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Effect of carbonate platform morphology on syndepositional deformation: Insights from numerical modeling

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ABSTRACT

We use finite element numerical modeling to show that carbonate platform morphology is a control on syndepositional deformation in steep-walled carbonate platforms. We simulate gravity application on three end-member carbonate platform margin morphologies: (1) a mixed planar-concave up shaped shelf margin from Tobacco Cay, Belize, (2) a concave up shaped system representing the Capitan Profile, Guadalupe Mountains West Texas, and (3) a sigmoidal, Jurassic Amellago ramp. We model the platform material with a brittle failure criteria that captures tensile and shear failure. We show that the presence of a vertical reef wall and, thereby, lack of lateral confining stress seaward leads to a tensile stress state in the middle of the shelf and the shelf edge, promoting the development of opening-mode (Mode I) tensile fractures. Fractures occur in the absence of additional loading or burial, indicating that their formation is consistent with a syndepositional setting. Overall, our results demonstrate that carbonate platforms with a near vertical reef wall are routinely modified by syndepositional deformation and failure in the absence of compaction. We show that zones of high tensile stress can result in brittle, tensile failure and confirm that tensile failure is a critical element of building and may contribute to maintaining steep-walled carbonate platform systems.

1. Introduction

Steep-walled carbonate platforms are ubiquitous throughout Earth's history despite differences in ocean water chemistry and organic binding potential (i.e. different organisms) from the Precambrian to the modern (Grotzinger, 1989; Read, 1985). Steep-walled carbonate platforms have been documented as far back as the Precambrian, where their morphologies and development are very similar to their Phanerozoic counterparts (Grotzinger, 1989). The occurrence of syndepositional and/or early deformation is intrinsic in steep-rimmed carbonate platforms, where early lithification coupled with biological reef growth (Grammer et al., 1993b, 1999; James and Ginsburg, 1979b; Land and Moore, 1977) can create steep, upper slope and reef wall angles prone to failure (Frost and Kerans, 2009, 2010; Hunt and Fitchen, 1999) (Fig. 1). Syndepositional shelf margin collapse, faulting, and fracturing may alter the evolution of carbonate platform architecture and stratigraphy through time (Carpenter et al., 2006; Collins et al., 2006; Frost and Kerans, 2009; Hunt et al., 1995; Hurley, 1986; Kerans and Tinker, 1999; Narr et al., 2008; Playford et al., 1984; Stanton and Pray, 2004; Tinker, 1998; Yurewicz, 1976).

The Permian steep-rimmed carbonate shelf margin of the Guadalupe Mountains provides world-class outcrop exposures and type examples of syndepositional deformation (King, 1948; Stanton and Pray, 2004). Large faults and open-mode fractures documented within McKittrick, Slaughter, and Rattlesnake Canyons represent syndepositional deformation (Budd et al., 2013; Hunt et al., 2012; King, 1948; Mathisen, 2014; Rush and Kerans, 2010). At these locales, deformation is often centralized over the antecedent shelf margin and at the shelf edge (Frost and Kerans, 2009, 2010; Hunt and Fitchen, 1999; Mathisen, 2014). The faults and fractures are often filled with skeletal carbonate and/or siliciclastic sediments and marine cements, indicating their syndepositional origin, and have been documented to be long-lived fluid flow conduits (Budd et al., 2013; Carpenter et al., 2006; Frost et al., 2012; Narr et al., 2008; Simon, 2014).

Multiple mechanisms have been proposed as drivers of syndepositional deformation in steep-rimmed carbonate platforms including differential compaction (Frost and Kerans, 2009; Hunt et al., 1995; Hunt and Fitchen, 1999; Rusciadelli and Di Simone, 2007; Saller, 1996) sea-level change (Rusciadelli et al., 2003), geometry and antecedent topography (Frost and Kerans, 2010; Harman, 2011; Hunt et al., 2003), gravitational instability caused by the free surface of the reef wall (Frost and Kerans, 2010; Hunt et al., 2002; Hurley, 1986; Playford, 1984;

