Prediction of Syn-Sedimentary Fractures within Carbonates: Geomechanical Models with Development of More-Realistic Constitutive Models for Carbonates*

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Abstract

Fractures within steep rimmed carbonate platform reservoirs can have significant impact on hydrocarbon migration, storage and permeability of the reservoir. This paper focuses on the syn-sedimentary fractures, which form contemporaneous with the development of the platform. We present 2D geomechanical models to investigate the effect of compaction-induced differential subsidence on the development of syn-sedimentary fractures, and attempt to predict their occurrence and distributions. A significant effort of the mechanical modeling is the development of proper constitutive laws for different carbonate facies of steep rimmed carbonate platforms as their rock types strengthen through time and burial. We calibrate the outcome of our models with field observations from the Devonian carbonate reef of the Canning Basin, W. Australia, and the Permian Capitan reef of the Guadalupe Mountains, NM, USA, both of which are field analogues for major carbonate platform reservoirs like Tengiz and Karachaganak in Kazakhstan.

Introduction

Prograding carbonate platforms often develop high relief margins with moderate to steep slopes. The carbonate sediments involved in the buildup of such systems consist of distinct platform-, reef- and slope facies. Experimental studies have shown that carbonate sediments undergo significant compaction during the early stages of burial (Goldhammer, 1997) and each of these facies is affected differently by compaction. Platform facies consists dominantly of moderately compactable mudstones and peloidal packstones, where the reef often consists of less compactable grainstones and non-compactable microbial boundstones that lithify at surface conditions. The difference in material properties for each of these facies is the cause for differential compaction during the buildup of the platform. The rapid progradation, leading to over-steepening of the slope, in conjunction with differential compaction of underlying sediments is suggested to be the cause for modification of depositional geometries and formation of faults and fractures (Frost and Kerans, 2009; Hunt et al., 2002; Resor and Flodin, 2009; Stanton and Pray, 2004). The early-formed fractures can strongly impact fluid flow within major carbonate reservoirs like Tengiz and Karachaganak, and are well exposed in outcrop analogues.

Fracture analysis within major carbonate reservoirs and field outcrops has shown that these syn-sedimentary fractures concentrate around the rim of the carbonate platform, mainly within the upper-slope and reef facies. The fractures dominantly trend parallel and perpendicular to the rim of the platform. Most of the fractures are filled with surficial marine and/or clastic sediment, illuminating their time of formation and opening. Details on the controlling factors of fracture generation, distribution and timing of fracture opening remain ambiguous and are the motivation for this study.

Discussion

We developed 2D finite element models to investigate the origin of fractures in carbonate platforms. This physics-based approach requires constitutive laws and properties that define how the material of interest reacts to an imposed stress field. The different lithofacies within the platform, reef or slope can vary significantly, giving rise to major heterogeneity in material behavior. For example, the slope of the carbonate platform can consist of a variety of lithofacies ranging from wackestone to packstone to grainstone, even microbial boundstone transported from the platform rim down to the slope. We represent the different facies by simplifying distinct ranges of material properties for the platform-, reef- and slope facies within a Drucker-Prager cap elasto-plasticity model. The Drucker-Prager cap elasto-plasticity model has the advantage over linear elasticity as it includes permanent irreversible strain (representing processes like breaking of bonds, pore collapse, slip between grains) with a cap surface to enforce hydrostatic yielding (representing mechanical compaction by grain crushing and pore collapse). The strengthening of the material during compaction is captured by introducing work hardening, allowing the cap surface to evolve with hydrostatic yield stress.

The shape of the cap surface is based on published data from rock mechanics experiments on the Salem Limestone (Fossum, 1995). The hydrostatic yield point and the work hardening curve for the Salem Limestone however, represent the properties of the Salem Limestone at its current condition, after it experienced hundreds of millions of years of chemical and mechanical compaction. At its current condition, the Salem Limestone would not compact until buried to a depth of ~ 10 km. We apply a similar approach to derive work hardening curves for the Lixhe Chalk, which is significantly weaker then the Salem Limestone. In addition, we derive work hardening curves by using average depth-porosity trends from carbonates in South Florida Basin (Schmoker and Halley, 1982), using the porosity loss as a proxy for volumetric strain. We find an elegant approach to combine the different data sets into a theoretical work hardening curve that represents the work hardening of a carbonate facies from surface conditions to deep burial.

