

Morphology of pillow-hollow and quilted-cover bedforms in Lake Geneva, Switzerland

N. Le Dantec ^(1,2), Y. Akhtman ⁽³⁾, D. Constantin ⁽³⁾, U. Lemmin ⁽²⁾, D.A. Barry ⁽²⁾, O. Pizarro ⁽⁴⁾

1. Laboratoire de Génie Côtier et Environnement, Centre d'Etudes Techniques Maritimes et Fluviales, Plouzané, France - nicolas.le-dantec@developpement-durable.gouv.fr

2. Ecological Engineering Laboratory, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland - andrew.barry@epfl.ch, ulrich.lemmin@epfl.ch

3. Geodetic Engineering Laboratory, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland - yosef.akhtman@epfl.ch, dragos.constantin@epfl.ch

4. Australian Centre for Field Robotics, University of Sydney, Sydney, Australia - o.pizarro@acfr.usyd.edu.au

Abstract

Extensive areas of the bottom of Lake Geneva are covered with bedforms that have been referred to as pillow-hollows and quilted-cover pattern by prior observers, as well as with sediment waves and trenches. These structures are decimeter to meter scale. A large dataset of video recording and stereographic camera imagery of the lake bottom was recently acquired during a campaign with the Russian MIR submersibles. We present a classification of the different types of sediment structures with a focus on distinctive morphological characters. The variations in the observed lake-bottom structures reveal a continuous range of morphologies between the aforementioned bedforms. Although the role of the bottom-dwelling Burbot fish in at least maintaining the bottom landscape has been suggested in previous studies, the origin of the observed bedforms is unclear. On the basis of our preliminary observations, other candidate mechanisms are briefly mentioned, including bottom currents generated by internal waves. Understanding the formation and evolution of lake-bottom morphology is important since the transport pathways of lake sediment condition to a large extent the fluxes and cycle of pollutants.

1. INTRODUCTION

1.1. Sediment structures and benthic processes

Sedimentary structures at the bottom of aquatic environments are of importance to various processes occurring in the bottom boundary layer. The benthic zone provides habitat for a number of species types, from bottom-dwelling fishes to burrowing invertebrates and microbial fauna (Thrush *et al.*, 2001; Hewitt *et al.*, 2005). The nature and properties of surface sediment control the type and rate of chemical reactions taking place near the lake bottom (e.g. Brandl *et al.*, 1990; Mermillod-Blondin and Rosenberg, 2006), which ultimately govern the transformation cycle and fate of the compounds input into the aquatic system (Warren and Haack, 2001). Bedform-scale topography has an ecological function, for

example in providing shelter for certain species, in particular during early development stages (Probst, 2008), or foraging grounds for others (Erlandsson *et al.*, 1999). Bedforms are observed at the interface between mobile sediment substrate and overlying fluid. Common in fluvial and shallow marine environments, bedforms also occur in lacustrine and deep marine realms. There, they usually exhibit slower dynamics because fluid forcing is generally weaker and episodic.

1.2. Prior studies in Lake Geneva

First observations of bottom structures in Lake Geneva were reported by Vernet (1966) after several dives with the submersible Piccard. He described a uniform landscape composed of a succession of humps and pits linked together by saddles, which he referred to as a quilted-cover where stitches are randomly distributed. The

hypothesis of interference of ripples generated by distinct current regimes was proposed to explain the formation of the observed morphology, noting that the origin of such currents was not well identified. The role of fish inhabiting the lake bottom in maintaining and enhancing the bedform pattern was already outlined.

Sedimentological studies were carried out on the pillow-hollow structures with radioisotopic, chemical and microbial analyses of short cores (Dominik *et al.*, 1992; Brandl *et al.* 1990). Troughs exhibited a stratigraphic hiatus compared to pillows, where sediment was relatively less consolidated. There were differences in the thickness and age of missing sediment between adjacent troughs. The above results suggested localized erosion and reworking of the surficial sediment with small-scale inhomogeneity in erosive events. Random changes in the intensity and frequency of Burbot fish activity from one structure to the next could explain the variability in the stratigraphy of the troughs.

1.3. Scope of the paper

This paper reports preliminary results on extensive observations of lake-bottom morphology in Lake Geneva using video recording and stereographic imagery. After describing the data acquisition and the analysis and processing methods, we focus on a description of the sediment structures. A classification is derived from the more extensive video record. Examples of 3D models are used to illustrate the added-value of scaled digital terrain models continuously covering long sections of the lake-bottom compared with raw video. The motivation for the study is to understand the mechanisms controlling the development of the observed bedforms. Several potential processes are mentioned, as well as the two main approaches of the analysis, currently in progress, to assess these processes.

