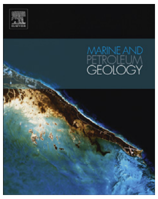
Marine and Petroleum Geology 86 (2017) 79–94

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo



Research paper

Modeling uncertainty in the three-dimensional structural deformation and stratigraphic evolution from outcrop data: Implications for submarine channel knickpoint recognition

Lisa Stright [a, *], Zane Jobe [b], Julie C. Fosdick [c], Anne Bernhardt [d]

[a] Department of Geosciences, Colorado State University, Fort Collins, CO, United States
[b] Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, United States
[c] Department of Geography and Center for Integrative Geosciences, University of Connecticut, Storrs, CT 06269, United States
[d] Institute of Geological Sciences, Freie Universität Berlin, Germany

ARTICLE INFO

Article history:
Received 30 August 2016
Received in revised form
14 April 2017
Accepted 1 May 2017
Available online 3 May 2017

Keywords:
Structural modeling
Stratigraphic modeling
Deep-water channels
Stratigraphic grade
Magallanes Basin
Cerro Toro Formation
Knickpoint
Digital outcrop model

ABSTRACT

Digital outcrop models help to constrain the interactions of stratigraphic and structural heterogeneity on ancient depositional systems. This study uses a stochastic approach that incorporates stratigraphic and structural modeling to interrogate the three-dimensional morphology of deep-water channel strata outcropping on Sierra del Toro in the Magallanes Basin of Chile. This approach considers the relative contributions, and associated uncertainty, of erosional downcutting versus post-depositional structural folding and small-offset faulting on the present-day configuration of the submarine channel complexes. Paleodepositional channel-belt gradients were modeled using a combination of three-dimensional visualization, stochastic surface modeling, palinspastic restoration, and decompaction modeling that are bound with errors constrained by stratigraphic and structural uncertainty. Modeling results indicate that at least 100 m of downcutting occurs over 6 km, and the resultant thalweg gradient of 64–125 m/km (decompacted) suggests that the Cerro Toro axial channel belt is an out-of-grade depositional system. Furthermore, the presence of steeper segments (100–175 m/km decompacted) suggests the preservation of one or more knickpoints that are similar in magnitude to tectonically-induced knickpoints on the modern seafloor. The interpreted knickpoints are correlated with a decreasing channel width-depth ratio and an increase of channel depth. These results indicate that stochastic surface modeling using digital outcrop models can constrain stratigraphic interpretations and post-depositional structural heterogeneity.

1. Introduction

Virtual outcrops are computer-rendered three-dimensional topographic representations of outcrop exposures (Enge et al., 2007). They provide a spatially referenced template to supplement data collected in field geology studies. These virtual outcrops enhance quantitative data collection from outcrops by providing an opportunity for more detailed, “birds-eye view” stratigraphic interpretations and measurements (e.g., Fabuel-Perez et al., 2009; Nieminski and Graham, 2017). Traditional field data (i.e., measured sedimentary sections, structural attitude measurements, and photopanel interpretations) are increasingly being combined with these digital data into three-dimensional computer models, or digital outcrop models (DOMs; Bellian, 2005; McCaffrey et al., 2005; Enge et al., 2007; Fabuel-Perez et al., 2009; Hodgetts, 2013). The recent proliferation of inexpensive unmanned aerial systems and Structure-from-Motion software has allowed much easier creation of virtual outcrops and DOMs (e.g., Nieminski and Graham, 2017). To create a DOM, the stratigraphy is interpreted directly from the virtual outcrop in a three-dimensional modeling software package (Tomàs et al., 2010; Eide et al., 2014). The polylines from this digital interpretation are then gridded into stratigraphic surfaces for the DOM framework; when the surface interpolation is simple, a ‘near-deterministic’ model of the outcrop can be created (Fabuel-Perez et al., 2010). If structural overprints exist, the surfaces need to be restored to obtain paleodepositional surfaces prior to DOM construction (e.g., Fernandez et al., 2004;

---

* Corresponding author.
E-mail address: lisa.stright@colostate.edu (L. Stright).

http://dx.doi.org/10.1016/j.marpetgeo.2017.05.004
0264-8172/

Falivene et al., 2006). Many outcrops are referred to as three-dimensional exposures, making surface construction straightforward. However, no outcrop is truly three-dimensional and nearly all offer incomplete exposures due to eroded or covered strata. Furthermore, surface construction from mapped outcrop points is only straightforward for planar stratigraphic surfaces across multiple outcrop exposures. Where outcrop exposures are limited or the relief on stratigraphic surfaces varies substantially (e.g., irregular erosional surfaces), establishing a precise and robust geometrical framework for a DOM remains a challenge.

In many cases, there may be significant uncertainty in interpreting and interpolating three-dimensional surfaces from outcrop data, even with the benefit from additional digital data of a virtual outcrop. Tectonic deformation may further complicate the preservation and interpretation of stratigraphic surfaces, either by minor folding and faulting or larger-scale post-depositional structural deformation. The traditional approach for DOM surface modeling is to generate surfaces that best fit data using available surface modeling algorithms (e.g., kriging, minimum curvature, etc.). Newer methods incorporate strike-and-dip data in the interpolation of a triangulated irregular network of points (TIN; e.g., Fernandez et al., 2009; Fabuel-Perez et al., 2010). With most methods, the modeled surface requires manual refinement to ensure that the data are interpreted correctly. Although this approach produces a surface that nominally fits the data, it is a single iteration that may be inaccurate and does not capture the uncertainty and full range of all plausible surface geometries. Moreover, errors in this surface modeling step will propagate through subsequent digital outcrop modeling processes; without capturing the range of uncertainty a priori, the impact on the interpretation and/or conclusions drawn from the model are unknown. When outcrop modeling is relied upon for prediction of stratigraphic relationships, these errors could generate misleading interpretations and thus should be modeled in order to understand their effects on interpretation.