We apply the cap elasto-plasticity models for each of the facies by using the geometry of the Salem Limestone cap model, and adjust it proportionally to the relative strength of the facies (see Figure 1). The hardening for each of the facies is defined by a different segment of the theoretical work hardening curve. These material models are used on a 2D model that represents the geometry and facies distribution of the Capitan Reef system, modified after Resor and Flodin (2009) who analyzed the linear elastic solution for this configuration. In this model, the platform is build up in a step-wise manner with loading (imposed stress) solely due to gravity, applied as a body force to each element. We demonstrate that the cap elasto-plasticity model predicts significant surface subsidence, supporting the suggestion that differential compaction forms a mechanism for basinward dips of platform strata associated with a number of carbonate platforms (“fall-in beds”). In addition, the model predicts localized concentrations of tensile stress within the reef facies near the surface of the platform suggesting potential locations for development of syn-sedimentary fracture development (see Figure 2).

In addition, the cap elasto-plastic material models are applied to a 2D model of the carbonate reef of the Canning Basin, W. Australia. The carbonate reef of the Canning Basin undergoes significant back stepping of the platform, after which it progrades over itself. We analyze the localization of tensile stress through time to predict locations prone to development of syn-sedimentary fracturing and compare these locations and suggested fracture orientations with detailed field observations.

Conclusion

The mechanical models of step-wise carbonate platform development, with proper constitutive models adjusted to the strength of different facies, successfully predict syn-sedimentary fracture development and enhance the understanding of the development of these fracture systems. Such models can be used as predictive tools for fracture development in major carbonate platform reservoirs like Tengiz and Karachaganak.

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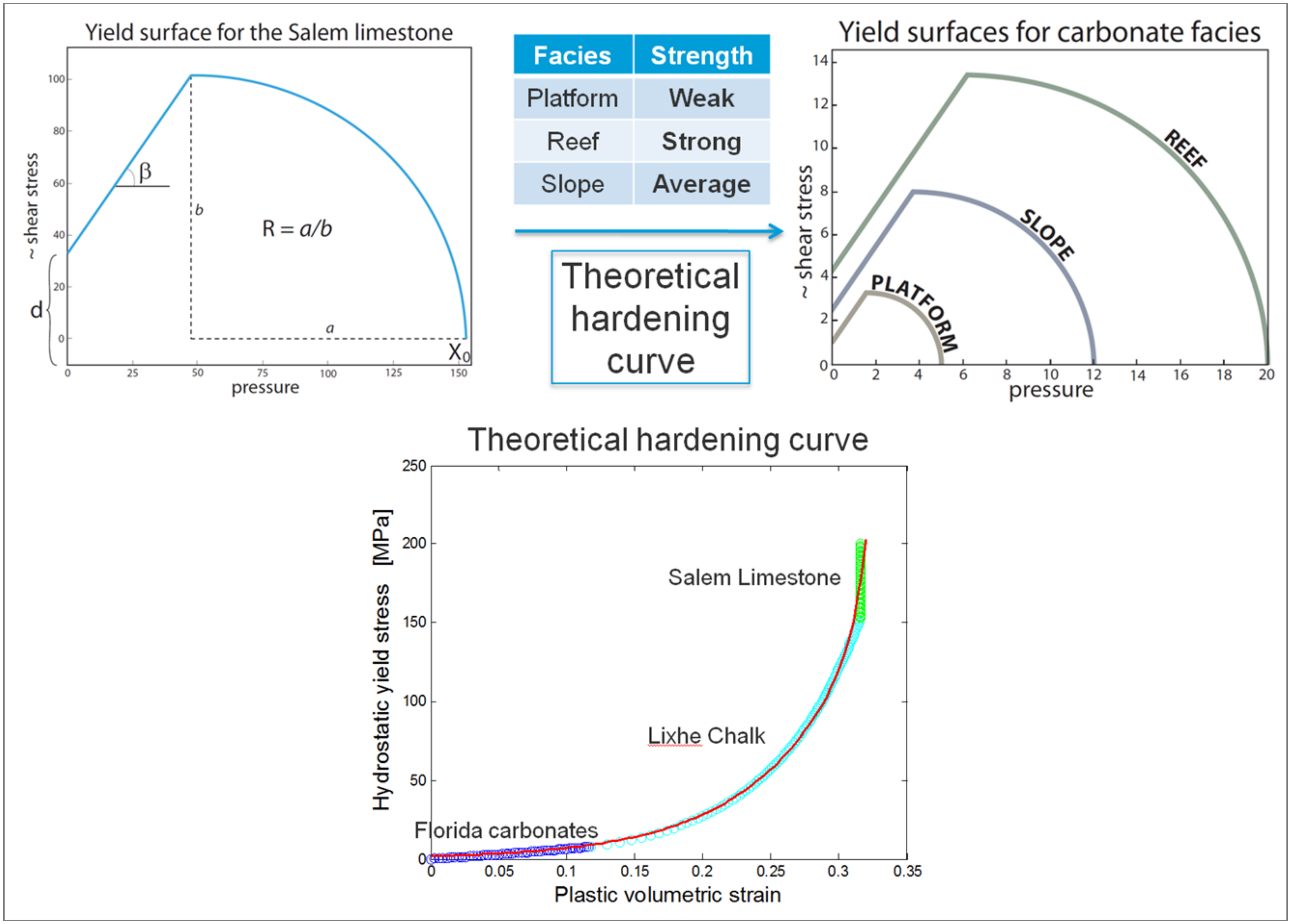

Figure 1. Development of Drucker-Prager Cap Elasto-Plasticity model for carbonate facies. The cap yield surface derived from the Salem Limestone is adjusted to the strength of different carbonate facies by a theoretical hardening curve that is composed of the work hardening curves from the Salem Limestone, Lixhe Chalk and Florida carbonates.

