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Sketch-based modelling and visualization of geological deposition

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ABSTRACT

We propose a method for sketching and visualizing geological models by sequentially defining stratigraphic layers, where each layer represents a unique erosion or deposition event. Evolution of rivers and deltas is important for geologists when interpreting the stratigraphy of the subsurface, in particular for hydrocarbon exploration. We illustratively visualize mountains, basins, lakes, rivers and deltas, and how they change the morphology of a terrain during their evolution. We present a compact representation of the model and a novel rendering algorithm that allows us to obtain an interactive and illustrative layer-cake visualization. A user study has been performed to evaluate our method.

1. Introduction

Geologists are interested in better tools for externalizing their ideas on the earth's behaviour. They want to do this in an expressive and simple way, which is particularly important for communicative purposes. Current modelling tools in geology have a high learning curve and are tedious to use (Caumon et al., 2009). We present a simple sketching interface and a data structure for compact representation and flexible rendering of subsurface layer structures. This is useful for representing mountains, basins, lakes, rivers and deltas. Rivers and deltas change the morphology of a terrain through erosional and depositional processes. This is left as imprints in layers of the terrain. Our technique provides a way to sketch and visualize such layers (Fig. 1). Our representation is well suited to obtain interactive layer-cake visualizations, resulting in geological illustrations that are helpful for education and communication. Conventional hydrocarbon reservoirs (and aquifers) are found in porous bodies of rock. Examples of such rock bodies include sandstone, which is found in sedimentary basins and has a high preservation potential (Hinderer, 2012). The sandstone might, under favourable circumstances and the right basin development (where hydrocarbon source rock and reservoir seal is present), become a reservoir for hydrocarbons. This is, in a crude sense, the reason why these rock bodies receive a lot of focus in geology, and a motivation to try to understand them to the full extent that data allows.

Available data (e.g. seismic, well logs or core) can often be of limited resolution and extent. In these cases, geologists have to develop conceptual ideas to describe the shape of rock bodies, and, from that, which processes were involved in their deposition. The processes involved in the deposition of sandstone bodies are known to vary between different depositional environments, and can thus be differentiated based on observations and interpretation (Reading, 1996). To develop good conceptual models for the reservoir sandstone, their horizontal and cross-sectional characteristics are often highlighted by schematic block diagrams (e.g. Gani and Bhattacharya, 2007, Porębski and Steel, 2003). In Fig. 2 (left), an example of a hand-drawn block diagram depicting a meandering river channel is shown. It illustrates the aerial and the cross sectional expression of sandstone point bars (sediments deposited along the inner bank of a meandering stream) and how one sandstone body is overlaid by another. Internal architecture is important in the sense that it tells how the depositional element (e.g. channel or delta) evolved, and subsequently how small-scale heterogeneities such as mudstone might be distributed within the overall sandy body. This can have direct implication for hydrocarbon fluid extraction. Our approach offers a new way of producing illustrations by performing interactive erosion and deposition that lets the illustrator mimic processes that she interprets to have been the cause for the sandstone deposition. An additional consequence of our 3D sketched models is their manoeuvrable cutting planes that enable multiple cross-section visualizations. This helps in understanding complex internal layering within the sandstone, otherwise not intuitively apprehensible (Bridge, 1993). Among the depositional systems that may result in hydrocarbon accumulation, rivers and deltas are central.

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In summary, our overall contribution is a sketch-based system that makes it possible to quickly build 3D interactive geological illustrations from scratch. Sequentially defining alterations on a model is less laborious than drawing 2D illustrations; this opens up for discussions, fast hypothesis testing and creation of time-series illustrations. A novel central aspect lies in the proposed data structure (each stratigraphic layer corresponds to a composition of one or more heightmaps) and the way it is processed to render volumetric models. The main features that characterize our tool consist of operators that interpret each sketch to generate deposition and erosion processes; in particular, rivers and channels, mountains, basins, deltas and intermediate stages of their evolution.

2. Related work

Little work exists on modelling and visualizing deltas in computer graphics. For modelling rivers and erosion in a geological setting, most of the methods are based on fractal noise generation and physical based processes (for instance the works of Benes et al., 2006 and Stava et al., 2008). Such procedural approaches reduce the degree of control over the landscape development. Other sketch-based techniques have been introduced to model landforms on a terrain (Hnaidi et al., 2010; Gain et al., 2009), but they only consider the top surface and not subsurface structures, as we do. Some work in geology focuses on producing layered representations of the earth by modelling the mesh of each separating surface individually, like Baojun et al. (2009), but are not sketch-based and therefore time consuming. Amorim et al. (2012) address 3D seismic interpretation by modelling one surface at a time, while Cutler et al. (2002) propose a procedural method to obtain layered solid models. None of these two last works consider fluvial systems consisting of lakes, rivers or deltas.

A state of the art report on modelling of terrains and subsurface geology was presented by Natali et al. (2013). There two works are reviewed that describe volumetric representations applicable in geology, although they do not discuss how to sketch them fast as we do. Takayama et al. (2010) obtain layered models using diffusion surfaces. Wang et al. (2011) represent objects using signed distance functions. Composite objects are created by combining implicit functions in a tree structure which makes it possible to produce volumes made of many smaller inner components.