2. METHODS

2.1. Data acquisition

Data presented here were acquired with the manned submersibles MIR-1 and MIR-2 operated by the Russian Academy of Sciences during the éLEMO campaign conducted in Lake Geneva in

summer 2011 (www.lemo.ch, last accessed 28 February 2013). The éLEMO project is an interdisciplinary research initiative where multiple research groups coming from different Swiss and international institutions have joined their efforts in a comprehensive study of lake processes.

The analysis carried out in the present paper relies on two types of imagery data: raw video and stereographic images. Video was recorded with the submersible's camera attached to the portside robotic arm. The two stereographic cameras were set about 9 cm apart from each other and both fired continuously at a frequency of 2 frames per second. For all dive profiles, the general strategy was to record video and stereographic imagery whenever the submersibles were navigating right over the lake-bottom.

2.2. Lake-bottom classification from video recording

Lake-bottom topography was characterized by visual inspection of the raw video to establish a list of sedimentary structures. The analysis was done using a collaborative, web-based GIS interface (Akhtman *et al.*, 2012) where the video record had been indexed with navigation data. Structures are defined as morphological elements shaping the lake-bottom landscape, consisting of accretions or incisions, with typical size ranging from decimeter to meter. They can be repeated with some degree of regularity in their spatial arrangement (e.g., pillow-hollows or sediment waves), organized in networks (e.g., trenches), or isolated (e.g., single depressions); see section 3.1 for a description of the structures. Structure identification can be affected by certain characteristics of the video record such as perspective, backscatter and image quality. Distinctive characters were used, such as the connectivity of local topographic lows between adjacent bedforms and the extent and uniformity of the lake-bottom coverage by the bedform pattern.

2.3. 3D model reconstruction

Image sequences used to generate 3D models of the lake bottom had to be manually selected to retain only high-quality images. Low-light settings required by underwater photography yield noisy images and the local descriptor-matching approach at the basis of image registration is highly sensitive to noise. Images were preprocessed using edge-detection methods to mask the submersible's

robotic arm which is sometimes present. After applying the resulting mask, images are subjected to histogram equalization before being fed to the commercially available image registration software Agisoft Photoscan Pro. The 3D models are finally scaled using an algorithm calibrated with the known distance between the stereographic cameras. The camera calibration allowed producing reliable 3D models up to 50 meters long, corresponding to sequences of about 1000 images. Depth maps are directly obtained by projection of the 3D models on the plane normal to the orientation of the cameras. The 3D point cloud is then interpolated using a distance-weighted function. Low frequencies are removed from in order to use the entire grayscale of the image to represent sediment structures only. Figure 1 (placed at the end of the paper) shows the products the above processing for one sequence of pillow-depressions used as an example.

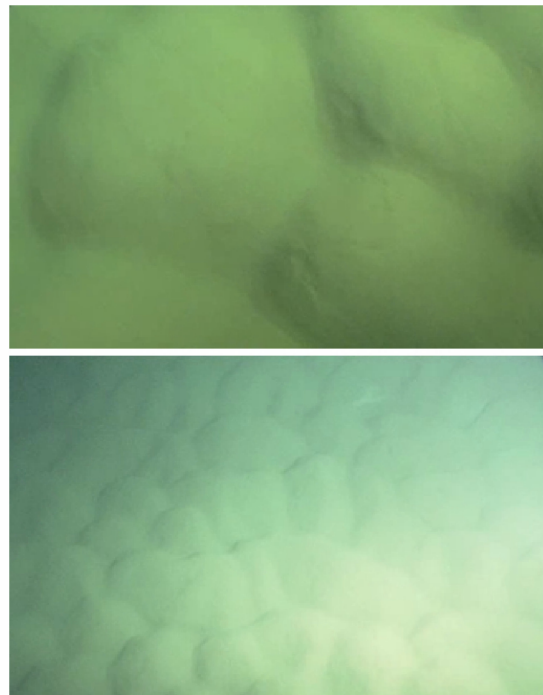


Figure 2. Pillow-hollows (close-up and perspective).

