Supporting Information for
The Oligocene-Miocene Guadalope-Matarranya Fan, Spain, as an Analog for
Long-Lived, Ridge-Bearing Megafans on Mars


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Additional Supporting Information
This supplement expands on the results from Site 4 and summary from other sites as reported in the main text. All methods used are described in the Methods section of the main text. Stratigraphic data and data on uneroded channel belts are attached in separate spreadsheets, 

SI_StratigraphicData.xlsx, SI_UnexhumedBodies.xlsx, and SI_CaprockData.xlsx.

**Introduction**

Site 1 (41.236N, 0.241W)  
Site 1 is notable for the numerous ridges intersecting in a pitchfork shape (Fig. SI1). Ridge tops are at comparable elevation in the DEM, but group into three stratigraphic positions in the stratigraphic model. Field observations show Ridge 1 superposes Ridges 2-5, and that there are notches eroded into Ridges 2, 3, and 4 where Ridge 1 superposes them. Combining the stratigraphic model and field observations, Ridge 1 superposes Ridges 2, 3, and 6, which superpose Ridges 4 and 5. Due to ridge alignment in planview and stratigraphic position, we interpret Ridges 2, 3, and 6 to represent a single channel belt, and Ridges 4-5 to be another channel belt.

We also made quantitative measurements from the DEM. Best-fit slopes to the ridge centerlines are $10^{-3}$, and all ridges have relief 3-16 meters above the surrounding plains. Caprock thickness varies from 2-3 meters along the ridges, and caprock breadth varies from 10-20 meters along ridge lengths.
Sedimentological investigation showed that caprocks are made of medium sandstone with some cross stratification (Fig. SI1c). Twenty-six sets of dune cross strata range in height from 10-30 centimeters and the 22 with recorded accretion direction indicate flow directions within 0°-90° to the ridge axis (Fig. SI1a). One dune set indicates paleoflow in the opposite direction from the other dune sets. We observed 19 truncated bar clinoforms with accretion directions 0°-90° to the ridge axis, and measured one to have a height of 90 cm. No planview expressions of lateral accretion sets were observed, either in remote sensing or field observation. Major erosional surfaces indicative of stories are absent, but bar clinoforms generally span half the caprock thickness so it is likely that caprocks have more than a single story. Amalgamation of multiple stories is further indicated by the DEM and UAV orthophotos, which suggest that Ridge 1 comprises a thin sinuous body atop a broader body (Fig. SI1a).

Mudstone dominates the ridge flanks beneath the caprocks (Fig. SI1c). Talus blocks cover these flanks abundantly but are absent beyond the flanks, likely due to heavy modification for agricultural use. Talus blocks are made of sandstone and are up to 3 meters in diameter (Fig. SI1b).
Fig. SI1 - Site 1 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). White circles indicate stratigraphic sections (shown in panel c). b) Orthophoto from the 3D model made from photogrammetry performed on UAV photos. c) Representative stratigraphic sections. All three are interpreted to be from the same ridge, so they are placed with tops at the same stratigraphic position.

Site 2 (41.222N, 0.217W)

Site 2 is notable for a ridge with high sinuosity that is bisected by an excavated railroad track (Fig. 7b). The site was briefly described in Cuevas Martinez et al. (2010). We add quantitative detail to their initial observations. The ridge has relief 0.1-4.8 meters
above the surrounding plains, caprock thickness varies from 0.3-3.3 meters along ridge length, and caprock breadth varies 11-51 meters.

Sedimentological observation of the caprock revealed sandstone with abundant cross-stratification from bars and dunes. Three observations of dune cross-strata indicate paleoflow directions aligning with the ridge axis. Fourteen observed bar clinoforms have accretion directions between 0°-90° from the paleoflow direction indicated by dune cross strata, including both towards and away from locations of planview ridge convexity (Fig. 7b). This is notable because lateral accretion sets associated with meandering accrete in the direction of bend convexity, so some accretion in the opposite direction indicates ridge caprocks were built over time rather than just representing one episode of river meandering.

The caprock overlies mudstone ridge flanks. Talus blocks up to 3 meters in diameter cover the flanks, and are made of similar sandstone to the caprock. Talus is absent from the flat areas at the bases of the ridges, though this is likely related to modification for agricultural use.
Fig. SI2 – Site 2 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). No stratigraphic data was collected.

Site 3 (41.204N, 0.074W)

Site 3 contains two ridges that intersect, and an isolated knob (Fig. SI3). The ridges and the knob are all at indistinguishable elevations in the DEM and stratigraphic model. Ridge 1 has a minor notch near its intersection with Ridge 2, potentially indicating scour by the river that formed Ridge 2 (between sections 1 and 2, Fig. SI3a). Best-fit slopes are \( \sim 10^{-3} \), and both ridges have relief 2.3-7.9 meters above the surrounding plains. Caprock thickness varies 2.9-4.4 meters and breadth varies 9.7-23.3 meters. Caprocks sit atop mudstone ridge flanks covered in talus blocks. Talus blocks are up to 8 meters in diameter, and are made of sandstone that resembles the caprocks.

