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Generalized maps for erosion and sedimentation simulation

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ABSTRACT

We propose a new approach, based on dynamic animation, to simulate geomorphological events such as erosion, sediment transportation and deposition. It relies on a *generalized map* representation of different geological layers. The topological evolution of these layers is driven by a set of displacements applied onto the vertices. The topological consistency of the model is guaranteed by a collision detection system that handles vertices, edges, or faces through generic operations. Experimental results show the ability of this approach to simulate various evolution scenarios studied in geology. Fluid simulation is added to implement fluid–solid interactions based on a hydrology model. These interactions generate animations of hydraulic erosion and sedimentation phenomena.

1. Introduction

Realistic landforms represent a key element in computer-generated scenes as they set the stage where all the other elements will be positioned. In Earth science, landscape formation and evolution are part of geomorphology, which studies how the Earth's surface has been shaped during millions of years. This paper focuses on *dynamic* geomorphology, *i.e.*, on external processes: erosion (due to wind and/or water), transportation, and sedimentation of carried elements. These phenomena affect the shape and topology of the terrain, with the creation of caves, arches, or tunnels. Fig. 1 shows the example of Percé Rock near Gaspé (Canada), which had two arches as depicted on the first picture of the island around 1760 [1]. Because of coastal erosion, one of them collapsed in 1845, leaving a separate stack above the sea surface, as shown on the top right photo.

We present a method that simulates the evolution of a terrain, topologically represented by a 3D generalized map or *3-G-map* [2]. This model is able to handle concavities or complex topological structures with holes, as shown for example in Fig. 1d–f, unlike traditional meshes that only represent surfaces. The animation model is based on vertex displacement, and a collision detection system is used for dealing with topological inconsistencies. Inconsistencies trigger corrective operations that can create new vertices with their own displacement. Differential erosion, *i.e.*, the variation of resistance of different rock types exposed to erosion, can be simulated with this approach. The most friable layers are eroded and disappear over time, whereas resistant rocks remain to form stacks, cliffs, or arches.

In computer graphics, different papers focus on the visible surface of the terrain represented as a heightfield [3–5]. They simulate the terrain alteration with physical approaches in order to create fine scale details, such as a fluid flow generating erosion and sedimentation through chemical and mechanical interactions. However, this type of representation cannot handle multiple geological layers. Voxel-based representations are more appropriate in this case but involve higher memory costs [6–8]. Layered-data structures combine voxels with height maps to alleviate this limitation [3,9–12]. Finally, other methods rely on a topological model representation of the geological layers composing a terrain [13]. The approach described in this paper belongs to the latter family. Its main advantages are its compact representation and its ability to express the global deformation of a geological volume through the displacement of its vertices.

As shown in Fig. 2, the input of the process is an initial model defined by the user with the 3-G-map formalism. Some of its vertices are selected and displaced over time. The displacement can also be computed automatically with a fluid simulation integrated in the system. The main animation loop involves two stages: as vertices are displaced, they can collide with volumes that represent geological layers. These collisions are handled by a set of different operations. They are also used to generate and define the displacement of new vertices. The animation loop can export an altered version of the initial model at various stages of its evolution.

The main contributions of this approach are:

- A set of generic operations able to handle the evolution of geological layers represented by a 3-G-map. These layers can have different resistances to erosion.