3. RESULTS

3.1. Designation of the sediment structures
A set of observation keys was defined to describe the lake-bottom structures. Representative examples of all structures are shown in Figures 2 to 5, where the image dimension ranges from 1 to a few meters, depending on the distance and angle between the camera on the robotic arm and the bottom. The structures most commonly observed are pillow-hollows, quilted-cover, sediment waves and trenches. Pillow-hollows (Figure 2) are large, well-rounded, cushion-like structures staggered over the lake bottom and usually separated by comparatively narrow troughs. The quilted-cover (Figure 3) consists of local topographic lows (depressions) alternating with local highs (bumps) in a regular and widespread pattern. The depressions are usually circular and smooth, separated by saddles or ridges that prevent the formation of fully connected drainage paths. Sediment waves (Figure 4A) designate sub-parallel ridges extending in one direction, with low-relief crests about 1 m wide and troughs narrower than typical dunes. In general, they are somewhat sinuous and not markedly asymmetric.

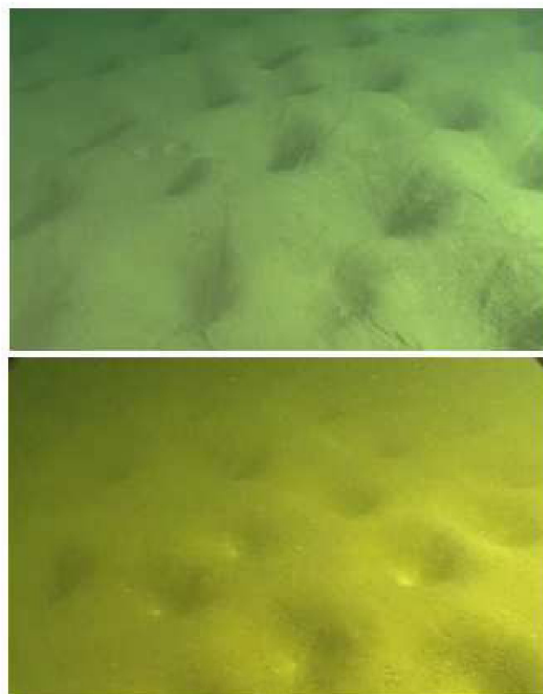


Figure 3. Quilted-cover on two different sediment types.

Trenches (Figure 4B) denote continuous troughs forming branching networks. Areas between trenches may either consist of flat bed or show bedforms, usually pillows and sediment waves.

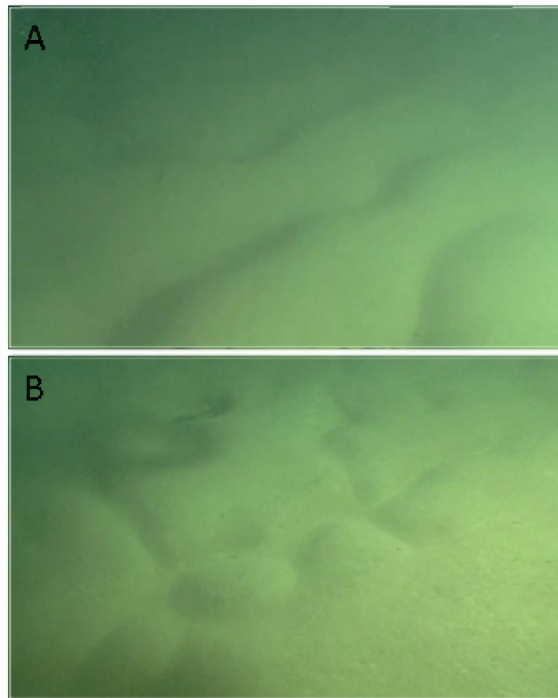


Figure 4. Sediment waves (A) and trenches (B).

Three additional types are defined to describe bedforms corresponding to a transition between structures or a variation on a structure. Pillow-trenches (Figure 5A) naturally refer to the combination of pillows and trenches. Cuspate pillows (Figure 5B) have the same planar geometry as pillow-hollows, but a flatter top and a steep lee side making them more markedly asymmetric than the rounded, cushion-like pillow-hollows. Pillow-depressions (Figure 5C) are similar to the quilted-cover but with lower saddles separating depressions and connecting bumps. Regions of the lake-bottom devoid of topographic structures are labeled as flat bed.

Finally, isolated depressions (Figure 5D) are observed, usually but not exclusively over a flat bed. These local topographic lows are circular with rims either fairly steep or smoothed. Their typical dimension of about 0.1 m is smaller than

pockmarks (Wessels *et al.*, 2010) but their shape is similar. They tend to happen in small groups but only cover a small fraction of the lake bottom. In some cases a narrow and shallow channel can connect a few single depressions, but their spatial arrangement is generally random.