Caprocks are made of medium sandstone with some cross stratification. We measured 60 dune cross strata with heights ranging from 3-31 centimeters and indicating flow directions within \( 30^\circ \) of the ridge axis. Six bar clinoforms with heights between 0.45-1.5 meters tall had accretion directions almost all within \( 20^\circ \) of the ridge axis. No planview expressions of lateral accretion sets were observed.
Fig. SI3 - Site 3 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). White circles indicate stratigraphic sections (shown in panel c). Ridges are all at comparable stratigraphic levels. b) Orthophoto from the 3D model made from photogrammetry performed on UAV photos. c) Representative stratigraphic sections. Both ridges are interpreted as being at the same stratigraphic position (grey bar) so the tops of all three stratigraphic sections are placed at the same stratigraphic level (black bars).

Site 4 (41.204N, 0.059W)

Site 4 is most notable for its complex arrangement of ridges that are arrayed like a five-pointed star (Fig. 4). We provide additional details here beyond those in the main text.

Three different stratigraphic levels are distinct in the DEM and imagery (Figs. 4a and 5b), with Ridge 3 superposing Ridge 1, and Ridge 1 superposing a smaller plateau in the northwest corner. Ridges 1, 2, 4, and 5 are visually similar in the DEM, so we relied on field investigation to discern their intersections. Ridge 4 appears to connect to a channel body beneath Ridge 1 (Fig. 5b), and Ridge 1 appears to erode into Ridge 2 (Fig. 5a). Ridges 2 and 5 are interpreted as continuous through Ridge 1 on the basis of their alignment in planview and stratigraphic position. Therefore, the order of ridges in which the parent paleochannels were active was the small plateau in the northwest, then Ridges 4 and 2/5, 1, and finally 3.

Extracting measurements from the DEM, we found ridge relief ranges 6-26 meters, caprock thickness ranges 0.3-7 meters, and caprock breadth ranges 10-34 meters. Thickness is greatest where caprocks are amalgamated, for example where Ridge 1 intersects with Ridges 2-5 (Fig. 4b). Caprocks are similarly widest where they intersect other caprocks (Fig. 4).
Caprocks are made of medium sandstone with abundant cross-stratification. We recorded 55 dune cross-strata measurements between 16-38 centimeters tall. Accretion directions indicate paleoflow within 30° of ridge axes. We recorded 31 measurements of bar clinoforms with measured heights between 1.5-2 meters tall and accretion directions ranging 0°-100° from the paleoflow direction. Ridge 1 presented long (~50 meters) lineations parallel to the accretion direction of associated rib-and-furrow structures near the intersections with Ridges 2 & 5 (Fig. SI4a). Because of their great length, association with interpreted dune sets, and accretion direction perpendicular to paleoflow direction interpreted from dune-set accretion direction, we interpreted these structures as lateral accretion sets from bank-attached bars. The lineations extend off both edges of the caprock, indicating that the caprock used to be wider in both directions. Because lateral accretion sets often indicate the bank of the paleochannel, this indicates that the ridge caprock represents an amalgamated set of fluvial deposits rather than the paleochannel at any individual timestep.

Sandstone caprocks sit atop mudstone and fine sandstone. A long stratigraphic section (Fig. 4c) shows one example of the underlying material, which we found to be 60% mudstone and 40% fine sandstone. The mudstone was also observed between caprocks at all intersections between Ridge 1 and the northwest plateau. Flanks are covered in sandstone talus blocks, and the bases of the ridges are all agricultural fields in current use. On Ridge 2 the caprock has split in half down the middle into parallel sets of blocks that are similar in geometry to the largest of the talus blocks (Fig. SI4b).
Fig. SI4—Additional images from Site 4. a) Nadir-looking UAV view of the junction between Ridges 1 and 2, showing bank-attached bars (dashed lines). View is of same location as Fig. 5a; lowercase “b” indicates a boulder shown in Figs. 5a and SI4b. White arrow indicates paleoflow directions from rib-and-furrow structures, black arrow indicates accretion direction of bar structures. The ridge is ~20 meters across at the black arrow. b) Oblique UAV view of Ridge 2, showing the caprock splitting (various dashed lines). The caprock is fully split in two in the foreground, and splitting into smaller pieces in the further distance. Lowercase “b” indicates a boulder shown in Figs. 5a and SI4a.

