Coupled fluid-mechanical modeling of salt-tectonic deformation

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SUMMARY:

We present coupled fluid-mechanical models that investigate the interaction of tectonic deformation and compaction-driven fluid pressure generation. We focus on the example of a salt-bearing sedimentary basin in an evolving gravity-spreading regime like that of the northwestern Gulf of Mexico. Model results show how large-scale variations of fluid pressures within the sedimentary basin influence the structural development. A stratigraphy comprising alternating layers of shale- and sandstone-type material is found to be necessary to build up sufficiently high fluid pressures beneath the shelf to destabilize the system. Fluid pressures in the distal regime control the style and amount of deep-water contractional deformation.

INTRODUCTION:

Pore-fluid pressures:

Pore-fluid pressures have been investigated in the context of sediment compaction and fluid flow in porous media for more than a century (Bjørlykke 1997). They are of major importance in petroleum engineering and hydrocarbon systems, as they influence the material strength, the reservoir porosity, formation of seal layers, as well as production rates. However, the feedback mechanisms that exist between mechanical deformation and compaction and overpressuring have only recently been addressed quantitatively (e.g., Mourgues and Cobbold, 2003).

Sediments are termed overpressured when fluid pressures exceed hydrostatic values – a setting that must deviate from the well-drained system of interconnected pore space. Fluid overpressures develop, e.g., through compaction, mineral transformations (e.g., smectite to illite) or hydrocarbon generation, whereby the first process is regarded to be the most widespread and best understood mechanism (Swarbrick and Osborne, 1998). Fluid pressures effectively weaken a material because the fluids bear a part of the overburden load (Terzaghi, 1943), and thereby facilitate deformation. The effective stress, defined as the difference between mean stress and fluid pressure, determines the effective strength of a material. Where deformation occurs, the stress regime changes, which may influence the compaction behavior and thereby the fluid pressure generation.

Salt tectonics:

We study a continental margin salt tectonic system, in which deformation is driven by gravity. In such a gravity-spreading system, the differential stresses in a tapering sedimentary wedge and the basal drag forces from the underlying salt layer may become large enough to bring the overburden to failure. Subsequently, it responds to the stresses by developing an upslope domain of extension, a central domain of translation, and a downslope domain of shortening (Gemmer et al.; 2004, Vendeville, 2005). The failure condition strongly depends on the strength of the overburden and therefore on its fluid pressure regime (Gemmer et al., 2005; Gradmann et al., 2009). Such a salt-based gravity-spreading system is therefore well-suited for studies of the interactions between pore-fluid pressures and deformation. An additional important process is the role of lateral compaction in the linked extensional-contractional system, which is addressed in this study.

Figure 1 shows the present-day setting of the northwestern Gulf of Mexico. Upslope extensional faults and the deep-water shortening structures, like the Perdido Fold Belt, provide evidence of the gravity-spreading regime.

This salt-cored, deep-water fold belt is known for the enormous thickness of the folded layer (4.5 km), and the short time it took the fold belt to form (Trudgill et al., 1999). The geometry and timing of this structure are fairly well known and provide adequate constraints for the numerical models. Gradmann et al. (2009) investigated the conditions leading to gravitational failure of the continental margin of the northwestern Gulf of Mexico and demonstrated that pore-fluid pressures play a crucial role in bringing this system to failure. Whereas their study invoked a simplified, parametric pore-fluid pressure regime with specified constant values throughout the overburden, here we include dynamic calculations of pore-fluid pressures in a gravity-spreading system, and their interaction with local and regional deformation.

METHOD:

We use a numerical, coupled fluid-mechanical model (Morency et al., 2007). This is a modification of the 2D finite element software SOPALE (Fullsack et al., 1995) to include compaction-driven Darcy fluid flow, calculated dynamically throughout the model evolution. The evolving fluid pressure field is coupled to the deformation of the grain matrix through the effective pressure (Figure 2). Additionally, fluid pressure directly enters into the calculation of material strength through the pore-fluid pressure ratio λ, defined as the fluid pressure divided by the mean stress.