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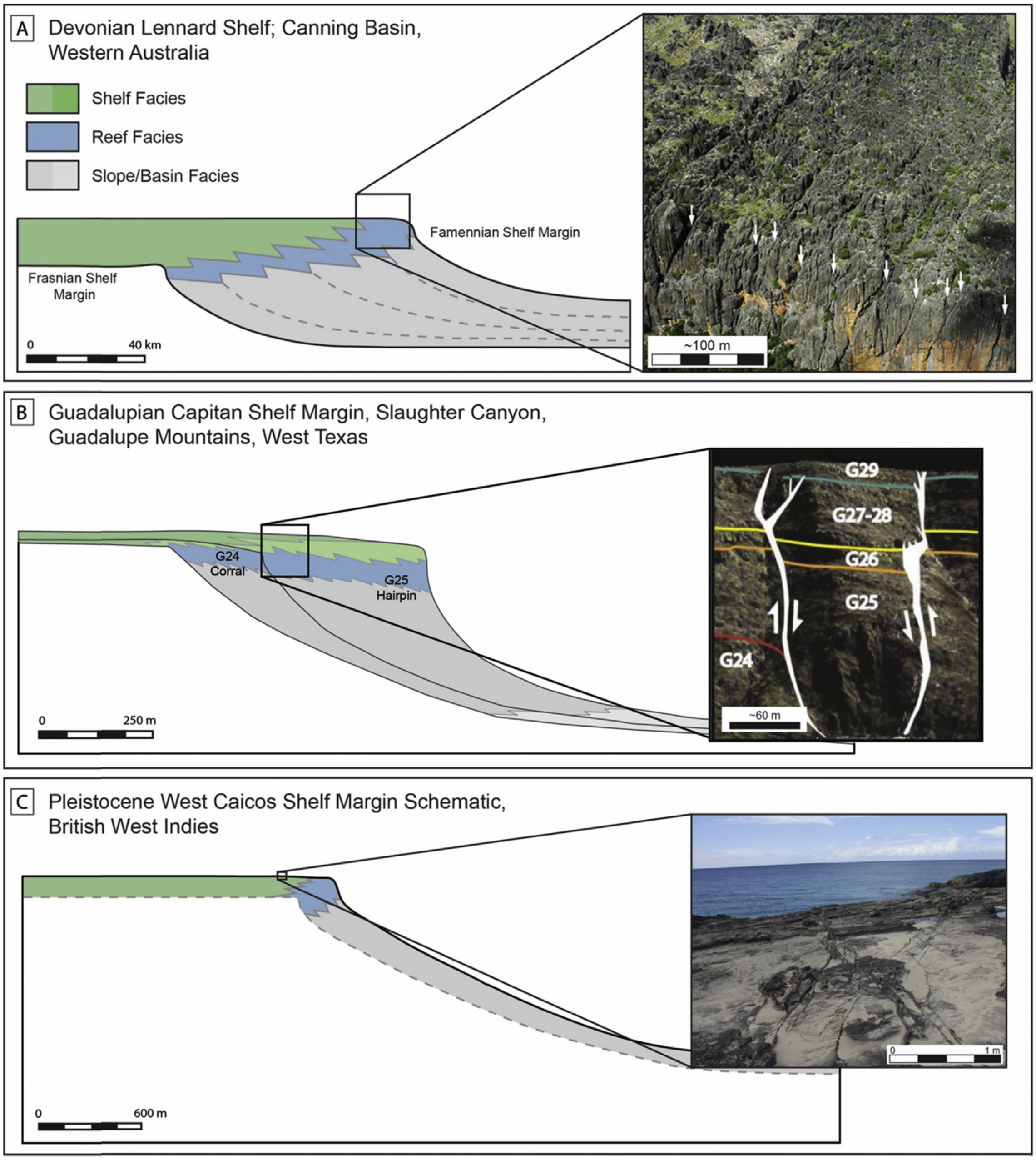

Fig. 1. Examples (both modern and ancient) of syndepositional fractures in steep-walled carbonate platforms. (A) Large continuous, margin-parallel, syndepositional fractures (white arrows) occurring in Famennian reef and forereef of Windjana Gorge, Canning Basin (after Frost and Kerans, 2010). (B) Large syndepositional faults over terminal early Capitanian G24 shelf margin in Slaughter Canyon, Guadalupe Mountains, New Mexico (after Kerans et al., 2017 and Mathisen, 2014). (C) Margin-parallel and margin-normal early fractures on West Caicos intersect, highlighting the often irregular, anastomosing nature of fracture networks present on the island. Note the relative scale of fractures compared to the Canning Basin and Capitan systems.

Playford et al., 1984) and heterogeneous rock properties (Nolting, 2017). While the proposed processes likely contribute to or partially control early deformation, one cannot quantify the effect from each mechanism on deformation without the use of physics-based geomechanical models. For example, it is unknown how much compaction of slope and basinal deposits is necessary to initiate deformation at the shelf edge. Nor can one quantify how much change in pore pressure due to sea-level variations is required to trigger the development of deformation. Similarly, evaluations of the stress state and kinematics of a carbonate platform under gravitational loading and conditions that facilitate over-steepening remain largely speculative.

Numerical models have been previously employed to aid in identifying the controls on early deformation, but their use is not common. Using 2D finite difference numerical code with a Drucker-Prager failure criterion, simulating both static and dynamic conditions, Rusciadelli et al. (2003), modeled the affects of changes in sea-level, movement along predefined faults, and seismic activity. Their results suggest that movement along an active fault is the most likely trigger for large-scale platform margin collapse of the Maiella platform. Later work by Resor and Flodin (2010) used a finite element, linear elastic gravity loaded numerical model to test the effects of variable elastic variable and progradation to aggradation (P/A) ratio on the development of syndepositional deformation. They identified compaction and slope geometry related to variable P/A ratio as a potential driver on syndepositional deformation. We build upon this understanding using numerical models that allows for the development of discrete failures under gravitational