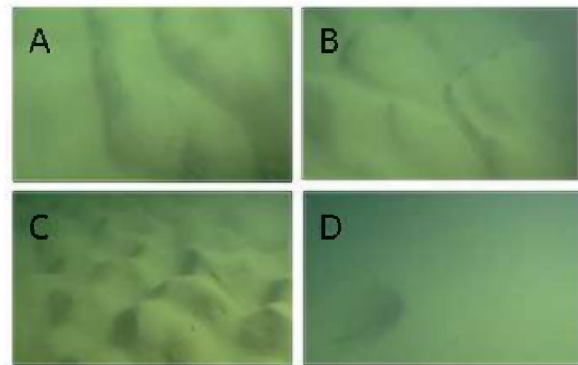


Figure 5. Lake-bottom images representing pillow-trenches (A), cuspate pillows (B), pillow-depressions (C) and an isolated depression (D).

3.2. New insight from selected 3D models
Reconstructed models yield additional information not included in the still images. Figure 6 (placed at the end of the paper) shows examples of 3D models for the four main structures. Continuous extension of the models along the submersible's track provides a spatial context to examine morphological properties and assess the uniformity of the lake-bottom landscape at the level of several consecutive bedforms. For example, models reveal the existence of more or less well-marked networks of channels connecting troughs or depressions in most sequences showing pillows, as can be seen both in the depth maps and in the perspective view (Figures 1 and 6A). Such continuous channel networks are absent in the case of the quilted-cover. For isotropic bedforms like the quilted-cover, the regularity of the pattern is confirmed over extensive sections of the lake bottom (Figure 6B). In the case of 1D-periodic bedforms like sediment waves, lateral continuity and wavelength homogeneity can be examined (Figure 6C).

The combination of multiple adjacent bedforms on a single model also reveals the existence of a low

spatial frequency perturbation on the main slope in most sequences. Removing background lake-bottom undulations enhances the morphology of the sediment structures. Figure 1 shows how the level of connectivity between the depressions more readily stands out after filtering. The height of the saddles separating depressions, which controls connectivity between depressions, can be used as a quantitative parameter to discriminate quilted-cover from pillow-hollows.

Finally, the possibility to manipulate 3D models with texture and shadowing voids biases related to the perspective of still images and ensures more objective assignments of structure types.

4. DISCUSSION

Our overall goal in characterizing the lake-bottom morphology is to infer the nature and origin of the bedforms. Their evolution as well as their interaction with transport and biogeochemical transformation processes may be predicted on the basis of proposed models for their formation.

4.1. Sediment transport driven by hydrodynamic processes

Geotechnical measurements (Stark *et al.*, submitted) as well as sedimentological analyses indicate that bottom sediment mostly consists of fine and poorly consolidated materials with very low shear strength. Small velocity thresholds, on the order of a few mm/sec, are sufficient for sediment resuspension. Most of Lake Geneva is over 200 m deep, so wind-induced surface currents are damped where bedforms are observed. However, some processes locally generate significant near-bottom currents, notably shore-hugging Kelvin waves and density flows acting along the slopes. Caused by a combination of wind stress-induced pycnocline tilting in stratified conditions and Coriolis forcing, Kelvin waves are internal waves rotating counter-clockwise (in the Northern Hemisphere) that are confined to a narrow band along the lake's shore (Lemmin *et al.*, 2005). Rapid cooling of surface waters can occur in shallow areas near the shores of cold-region lakes (alpine or high altitude and high latitude lakes) during winter. The denser water masses near the shores plunge and cascade downslope as density currents (Fer *et al.*, 2002). The orientation

of asymmetric bedforms like the cusped pillows relative the main slope can be used to distinguish these two mechanisms. In addition, episodic currents with velocity on the order of cm/s have been recorded at a long-term monitoring site on the lake bottom (Lemmin, unpublished data). They are assumed to be related to internal wave dynamics of the lake.

4.2. Other processes

Entrainment of sediment from the bottom can arise through mechanisms other than fluid shear. Boyer *et al.* (1990) have observed foraging trenches about 30 cm deep made by Burbot fish in Lake Superior, showing the capacity of Burbot fish to rework large amounts of sediment. Katz *et al.* (2012) report that significant sediment resuspension by bottom-dwelling fish along the oxygenated margins of Saanich Inlet in British Columbia is at the origin of an intermediate nepheloid layer in the inlet. There is no doubt that Burbot fish play a significant role in at least maintaining the depressions in most sediment structures occurring at the bottom of Lake Geneva, as confirmed by repeated observations of turbation activity of Burbot fish at the lake bottom during this and prior campaigns.