Site 5 (41.205N, 0.184W)

Site 5 contains a main ridge with a pair of smaller ridge segments branching off at each end (Fig. SI5). The segments connect with the main stem and appear to form two distinct ridges at stratigraphic levels offset from each other by 1-2 meters and amalgamated for the main central stretch. The higher ridge (Ridge 2) is continuous from the southeast to the northwest, and the lower ridges (Ridges 1 and 3) run from the southwest to the northeast. Ridges 1 and 3 take sharp bends at their junctions with Ridge 2. Field investigation of the ridge intersections showed that the ridge caprocks are
separated by mudstone at the south intersection (Fig. 5c) and by an erosional surface at
the north end (Fig. 7c).

Ridges have relief 0.3-4.8 meters above the surrounding plains. Caprock thickness
varies from 0.2-3.2 meters and breadth varies from 12-35 meters. Caprocks are made of
medium sandstone with thickness measurements recorded for six dune strata and two
observations of bar clinoforms. Dune sets indicate paleoflow direction within 30° of the
ridge axis, and the bar accretion directions are within 15° of perpendicular to the ridge
axis. Ridge flanks are largely mudstone, covered in talus blocks up to 3 meters in
diameter that are made of medium sandstone.

We interpret Ridges 1 and 3 as continuous under Ridge 2 based on the
stratigraphic positions, alignment of ridges and flow directions, and inspection of the
junctions. This suggests a case where two channel bodies of similar dimensions
amalgamate for a short length before splitting again. The amalgamated portion does not
appear to have significantly larger dimensions than either single channel body, suggesting
that the later generation at least partially scoured the earlier generation before deposition
occurred.
Fig. SI5 - Site 5 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). White circles indicate stratigraphic sections shown in panel c. b) Orthophoto from the 3D model made from photogrammetry performed on UAV photos. c) Representative stratigraphic sections. Ridges 1 & 3 are interpreted to be the same channel body (see Supplement text), and so they are placed at the same stratigraphic level, offset from the top of Ridge 2 (black bars indicate ridge tops, gray bar indicates offset).

**Site 6 (41.211N, 0.209W)**

Site 6 is notable for a ridge with a sequence of bends that resemble point bars going different directions (Figs. 7a; SI6). The ridge caprock increases in elevation towards the outside of each curve, such that the highest-elevation component of the caprock is also the highest sinuosity. Non-ridge-forming sandstone bodies occur under
this main ridge at its east end, and another sandstone body superposes the main ridge at its west end. Field observation shows mudstone between the main ridge and the sandstone bodies in both locations. We fit slopes to the axis of the main ridge along its highest-elevation segment and found $6 \times 10^{-4}$. Ridge relief is 0.7-7.9 meters above the surrounding plains. Caprock thickness varies from 0.7-5.9 meters and breadth varies from 9.9-68.5 meters.

Caprocks are made of medium sandstone, and we recorded 27 measurements of dune cross-strata thickness and 9 measurements of bar clinoform thickness. Dune cross strata range in thickness from 5-29 centimeters and indicate flow directions that generally parallel the local ridge axis. One dune set indicated flow in the opposite direction from the others. Bar clinoforms range from 0.6-1.5 m thick. Bar accretion directions are all within 40° of perpendicular to ridge axis. Bars are truncated by major erosional surfaces that we interpreted as the bounding surfaces between stories. Caprocks have between one and four stories (Fig. 6b). Ridge flanks are dominantly mudstone and are covered in talus blocks up to 8 meters in diameter that are made of medium sandstone.
Fig. SI6 - Site 6 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). White circles indicate stratigraphic sections shown in panel b. b) Representative stratigraphic sections.

Site 7 (41.280N, 0.143W)
Site 7 contains two ridges branching in a Y shape, with the Ebro river immediately to the east (Fig. SI7). Ridge 1 is stratigraphically higher in the DEM and shorter in length than Ridge 2. Field observation shows that the sandstone caprocks of
Ridges 1 and 2 are separated by ~2 meters of mudstone (Fig. 5d). The best-fit slope for Ridge 2 is $8 \times 10^{-4}$, and both ridges have relief 8.6-12.9 meters above the surrounding plains. Caprock thickness varies from 3.2-5.4 meters and breadth varies from 17.3-46.9 meters. Ridge 2 is widest at its intersection with Ridge 1.

Caprocks are made of medium sandstone, and observations of 43 dune cross sets and 9 bar clinoforms were recorded. Dune cross-strata range in height from 5-27 centimeters and indicate flow directions that parallel the ridge axis. One set of climbing dunes was observed on the caprock of Ridge 2, near its intersection with Ridge 1. Bar clinoforms are 0.45-2.5 m tall, and have accretion directions within 90° of the paleoflow directions. No planview expressions of lateral accretion sets were observed, either in remote sensing or field observation.

