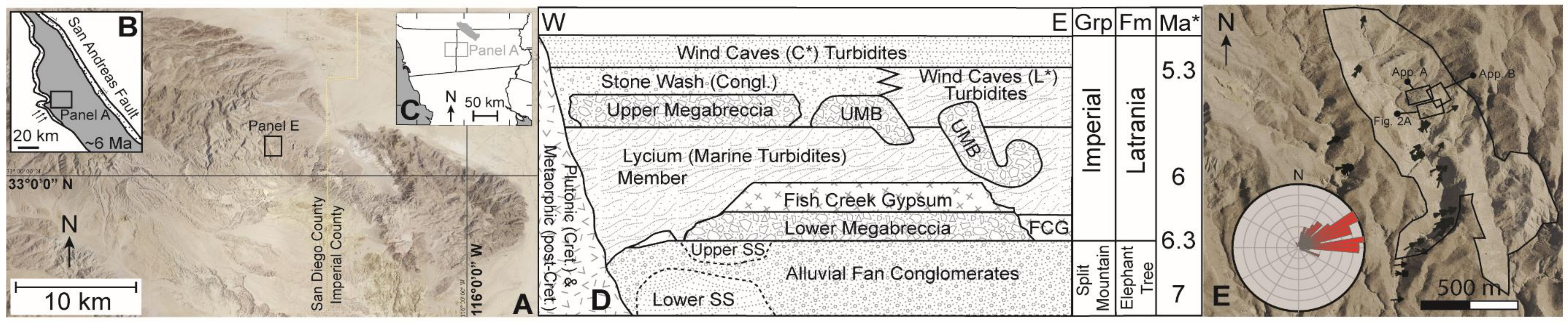
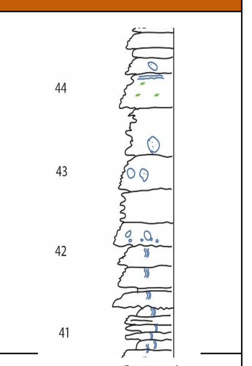
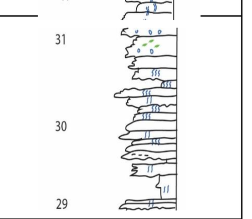
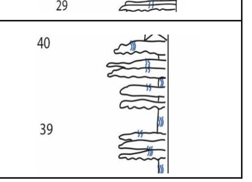


Figure 5: (A) Fish Creek-Vallecito Basin. (B) Paleogeography at Lycium Deposition (after Dorsey et al., 2007). (C) Study area location. (D) Stratigraphy. (E) Area of focus showing paleoflow directions (n=131).

Facies & Geometries

Facies	Lithologic Description	Interpretation	Logging
Clean Sand Beds	• Dominant, 15-45 cm-thick, sharp based, sorted, quartz-rich arkosic sandstone • Grainsize – Median: Grades medium-upper into medium-lower. Coarse: - pronounced fining (coarse-tail grading) • Capped by 1-3 cm layers of bioturbated silty mudstone ("mud caps") • Structure - Low amplitude wavy laminae, parallel laminae, and 1-3 cm-deep scour troughs • Features - Mud-clasts, gravel lenses, and rare outsized clasts (50-110 cm diam.) • Soft sediment deformation – common where overlies relatively thick mudstones. • Bioturbation – light to moderate in sandstones; extensive in mud caps	Deposited in the central areas of supercritical bedforms. Comprise the bulk of antidunes and areas between hydraulic jumps on axis of any cyclic steps	
Interbedded Sands & Fines	• Alternating beds of sharp-based sandstone and silty mudstone • Thickness – SS → Thinner (1-15 cm) & finer (medium lower-to-fine upper); silty mudstone (2-10 cm) • Structure – long wavy and parallel laminae • Bioturbation – SS → heavy; silty mudstone → extensive	Deposited on margins of supercritical bedforms or as a coarser fraction of bypass fallout	
Thick Mudstones	• Thicker (40-50 cm) units of poorly laminated silty mudstone beds • Most heavily bioturbated, very fine sands to silts • Occur over pronounced, oblique, erosional truncation	Fallout from periods of bypass or shifts in flow centers	