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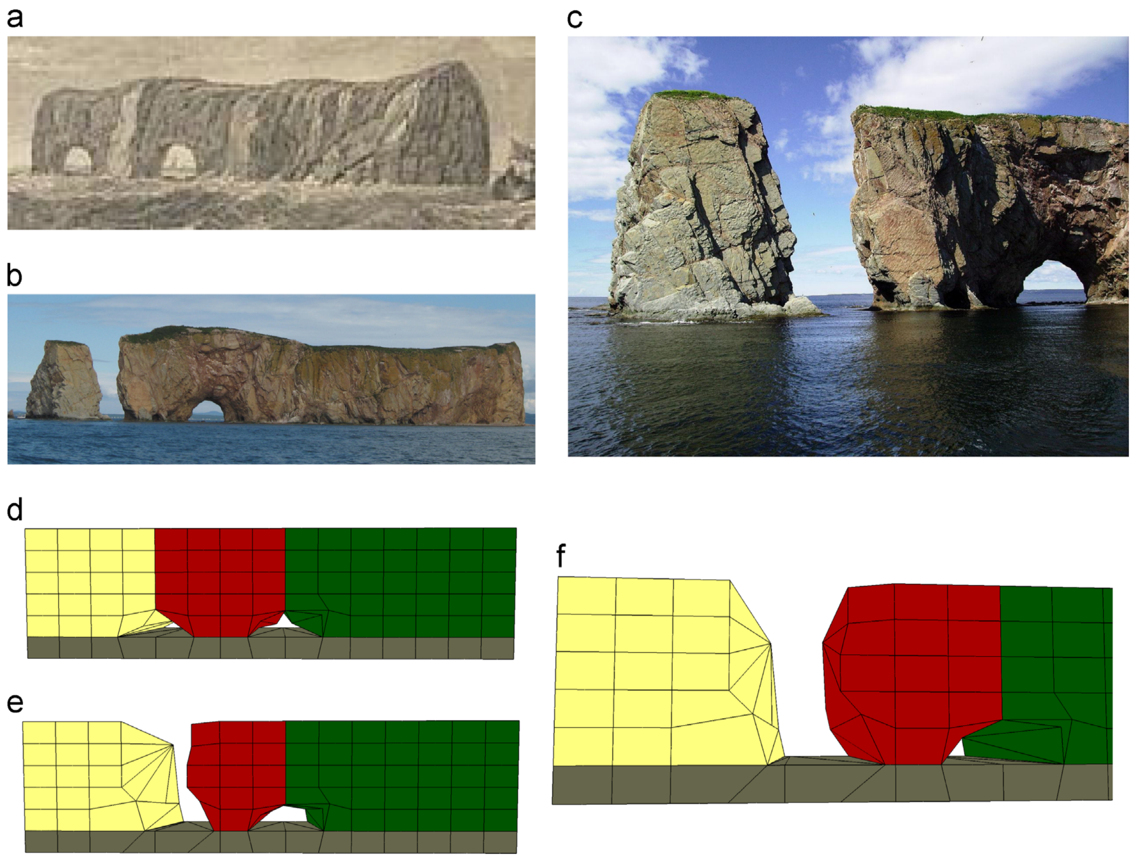

Fig. 1. Percé Rock island near Gaspé (Canada): (a) *Circa* 1760 with two arches [1]. (b) Same view nowadays with only one arch remaining. (c) Zoom on the left part of the island; (d–f) Similar models produced by our method.

- An implementation of erosion and sedimentation processes at large spatial and temporal scales. Geology teachers and researchers could benefit from this work to generate various illustrative descriptions of geomorphological scenarios.
- An interaction model between the terrain and a fluid simulation, based on sediment transport models used by hydrologists and geologists.

The following section presents related work on terrain generation and evolution through geomorphological phenomena. Section 3 recalls the basic definitions attached to 3-G-maps. Section 4 describes the evolution of our model using a set of topological operations. The fluid/solid interaction model is introduced in Section 5. Section 6 details several applications to generate landforms through user-defined scenarios and interactions with the fluid simulation. We conclude and present future work in Section 7.

2. Related work

Computer applications specifically intended for geomorphological studies are usually related to Geographic Information Systems, but limited to surface representations. For instance, such systems can help model terrains consistent with aerial photography [14], visualize erosion patterns on a complicated land surface topography [15], or study the dynamics of sheet erosion [16]. An example of inner structures representation is given by Lidal et al. [17]. Geologists can generate visualizations of structural processes that take place in the subsurface using sketch-based modeling. However, in this case, the consistency of modifications in rock layers is solely guaranteed by experts, and the 3D model is merely obtained by an extrusion of 2D sketches. Sketches are also used by Amorim et al. [18] to build the structural framework of a reservoir model.

In computer graphics, the key feature of existing methods that deal with terrain generation and evolution over time is the representation of the terrain's surface and/or the subsoil. Early work [19] uses a discrete representation of the surface, *e.g.*, 3D meshes or height maps, to limit memory consumption. This approach is used by different authors [3,4,20–22] to produce visually realistic scenes involving erosion and sedimentation interactions with a fluid model. Other work focuses on micro-scale degradations such as aging [23], stone weathering [24], or corrosion [25]. Large-scale surfaces built by Geneveaux et al. [5] are based on an implicit representation of ridges and valleys that are consistent with a hydrological network. However, surface models are not able to represent concavities or holes if they lead to vertical overlap. The geomorphological phenomena that can be handled by this approach are thus limited to vertical deformations in order to avoid topological inconsistencies, such as self-intersections in the 3D mesh.

In order to overcome these problems, other approaches rely on a voxel-based representation, where each voxel accounts for a different portion of the terrain with its own type of rock material and resistance to erosion. Voxels can be tagged as containing air that allows complex geometries and topological changes [6–8]. Fluid/solid interactions are simulated by Chen et al. [26] to create shapes resulting from hydraulic erosion. Surface degradation by rainfall is also studied by Valette et al. [27] at a square-meter scale. It uses an