Geostatistics: The Surface- and the event-based modelling have recently been developed as a branch of geostatistics. Xie et al. (2000) suggest depositional and erosional surface-based models as collections of separate sediment units, each of them stochastically generated. Lopez et al. (2001) create their 3D models, in the context of meandering channelized reservoirs, combining a process-based approach to model river motion and deposition, and a stochastic approach to respect vertical proportion curves that reflect natural behaviour. Pyrcz et al. (2005), Pyrcz (2004), Michaels et al. (2010), and Abrahamsen et al. (2012) use statistical analysis on process-based models to create surface-based distributary lobe models with the addition of available geologic information. Pyrcz et al. (2012) present new applications for event-based models and methods to

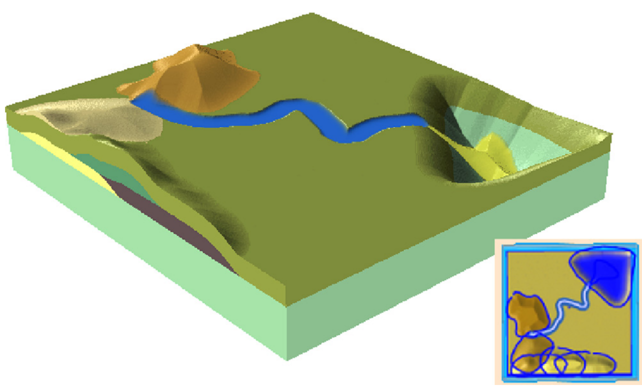

Fig. 1. A 3D model created using our sketch-based approach to shape surface and subsurface geological features. Bottom right inset shows a map view of the sketched strokes in blue overlaid on the model. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

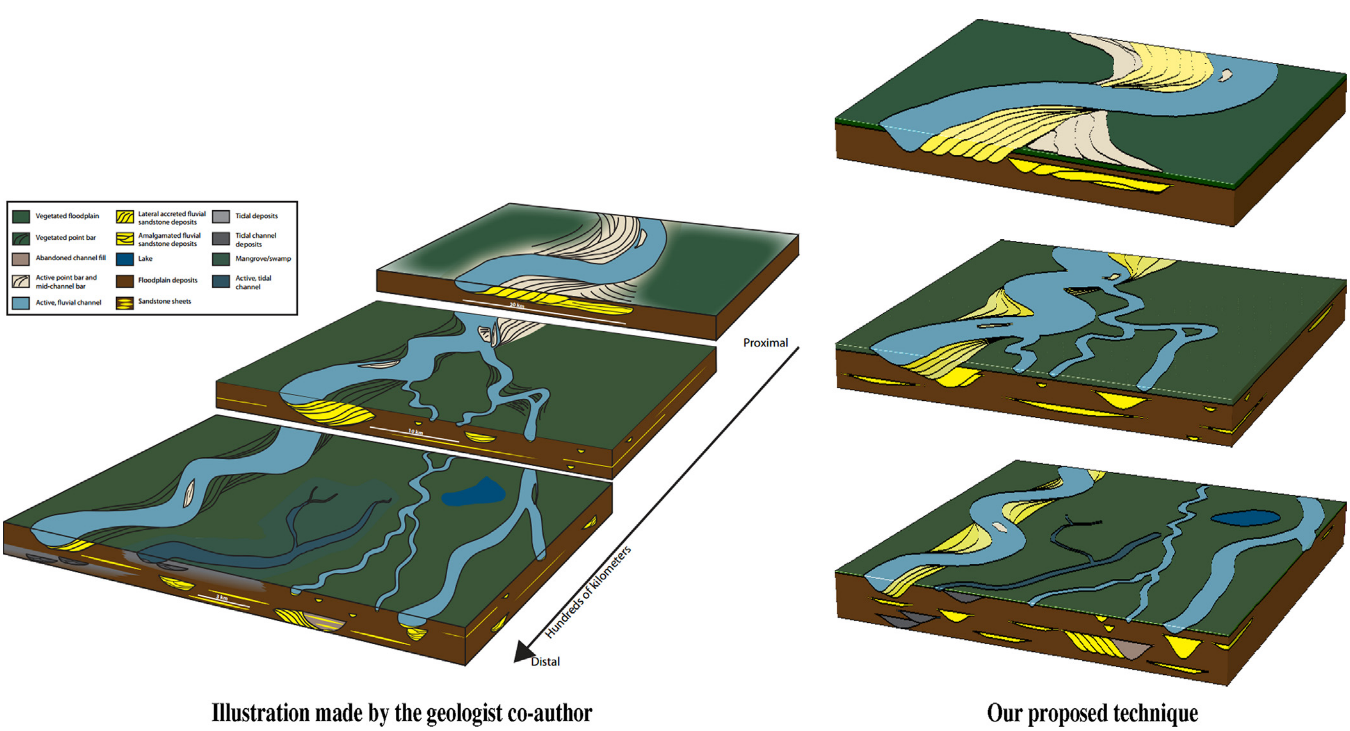

Fig. 2. Comparison between a 2D hand made illustration of a river sedimentation process (left) which took one working day to produce and the result achieved with our approach (right) which took 1 h to produce. The example is a real case analysis built from field observations.