<u>Waveform Geometries</u> –Reflective of the approximate bathymetry at deposition ~**2-7 m amplitude**; **wavelengths ~75-100 m; widths ~100-150 m**. (Fig 6)
<u>Bed Geometries (Dip-View)</u> –**Low-angle, undulating dip-view waveform geometries; accrete upflow**. Incise locally (5-10) cm. Most are **sigmoidal lenses**. Along dip, beds emerge tangentially from basal bounding surface, thicken and incline up, flatten & thin, and pinch out tangentially at crest or recline down
<u>Bedset Geometries (Dip-view)</u> – **Isolated or bundled** units; **5-10 m thickness** (> internal waveform amplitudes); separated by parallel regional bounding surfaces (tabular macroform); Locally scoured 1-3 m; Internal backsets steeper than bounding surfaces; bundled bedsets contain multiple bedsets stacked into each other.
<u>Bounding Surfaces</u> – *Regional*: extensive across the outcrop, accentuated by facies changes, and near parallel with regional dip. *Bedset* (where bundled): lack distinct, through-going surfaces or facies changes, have variable orientations oblique to regional bedding.
<u>Strike-View Geometry</u> – Lobate geometries across full width. Appear more tabular in narrow strike view.

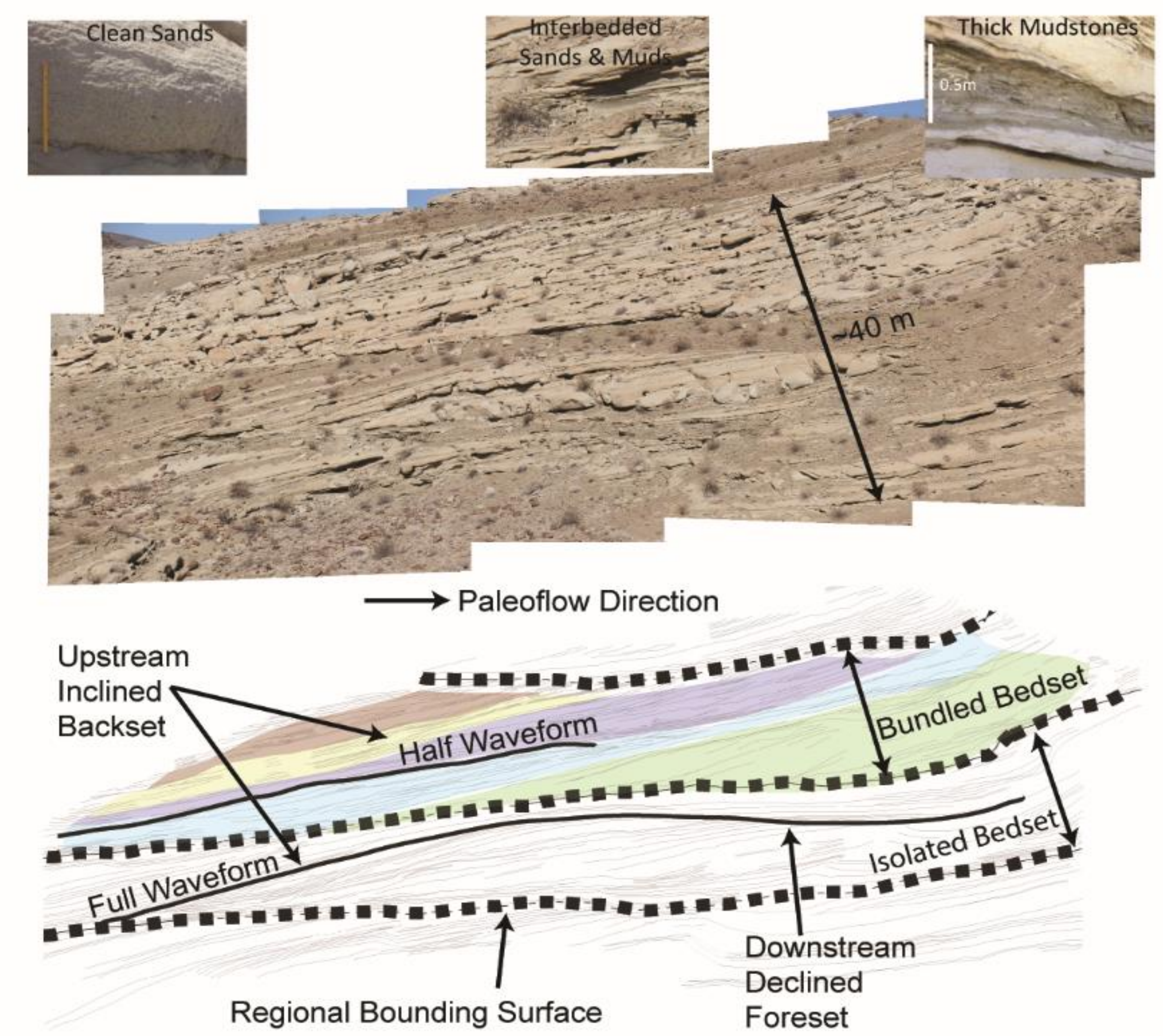
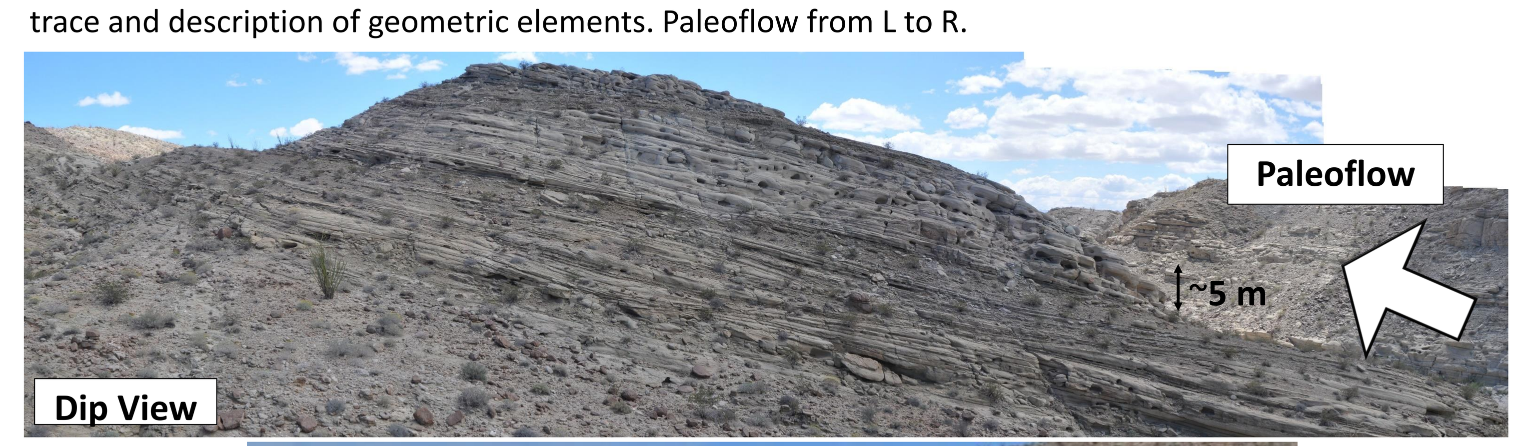


Figure 6: (Top) Facies examples. (Middle) Image of antidune deposit (see Fig 1E, marked 2A). (Bottom) Bed trace and description of geometric elements. Paleoflow from L to R.