The model domain comprises a salt layer overlain by shale- and sandstone-type sediments, which are deposited as the model evolves. Salt is modeled as linear-viscous material, sediments as frictional-plastic with a Drucker-Prager failure criterion. The two sediment materials differ in their hydraulic properties. The shale-type lithology leads to efficient compaction, porosity loss, and seal formation, whereas the sandstone-type lithology yields longer preservation of pore space and better drained sediments with less tendency for intrinsic overpressure development. Porosity reduction occurs through mechanical compaction (re-arrangement of grains) as well as viscous compaction (local pressure solution and re-precipitation). Both mechanisms contribute to the overpressuring of sediments. Salt and crustal materials are considered to be highly impermeable and fully compacted in their initial state, such that they are not a source of fluids which would influence the fluid pressure regime in the overlying sediments. Their low hydraulic conductivities do, however, make them good seals. Model experiments also include sediment progradation and aggradation, flexural isostasy of the entire system, and loading by the water column.

RESULTS:

Figure 3a and 3b show the evolution of a coupled fluid-mechanical model which develops fluid overpressures, and exhibits gravity spreading and fold belt formation. A prograding sediment wedge, here consisting of alternating shale-type and sandstone-type deposits, overlies a salt basin with an initial sediment cover of 4.5 km (Figure 3, top panels). This aggraded sediment layer was deposited in an earlier phase of the model. As sediments underneath the prograding shelf become sufficiently overpressured (Figure 3, middle panels), the overburden fails, gravity spreading sets in, and the overburden and underlying salt translate seaward. Continuing sedimentation and high fluid pressure maintains the mobility of the system. The translation of the overburden is accommodated by formation of a fold belt at the distal end of the salt basin (Figure 3, bottom panels). The shortening structures resemble the Perdido Fold Belt in the northwestern Gulf of Mexico (Figure 1).

Multiple test series have shown that gravitational failure and folding of the overburden depend on various aspects of fluid pressure generation. First of all, sufficiently high fluid pressures need to develop and be maintained, for which multiple shale layers (as in the model of Figure 3) are needed (more than 2, depending on the sealing efficiency of the shale). Furthermore, high fluid pressures within the deep sediments underneath the shelf are crucial for gravitational failure to occur, whereas the distal fluid pressure regime has more influence on the style of deformation (folding vs. pure shear thickening) and on lateral compaction. We conclude that regional variations of the fluid pressure regimes on continental margins can therefore play a major role in their structural evolution. In particular, for salt basins, where sedimentation rates are high and fluid pressure plays an essential role in mobilizing the system, an integrated approach to study both fluid pressures and deformation becomes important.

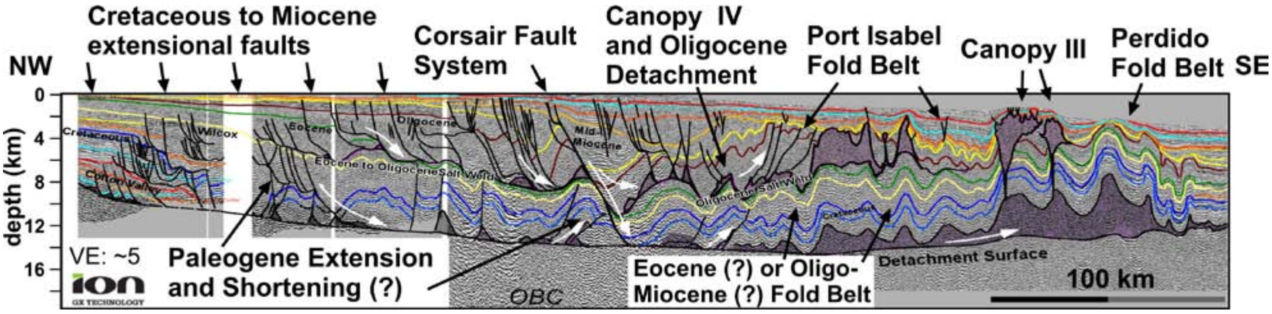

Figure 1: Regional NW-SE trending seismic profile from the northwestern Gulf of Mexico extending from onshore into deep water (from Radovich et al., 2007, courtesy of ION-GXT). Large-scale gravity-spreading structures (extensional faults, allochthonous salt, fold belts) are indicated.