Caprocks sit atop mudstone ridge flanks. Talus blocks up to 4 meters in diameter cover ridge flanks, and are made of medium sandstone. Ridge 2 is fractured along much of its length into pieces that are a similar size to the talus blocks on its sides (Fig. SI7b).

Together, these observations indicate an example where branching ridges result from distinct channel bodies representing rivers at different points in time. In particular, the upper ridge appears to be protecting the thinner wings of the lower ridge from erosion because their intersection is where the lower ridge is widest. The wings of Ridge 2, preserved in the intersection, are the only location in the study where we observed climbing dunes, which form in rapid deposition rates and are therefore suggestive of overbank deposits.
Fig. SI7 - Site 7 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). White circles indicate stratigraphic sections shown in panel c. Section 2 is where climbing dunes (Fig. 3c) were observed. The Ebro River is just off the edge of the image to the east, leading to the high relief in the field area. b) Orthophoto from the 3D model made from photogrammetry performed on UAV photos. c) Representative stratigraphic sections. Sections 2 & 3 are from the same ridge so the caprock tops are placed at the same stratigraphic position (black bar), and offset from the caprock base in Section 1 by 2 meters as observed in the field (Fig. 5d).

**Site 8 (41.285N, 0.149W)**

Site 8 contains four parallel ridges, perched atop a sandstone mesa (Fig. SI8). Ridge 4 is the lowest stratigraphically, and the other three ridges are lower and at equivalent heights. The underlying sandstone sheet forms a cliff with 19 meters of relief above the surrounding area. Ridges have relief 0.1-1 meters above the sheet sandstone. Caprock thickness is 1 meter and the sandstone sheet is 2 meters thick. Caprock breadth of the four small ridges varies from 6-20 meters.

Caprocks are made of medium sandstone with some cross stratification. We observed six dune cross-sets indicating paleoflows to the north on Ridge 2, and six dune cross-sets indicating paleoflow to the south on Ridge 3. One bar clinoform on each of these ridges has accretion direction perpendicular to the paleoflow direction. Bar clinoforms span most of the caprock thickness. We also observed straight, parallel lineations on the top of the sheet sandstone that extend for tens of meters. These lineations appear in cross section to be connected to bar cross-strata, so we interpreted them as representing laterally accreting bank attached bars.

A larger body outcrops in the cliff formed by the sandstone sheet, enabling detailed examination (Fig. 6a). It is 4.5 meters thick and 21 meters wide. The body is made of medium sandstone and contained many levels of truncated bar clinoforms, and
itself truncates other sandstone and mudstone layers in the cliff. We interpreted this body as a channel belt with laterally accreting bars.

Fig. SI8 - Site 8 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). White circles indicate stratigraphic sections shown in panel c. Ridges are all at comparable stratigraphic levels. b) Orthophoto from the 3D model made from photogrammetry performed on UAV photos. c) Representative stratigraphic sections. The two stratigraphic sections are observed at similar stratigraphic levels and also similar elevations above the sheet sandstone (~2 meters), so their caprock tops are placed at the same stratigraphic level.

**Site 9 (41.225N, 0.232W)**

Site 9 contains three ridges that intersect (Fig. SI9). Ridge 1 is the highest stratigraphically, and the other two ridges are lower and at equal heights. The best-fit slope for the Ridge 1 is $9 \times 10^{-4}$, and all three ridges have relief 0.1-7.1 meters above the sheet sandstone. Caprock thickness varies from 0.4-5.2 meters and breadth varies from 8-30 meters along ridge lengths.

Caprocks are made of medium sandstone, and we recorded observations of 14 dune cross sets and 6 bar clinoforms. Dune cross strata ranged in height from 4-23 centimeters and indicated flow directions that paralleled the ridge axis. Bar clinoforms
were 1-2.6 m tall and had accretion directions within 20° of the paleoflow directions, except for one bar on Ridge 2 that was accreting laterally; however, no planview expressions of lateral accretion sets were observed.

Caprocks sit atop ridge flanks made dominantly of mudstone, and mudstone separates the caprocks of Ridge 1 from the other two at their intersections. All ridges have flanks covered in talus blocks up to 14 meters in diameter, and the blocks are made of medium sandstone with cross-stratification similar to the caprock. The caprock of Ridge 1 is fractured along much of its length into pieces that are a similar size to the talus blocks on the ridge flanks, and such pieces are all that remain of the caprock in many locations along the ridge.

Fig. SI9 - Site 9 data. a) Background is the elevation and hillshade from lidar DEM. Rose diagram represents paleoflow direction observations (blue) and bar accretion directions (red). b) Orthophoto from the 3D model made from photogrammetry performed on UAV photos.