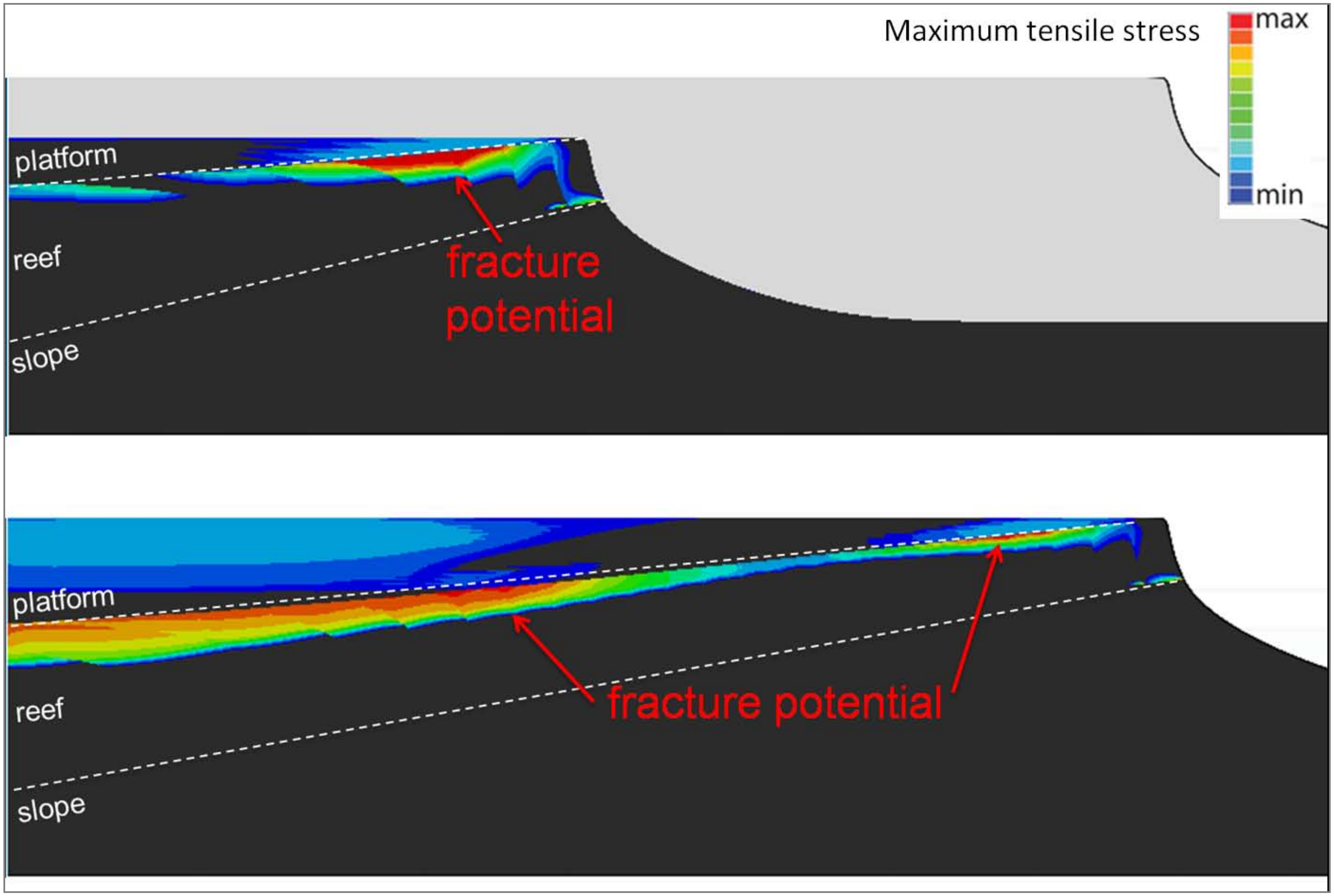

Figure 2. 2D Finite Element Model for the Capitan Reef System, NM. Maximum tensile stress concentrations representing areas for syn-sedimentary fracture development. Top: Half of platform buildup completed. Bottom: Entire platform buildup completed. Note that the maximum tensile stress concentrates within the reef facies. Model is modified after Resor and Flodin (2009).