Idealized Bedforms

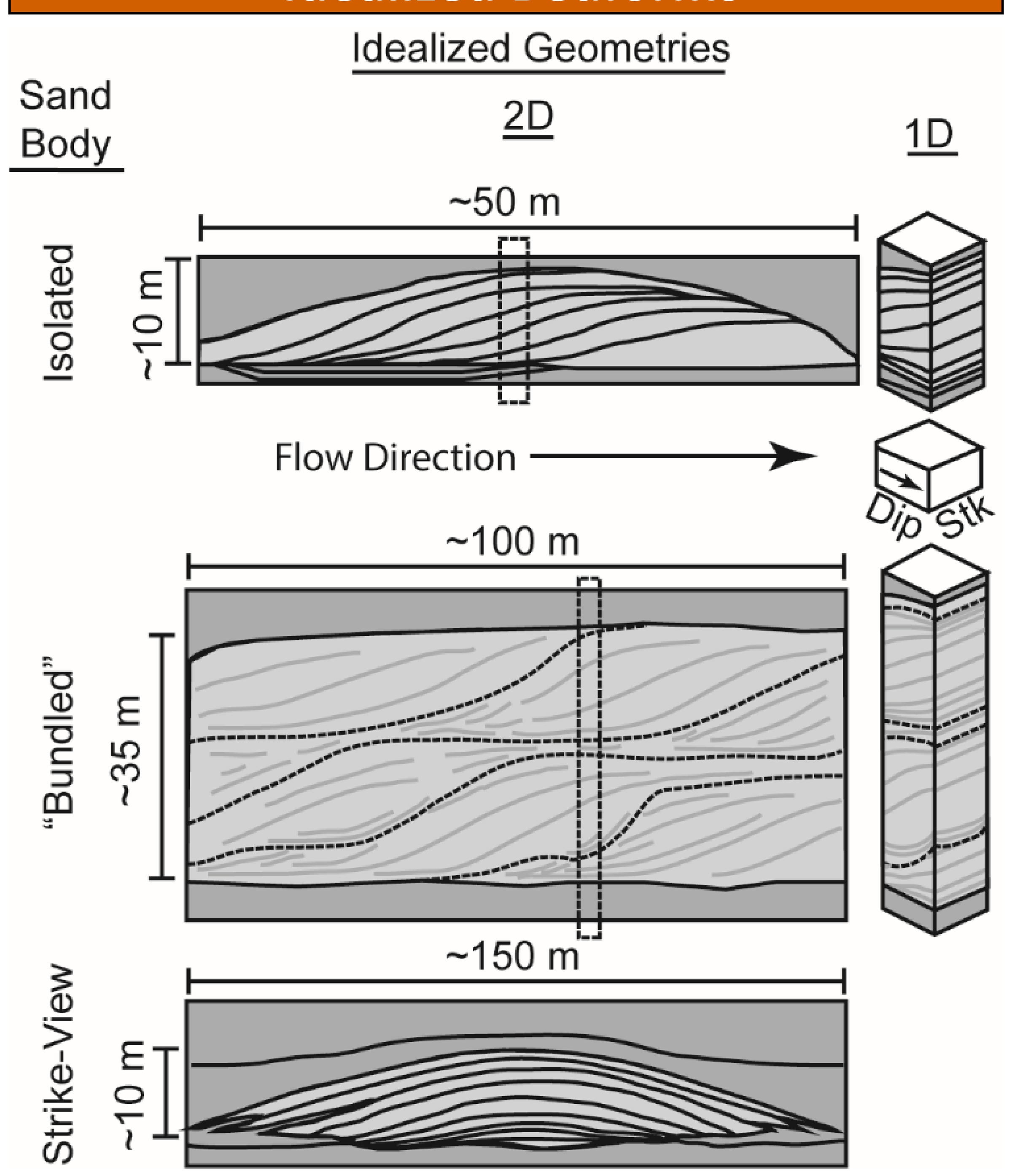
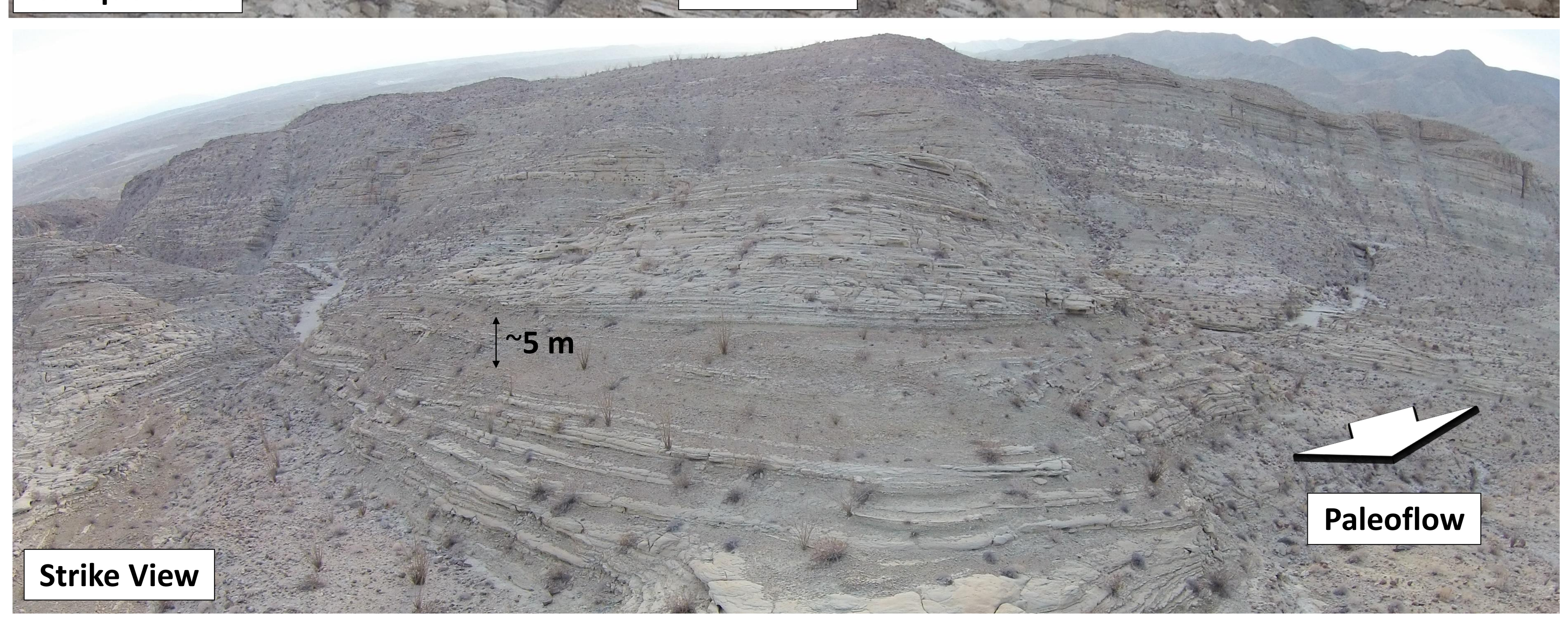