This study quantifies the range of uncertainty surrounding surface modeling of digital outcrop models (DOMs) and applies stochastic surface modeling methods to address stratigraphic questions in an outcropping submarine channel complex. The goal is to decipher the uncertainty of erosional processes and the related channel geometry at the time of active channel formation and post-depositional structural deformation that later obscured the initial channel margin and channel bottom geometry. Jobe et al. (2010) studied and named the “Wildcat” channel complex, a coarse-grained conglomeratic unit of the Upper Cretaceous Cerro Toro axial deep-water channel-belt exposed on Sierra del Toro in the Magallanes Basin, Southern Chile. The data, analysis and interpretation from Jobe et al. (2010) were used in this study and augmented with the addition of nearly 200 new strike and dip measurements to bolster the structural deformation analysis. Our modeling framework also accounts for structural deformation by using a palinspastic restoration to constrain the post-depositional shortening. This reconstruction is an important step in understanding the paleo-channel geomorphology and channel thalweg gradient, as slight changes in structural deformation could obscure gradient predictions and interpretation of features such as knickpoints.

Analyses of (paleo)-channel morphology can yield important insights into the tectonically and climatically induced erosional processes. In terrestrial geomorphology, migrating knickpoints have long been recognized as important indicators for changes in base-level fall (Howard et al., 1994). These processes are crucial to terrestrial landscape evolution as fluvial incision in response to climatic and tectonic forcing drives hillslope erosion and therefore controls landscape-wide denudation rates (Howard et al., 1994; Whipple and Tucker, 1999; Crosby and Whipple, 2006). In marine systems, knickpoints have been shown to be caused by meander cutoffs (Sylvester and Covault, 2016), channel confluences (Jobe et al., 2015) and tectonic perturbation (Pirmez et al., 2000; Heiniö and Davies, 2007). However, the effects of knickpoint migration on deep-marine stratigraphic architecture are, in general, still poorly understood.

Three-dimensional stochastic surface modeling of this outcrop captures a range of plausible stratigraphic surfaces that match the partially-exposed erosional surface around the outcrop face, and help to quantify 1) the channel surface morphology, and 2) channel thalweg gradient in the Wildcat channel. Finally, this study assesses the uncertainty of the relative contributions of erosional processes at the time of channel formation versus post-depositional structural deformation through coupled stochastic stratigraphic and structural modeling.

2. Study area

2.1. Magallanes Basin

2.1.1. Basin formation and filling

The Magallanes Basin is a retroarc foreland basin that records Upper Cretaceous through Miocene orogenesis during tectonic development of the Patagonian Andes (Fig. 1A; Dalziel, 1981; Wilson, 1991; Fildani and Hessler, 2005; Fosdick et al., 2011). Its predecessor basin, the quasi-oceanic Rocas Verdes backarc basin, was a rift basin formed during the break-up of Gondwana in the Late Jurassic (Dalziel et al., 1974; Biddle et al., 1986; Fildani and Hessler, 2005; Calderón et al., 2007). During the Late Cretaceous onset of the Andean orogeny in the Southern Andes, the basin was inverted from a backarc extensional setting to a retroarc foreland basin (Wilson, 1991; Fildani and Hessler, 2005). Flexural loading and subsidence of the foredeep formed an elongate north-south deep-water basin with bathyal water depths (Natland et al., 1974). This retroarc foreland basin was filled by sediments transported from the north and northwest along the narrow axis of the foredeep toward the south (Fig. 1A). Over a period of ca. 20 Myr, ~4000 m of sediment accumulated in the basin (Romans et al., 2011). For a full discussion of the basin filling and evolution, see Bernhardt et al. (2008) and Romans et al. (2011).

The Upper Cretaceous Cerro Toro Formation (>2000 m thick) is predominantly shale interbedded locally by meter-scale sandstone units and nearly 400 m of sandstone and conglomerate (Fig. 1C). These coarse-grained units are interpreted as a basin-axial deep-water channel-belt (Hubbard et al., 2008; Jobe et al., 2010). Extensive paleocurrent measurements in the Cerro Toro Formation suggest at least one tributary channel feeding a main trunk of the basin-axial channel-belt (Fig. 1B; Hubbard et al., 2008 and references therein). Bernhardt et al. (2012) further demonstrate that development of the basin-axial channel fill is contemporaneous with a tributary channel that lies 20 km west of this main channel belt (Fig. 1B).

2.1.2. Post-depositional deformation and exhumation

The Sierra del Toro mountain range resides in the eastern thrust domain of the basin, characterized by thin-skinned folding within the Upper Cretaceous foreland basin fill and superimposed basement-seated uplift (Fosdick et al., 2013). During Cenozoic time, the thrust front propagated eastward into the foreland basin, deforming and incorporating the Upper Cretaceous foredeep strata into the fold-thrust belt (Fig. 1B). Fosdick et al. (2011) document at least 30 km of Cenomanian-Miocene shortening across the fold-thrust belt as a result of both thin-skinned shortening within basin fill and deep-seated reverse faults revealed by seismic-