Processes occurring within the sediment could also be at the origin of the development of the observed sediment structures. For instance, bioturbation causes local changes in the rheological behavior of the sediment and may induce spatial heterogeneity in the response of the sediment substrate to erosion and deposition processes.

Gas expulsion is known to form craters in immersed granular layers (Varas *et al.*, 2009) and could be responsible for the development of depressions at the lake bottom, in particular the isolated depressions. Significant methane bubbling has been observed in Lake Geneva (Sollberger *et al.*, submitted), although there is no evidence of large pockmarks as in Lake Constance (Wessels *et al.*, 2010).

Finally, in hydrodynamically quiescent environments, slow deformation of lake-bottom sediment under their own weight is possible given their very low strength. Bedform asymmetry could then result from long-term creep.

4.3. Direction of continuing work

Further analysis of the dataset is in progress following two main approaches. First, a distribution map will be generated from systematic classification of the entire video dataset. Correlations with the variations of relevant limnological parameters like depth, topography or near-bottom current velocity will be investigated to assess candidate mechanisms for bedform development. Second, a quantitative analysis of morphological characters will be carried out using the depth maps. Identifying metrics for bedform geometry that yield an objective discrimination will allow validating the visual classification. Contextual analyses of descriptors such as connectivity and anisotropy will be conducted on extensive 3D models.

5. CONCLUSION

With the exception of the isolated depressions, for which the authors are not aware of prior reference in the literature, all structure types described in this paper had been previously reported in Lake Geneva. However, the extent of the video dataset coverage and the 3D model reconstructions enabled a finer assessment of the variations in the observed lake-bottom structures and of their spatial consistency, revealing a rather continuous range of morphologies. Future work on the dynamics of these sediment structures is under consideration. Understanding the formation and evolution of bottom sediment structures is relevant for the benthic processes on which bottom topography has a significant impact.

6. ACKNOWLEDGMENT

Funding for this study was provided via the éLEMO project supported by the “Fondation pour l’Etude des Eaux du Léman”. The authors are grateful to the MIR crew and in particular to the pilots.

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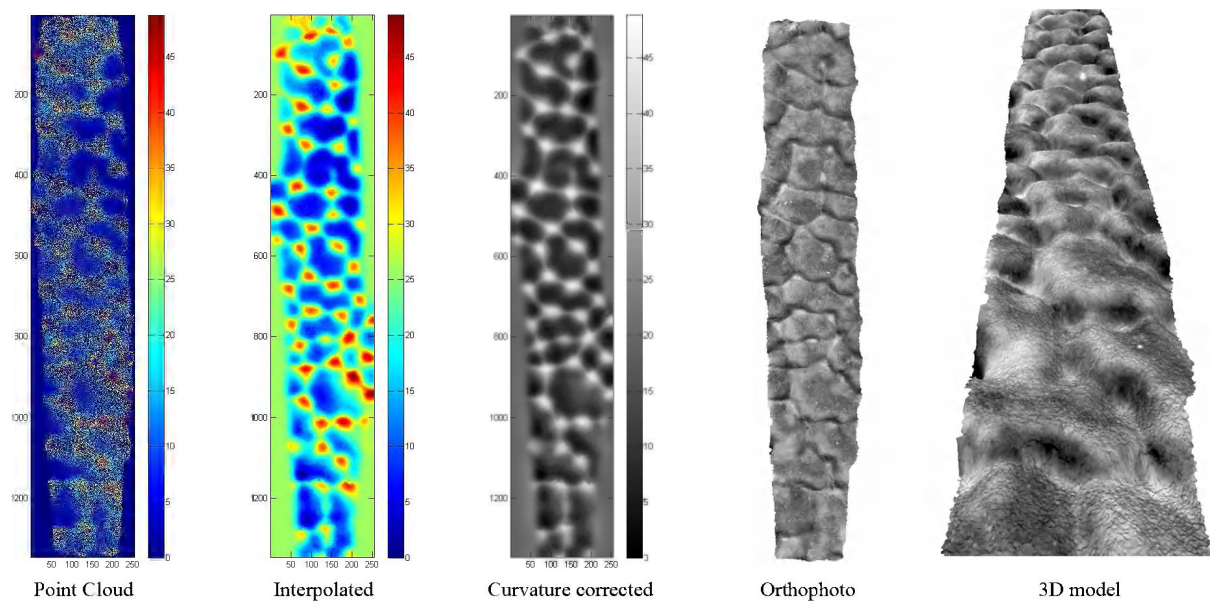