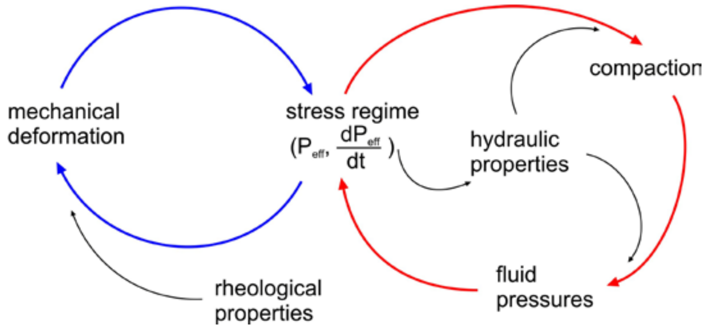

Figure 2: Conceptual diagram of fluid-mechanical calculations coupled through the stress regime. The blue loop describes the purely mechanical part and its dependencies, the red loop describes the fluid part and its dependencies.

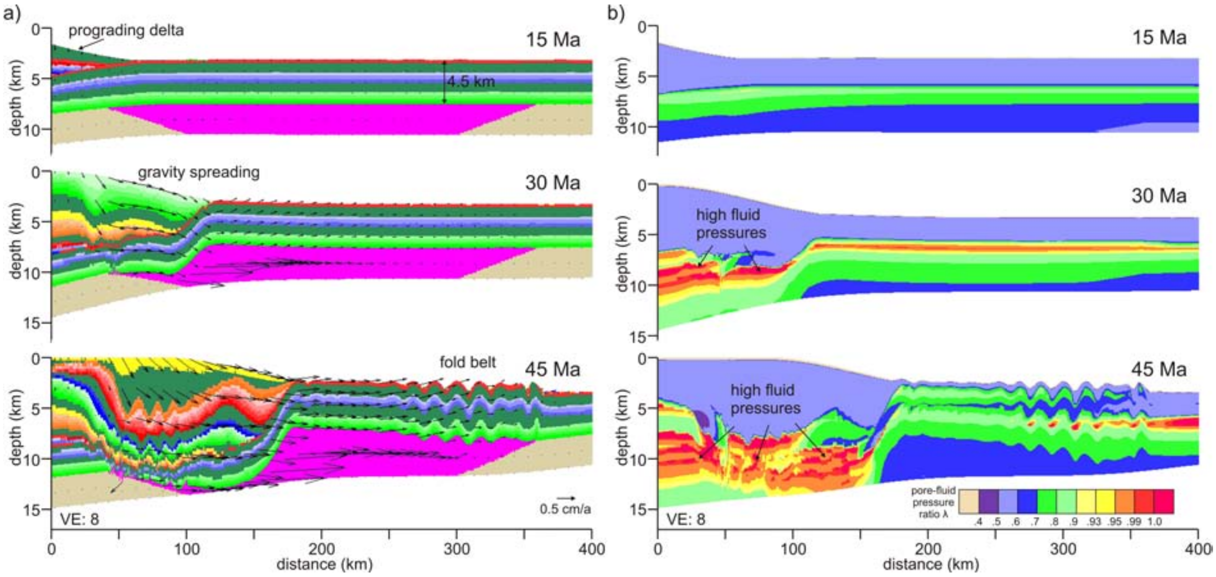

Figure 3: Result of a numerical model designed to approximate progradation of a clastic delta above a salt basin (magenta). Both material properties (a) and pore-fluid pressure ratio λ (b) are shown. The delta is composed of alternating shale-type lithology (dark green) and sandstone-type lithology (other colours). Crustal material surrounding the salt basin is coloured grey. Top panels: onset of deltaic progradation above salt basin and uniformly deposited sediment layer, which was designed to match the pre-kinematic configuration of the Perdido Fold Belt. Middle panels: onset of gravity spreading as high fluid pressures develop underneath the shelf area. Bottom panels: Fold belt formation during ongoing gravity spreading. Fluid pressures underneath shelf area are high. The resulting structures resemble the Perdido Fold Belt in the northwestern Gulf of Mexico.

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