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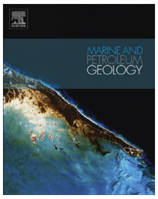

Research paper

Assessing the implications of tectonic compaction on pore pressure using a coupled geomechanical approach

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ABSTRACT

Overpressure prediction in tectonic environments is a challenging topic. The available pore pressure prediction methods are designed to work in environments where compaction is mostly one dimensional and driven by the vertical effective stress applied by the overburden. Furthermore, the impact of tectonic deformation on stresses, porosity and overpressure is still poorly understood. We use a novel methodology to capture the true compaction phenomena occurring in an evolving 3D stress regime by integrating a fully-coupled geomechanical approach with a critical state constitutive model. To this end, numerical models consisting of 2D plane strain clay columns are developed to account for compaction and overpressure generation during sedimentation and tectonic activity. We demonstrate that a high deviatoric stress is generated in compressional tectonic basins, resulting in a substantial decrease in porosity with continuing overpressure increase. The overpressure predictions from our numerical models are then compared to those estimated by the equivalent depth method (EDM) in order to quantify the error induced when using classical approaches, based on vertical effective stress, in tectonic environments. The stress paths presented here reveal that a deviation from the uniaxial burial trend can substantially reduce the accuracy of the EDM overpressure predictions.

1. Introduction

During the history of a sedimentary basin the clay sediments may experience different episodes since their deposition including burial, tectonic activity and diagenesis. These episodes trigger physical and chemical processes which have a great influence on sediment properties and the resulting transient pore pressure field (Osborne and Swarbrick, 1997; Wangen, 2001; Swarbrick et al., 2002). The physical processes are termed as mechanical compaction which accounts for porosity loss caused by the change in effective stresses, sediment strength and compressibility (Gutierrez and Wangen, 2005). On the other hand, chemical compaction encompasses all the chemical processes occurring in sediments during diagenesis including mineral dissolution and precipitation.

In this paper, chemical compaction is neglected and attention is focused only on mechanical compaction, which may result from both the increasing vertical stress during burial, and the increase in lateral stresses resulting from tectonic deformation. Compaction of sediments requires fluid flow outward from the void spaces as the rock volume and porosity decrease. If the velocity of fluid escaping from the pores is too low, relative to the compressive load rate, part of the load will be carried by the fluid. As a result, the pore pressure will increase and the sediments will become overpressured (the pore pressure will be higher than the hydrostatic pressure). This overpressure generation mechanism is known as disequilibrium compaction. In the present paper two types of disequilibrium compaction are distinguished: disequilibrium compaction due to (1) ineffective dewatering during burial and (2) the tectonic induced overpressures resulting from ineffective dewatering during tectonic compressive deformation.

Knowledge of the pore pressure in the subsurface is a valuable tool for many applications within the oil industry that can help to minimize costs and risks. For example, it is used to design drilling mud weight programs and well casings. Furthermore, it can provide valuable information to assess fluid migration pathways, trap volumes and seal trap integrity (Brown and Karim, 2008). In addition, high overpressures may play a role in fault formation and can facilitate structural detachments (Hubbert and Rubey, 1959;

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Corredor et al., 2005; Krueger and Grant, 2011). Thus understanding of the sub-surface pore pressure regime could potentially help geological structural interpretations.

Therefore, pore pressure prediction is a topic of great interest for a wide scientific community of different disciplines. Because accuracy is crucial, several techniques are commonly used in combination to reduce uncertainty in predictions. Two main approaches are used for pore pressure prediction: (1) porosity-based methods which depend on rock property relationships and the analysis of the trends with depth (Van Ruth et al., 2002; Yang and Aplin, 2004; Bera, 2010; Zhang, 2011) and (2) forward basin modelling (Schneider et al., 1996; Bekele et al., 2001; Schneider and Hay, 2001; Bolås et al., 2004; Allwardt et al., 2009; Hantschel and Kauerauf, 2009; Neumaier et al., 2014), which provides numerical simulations of different physical and chemical mechanisms of overpressure generation and dissipation during basin evolution and therefore is capable of capturing pore pressure history over geologic times. The main limitation of both approaches is that the adopted mechanical compaction models are unidimensional and based on the vertical effective stress. Therefore, the impact of tectonic activity on sediment properties and pore pressure generation is not accurately captured by these methods which may result in significant inaccuracies in estimates of pore pressure in tectonic environments (Hennig et al., 2002; Swarbrick, 2002).

Geomechanical modelling can be employed in conjunction with advanced constitutive models to simulate sediment rheology which are capable of accounting for the full 3D stress tensor and its impact on compaction (Albertz and Lingrey, 2012; Albertz and Sanz, 2012; Luo et al., 2012; Smart et al., 2012) and overpressure generation (Nikolinakou et al., 2012; Thornton and Crook, 2014).