Figure 1. Depth map and model computed at 100 pixels per meter depicting a 14 m × 3 m section of the lake bottom with sediment structures about 0.5 m in height; see section 2.3 for details on the processing steps. Height is positive downward, *i.e.* low-relief is red in color images and white in black-and-white images. All scales are in cm.

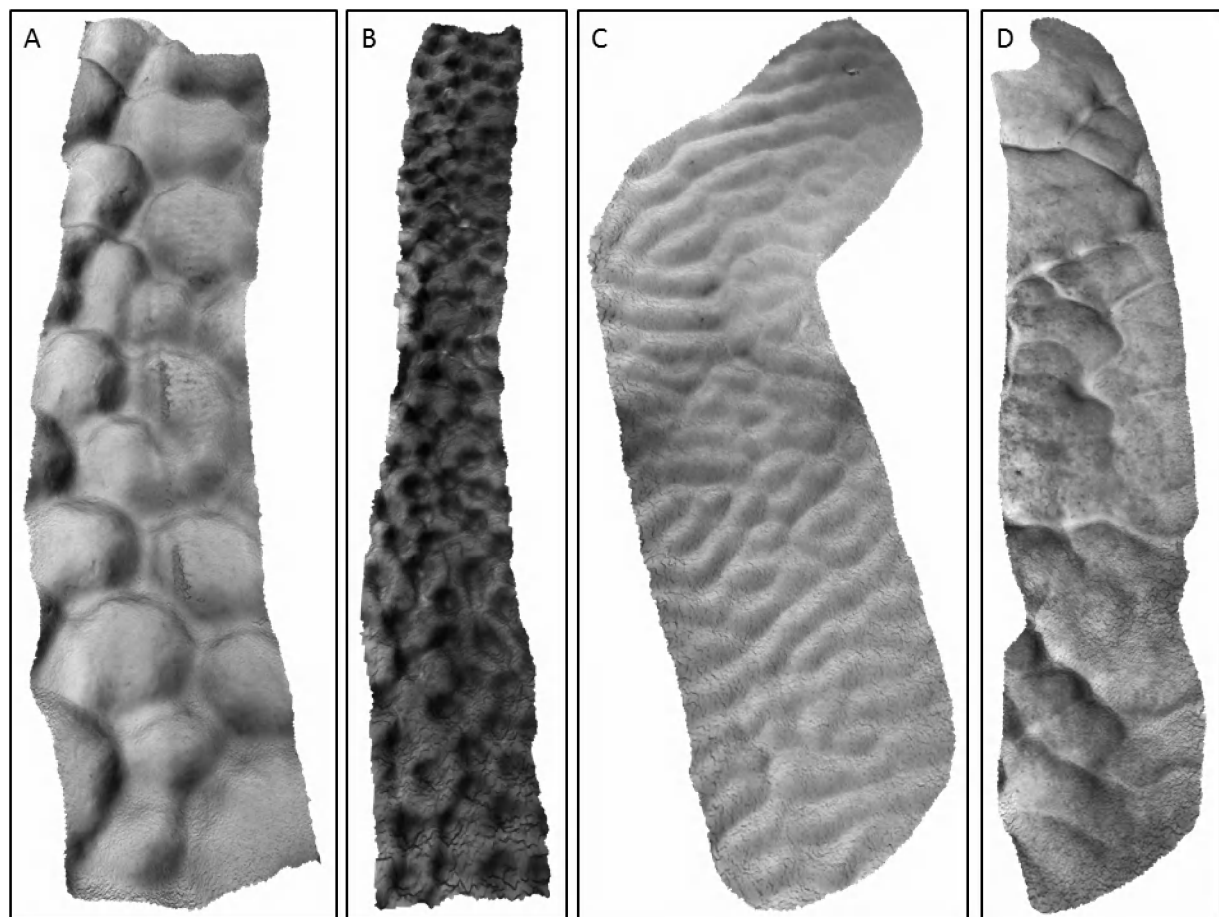


Figure 6. 3D models of pillow-hollows (A), quilted-cover (B), sediment waves (C) and trenches (D).