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Research paper

Geomechanical modeling of pore pressure in evolving salt systems

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ABSTRACT

We predict pore pressure and stress in an evolving salt basin (salt rising as a diapir and developing into a sheet) using a transient, large-strain, evolutionary geomechanical model. This model simulates mudrocks with a poro-elastoplastic material and couples sedimentation with salt deformation and porous-fluid flow. We show that pore pressures near salt are higher than predicted by assuming vertical uniaxial deformation. During salt-sheet emplacement, subsalt pore pressures equal the weight of salt, resulting in low effective stresses and very low sediment strength. We find that a dissipation zone develops parallel to the base of salt, allowing excess pore pressure to decrease with time by lateral drainage. In addition, we show that welding of the source layer and pedestal subsidence affect pore pressure in the deeper parts of the basin. We discuss how changes in both pore pressure and least principal stress lead to a narrow drilling window subsalt. We translate our stress field into an equivalent P-wave velocity field and find very low seismic velocities below salt. Finally, we compare our geomechanical pore-pressure prediction with that of porosity–effective stress workflows. We demonstrate the role of mean total stress in pressure prediction. In addition, we show that the prediction accuracy of porosity-based workflows depends on the relative level of shear (q/σ'_m) in their calibration dataset, and how this ratio compares to the field $(q/\sigma'_m)_{\text{field}}$. Overall, our transient evolutionary model provides an estimate of the full stress tensor and pore pressure over time, and can help identify potential hazardous areas below salt. Our study illustrates the relative contribution of stress-tensor invariants to pore pressure and errors resulting from their omission. Furthermore, it advances our fundamental understanding of the interaction between fluid pressure, stress, and deformation in salt basins.

1. Introduction

Prediction of pore pressure prior to drilling is crucial for the planning of safe and economic well trajectories, stability of boreholes and design of casing plans (Dodson, 2004; Dutta, 2002; Zhang, 2013). It is also a key input in energy exploration for determining the integrity of reservoir seals and regional hydrocarbon-migration behavior. High pore pressure, shear zones, and narrow drilling windows are routinely reported when drilling through the base of salt bodies (Harrison et al., 2004; House and Pritchett, 1995; O'Brien and Lerche, 1994; Willson et al., 2003; York et al., 2009; Zhang, 2013). According to York et al. (2009), 12.6% of drilling time in subsalt wells is associated with pore pressure and wellbore-stability problems. Despite the many economic and safety incentives, pre-drill analyses often underestimate pore pressure near salt (e.g., Shumaker et al. (2014)).

Successful prediction techniques should account for the mechanisms that cause excess pore pressure. It is generally recognized that the dominant mechanism in young basins is the increasing overburden weight due to sedimentation. This external vertical load causes vertical compression of the sediment column and increase in the stress between soil particles (effective stress). Because both applied load and deformation are vertical (uniaxial conditions), a unique relationship exists between porosity decrease and vertical-effective-stress increase. This relationship is known as the uniaxial compression (compaction) curve. Assuming incompressible grains, compression is achieved by decreasing the pore volume; however, this is possible only when the pore fluid is able to flow out of the porous space. Porous-fluid flow depends on the permeability and compressibility of the sediment column, as well as on the distance to a free draining surface (Gibson, 1958). When the porous fluid cannot flow freely in response to an external load, excess pore pressures develop. Hence, over a transient period, this external load (total stress) is supported in part by excess pore pressures and in part by effective stresses (Terzaghi (1925) consolidation theory). If porosity can be estimated through empirical relationships (Aplin et al., 1995;

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Butterfield, 1979; Rubey and Hubbert, 1959) or velocity/resistivity measurements (Eaton, 1975), effective stress can be obtained from the unique compression curve. Then, pore pressure can be calculated as the difference between overburden and effective stress. This is the basis for most pore-pressure-prediction workflows (e.g., Bowers (1995); Gutierrez et al. (2006); Hart et al. (1995); Hottman and Johnson (1965); Rubey and Hubbert (1959)).

However, deformation is not uniaxial near salt (Heidari et al., 2016b; Koupriantchik et al., 2004; Nikolinakou et al., 2014; Orlic and Wassing, 2013; van-der-Zee et al., 2011). Salt imposes nonvertical loading, and porosity changes may result from strains in nonvertical directions. Thus, a uniaxial compression (compaction) curve should not be used to estimate effective stress and predict excess pore pressure near salt. The same applies in other nonuniaxial geologic settings, such as thrust-and-fold belts (e.g., Couzens-Schultz and Azbel (2014)).

To address the contribution of nonuniaxial loading, some porosity-based, pressure-prediction workflows have been modified to use the mean total stress (e.g., Alberty and McLean (2003); Harrold et al. (1999); Katahara (2005)). Mean total stress incorporates any non-uniaxial external loading and thus drives pore pressure. However, mean effective stress is still calculated from porosity measurements using a compression curve that often assumes uniaxial conditions and a horizontal-to-vertical effective-stress ratio (e.g., Breckels and van Eekelen (1982); Hubbert and Willis (1957); Matthews and Kelly (1967)). Alternatively, Couzens-Schultz and Azbel (2014) proposed modifying the compression curve with an empirical tectonic term to account for nonuniaxial stresses. In addition, studies have pointed out the importance of considering the role of shear in compression and pore-pressure generation (Goulty, 2004; Hauser et al., 2014; Heidari et al., 2017-in review; Nikolinakou and Chan, 2012). Recently, transient geomechanical models have been developed to study pore-pressure generation coupled with geologic processes; these models include transient pore-pressure dissipation near a simple salt geometry (Nikolinakou et al., 2012), pore pressures near a rising salt wall (Luo et al., 2017), and pore-pressure changes associated with tectonic compression (Obradors-Prats et al., 2017).