Figure 7: Idealized schematics of bedset geometries in 1 and 2D

<u>Idealized Pattern</u> - Cyclical transition from bedding parallel thick mudstones into upflow dipping interbedded sands and fines followed by rapidly thickening and upflow steepening clean sands before transitioning back to flatter, interbedded sands and fines and eventually thick fines. In dip-view fans out downstream from the base towards the middle of the bedform, then thins and flattens in the uppermost portions. In strike view coarsens and thickens before thinning and fining
<u>Antidune Identification</u> - No facies stacking pattern is consistent across all bedsets. **Geometric patterns are most reliable for identification** of Lycium Mbr bed architecture.

Additional Outcrop Imagery



Antidunes vs Cyclic Steps

- **Antidunes and cyclic steps** have **no definitive stratigraphic description**.
- The deposits featured **here** are **consistent with antidunes** in their **low-angle, symmetrical upstream migrating waveforms**.
- Expected **indicators of hydraulic jumps are largely absent** rather than pervasive (they are found elsewhere).
- Geometrically, these deposits **lack the sharp, high-angle erosional bedset boundaries** intrinsic to cyclic step migration.

Key Findings & Implications

- First recognized large-scale deepwater antidunes in the rock record
- Reject the hypotheses that antidunes in deepwater behave similarly to antidunes in shallow, open-channel settings → ephemeral without rock record
- Antidunes are sustained over multiple flow events over ~1 My
- Antidunes should be incorporated into interpretive framework of deepwater deposits
- Establish preliminary criteria for identification of antidunes elsewhere