In this paper, we present fully coupled, 2D plane strain geomechanical models using the finite element method to solve the governing equations for the mechanical and fluid flow fields. The models consider the sedimentation, burial, compaction, fluid flow and tectonic deformation during the history of a basin. It should be pointed out that the development of deformation structures resulting from tectonic activity as folds and thrusts are not considered in the numerical models. With the present work we aim to: (i) provide a qualitative and quantitative understanding of the impact of tectonic deformation on sediment properties, stresses and overpressure and (ii) quantify the inaccuracy of the classical pore pressure prediction methods in tectonic environments. To this end, a parametric study has been undertaken to analyze the effect of basin history on the final observed overpressures and to elucidate the main factors that lead to the failure of overpressure prediction methods.

2. Modelling approach

The Finite Element software ParaGeo (Crook, 2013) has been used to create the numerical models. Both fully implicit and quasistatic explicit algorithms are implemented in the software for solving the governing equations which are described in the following section.

2.1. Governing equations

The work presented in this paper adopts a fully-coupled staggered sequential approach to solve geomechanical and fluid flow equations taking into account the influence that these fields have on each other at every coupling time step. The linear momentum balance equation for a saturated medium containing a single fluid phase is written as (Lewis and Schreffler, 1998):

$$\boldsymbol{L}^T\left[\boldsymbol{\sigma}\prime + \alpha(\phi)\boldsymbol{m}p_f\right] + \rho_b\boldsymbol{g} = 0 \tag{1}$$

where $\boldsymbol{L}$ is the standard continuum mechanics differential operator, $\boldsymbol{\sigma}'$ is the effective stress tensor defined as:

$$\boldsymbol{\sigma}\prime = \left[\sigma\prime_x \sigma\prime_y \sigma\prime_z \tau_{xy} \tau_{yz} \tau_{zx}\right]^T \tag{2}$$

σ_x', σ_y' and σ_z' are the normal stresses to orthogonal planes x, y and z respectively, τ_{yz}, τ_{zx} and τ_{xy} are the tangential stresses acting in planes x, y and z respectively, $\alpha(\phi)$ is the Biot's coefficient as a function of porosity, p_f is the pore fluid pressure and is the hydrostatic unit tensor, which is defined as:

$$\boldsymbol{m} = [1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0]^T \tag{3}$$

ρ_b is the saturated bulk mass density which is defined as:

$$\rho_b = (1-\phi)\rho_s + \phi\rho_f \tag{4}$$

in which ρ_s and ρ_f are the solid and fluid densities respectively and $\boldsymbol{g}$ is the gravitational vector.

Effective stress is the component of the total stress exerted by the solid matrix. It is defined as:

$$\boldsymbol{\sigma}\prime = \boldsymbol{\sigma} - \alpha(\phi)\boldsymbol{p}_f \tag{5}$$

where $\boldsymbol{\sigma}$ is the total stress tensor.

For the current application we have assumed a constant value of $\alpha(\phi)=\alpha=1$ which results in the Terzaghi's definition of the effective stress (Terzaghi, 1967). The fluid transport over geological time frames is modelled by the single phase Darcy's flow equation as defined in (Lewis and Schreffler, 1998):

$$\operatorname{div}\left[\frac{(\boldsymbol{k}(\phi)}{\mu_f}\left(\nabla p_f - \rho_f\boldsymbol{g}\right)\right] = \left[\frac{\phi}{K_f} + \frac{(\alpha(\phi)-\phi)}{K_s}\right]\frac{\partial p_f}{\partial t} + \frac{\alpha(\phi)}{(1-\phi)}\frac{\partial \phi}{\partial t} \tag{6}$$

where K_f is the fluid stiffness, K_s is the solid grains stiffness, μ_f is the fluid viscosity and $\boldsymbol{k}(\phi)$ is the permeability tensor which is a function of porosity. Note that the last term in Eq. (6) represents the fluid flow due to a change in porosity and provides the coupling between the mechanical and flow fields.

2.2. Constitutive equations

The SR4 is a three-invariant rate-independent poro-elastic-plastic critical state constitutive model with non-associative plasticity. In the formulation, stress states are expressed by means of the effective mean stress p' and the deviatoric stress q defined as:

$$\begin{aligned} p\prime &= \frac{\sigma_1' + \sigma_2' + \sigma_3'}{3} \\ q &= \sqrt{\frac{1}{2}\left[(\sigma_1' - \sigma_2')^2 + (\sigma_1' - \sigma_3')^2 + (\sigma_2' - \sigma_3')^2\right]} \end{aligned} \tag{7}$$

where σ'_1, σ'_2 and σ'_3 are the three principal effective stresses.

2.3. Yield surface

The yield surface delimitates the domain of stress states that produce elastic and elastic-plastic strains (Fig. 1a). Stress paths moving inside the yield surface produce elastic deformation whereas stress paths that reach the yield surface produce elastic-