Some of these prior studies have proposed methods of incorporating the full stress tensor (mean and shear stress) into pore-pressure prediction. Here, we offer a more complete path to estimating both stress and pressure in a broad class of structural settings. We present a transient evolutionary model of a salt system rising as a diapir and developing into a salt sheet. The model couples sedimentation, salt flow, and porous-fluid flow in a basin consisting of low-permeability sediments (Fig. 1). This coupling allows us to account for the effect of deposition, salt loading, and basin deformation on the development and dissipation of excess pore pressures. We find that excess pressures near salt are higher than predicted by assuming vertical uniaxial deformation. We also find that pore pressure supports the weight of the overlying salt sheet during salt emplacement, which results in very low sediment strength and a narrow drilling window below salt. We show how excess pore pressures and stresses change over time, as salt advances on the basin surface and evacuates from the pedestal. In addition, we compare our geomechanical prediction with that of a porosity–effective stress workflow and show that pore-pressure prediction depends on the estimate for mean total stress and on the ratio of shear to mean effective stress assumed in the compression curve used in the workflow.

2. Evolutionary numerical model

We build a transient evolutionary model in Elfen (Rockfield, 2010). The model is based on a finite-strain, quasistatic, finite-element formulation, complemented by automated adaptive-remeshing techniques (Peric and Crook, 2004; Thornton et al., 2011). Adaptive remeshing is activated after a distortion threshold has been reached. The finite-element mesh is composed of unstructured quadrilaterals with an initial element size of 200 m and a re-meshed size down to 50 m. Geometric

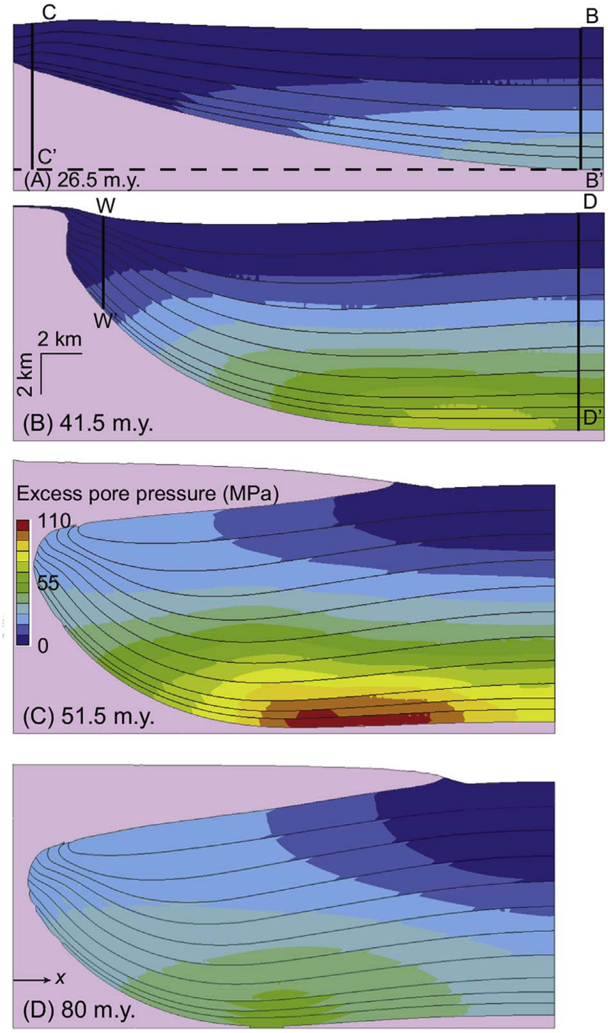

Fig. 1. Transient evolutionary model of rising salt wall developing into salt sheet. Color contours show excess pore pressure. (A): Differential loading (resulting from sedimentation at a slope) drives rise of salt wall in middle of model ($x = 0$). Pore pressures are higher in deeper parts of basin. (B): Salt wall upbuilds to basin surface. Pore pressures near the salt wall are lower than at equivalent depths in parts of the basin where the sediment column is taller (WW′ vs. DD′). (C): Salt sheet advances on basin surface; tectonic shortening is applied on basin. High excess pore pressures develop below salt and near the welding source layer. (D): Tectonic shortening ends at 52 m.y. and system is left to equilibrate. Pore pressures decrease, but remain elevated below salt. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

pinching allows the removal of very thin, unnaturally stretched layers, facilitating salt growth, and the eventual development of a salt sheet (Fig. 1). Lagrangian and Eulerian reference frames are used for the mechanical and fluid phases respectively. Fluid flow in the seepage field is relative to the deformation of the mesh in the mechanical field. Pore pressure calculated in the seepage field is transferred to the mechanical field using the volumetric strain at user-specified time intervals, which ensure that the difference between seepage and mechanical pore pressure remains minimal.

We model the salt as a solid viscoplastic material using a reduced form of the Munson and Dawson formulation: the transient term is omitted as negligible over geologic time scales, and only the two steady-state terms are included (Munson and Dawson, 1979). This constitutive model provides a unified approach to both creep and plasticity, and results in a salt viscosity that is a function of both stress and temperature. The formulation has a series of input parameters (Appendix A, Table A.1) that are calibrated according to Fredrich et al.