Tectonophysics 683 (2016) 172–181

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Geomechanical analysis of a welding salt layer and its effects on adjacent sediments

Mahdi Heidari [a,*], Maria A. Nikolinakou [a], Michael R. Hudec [a], Peter B. Flemings [b]

[a] Bureau of Economic Geology, The University of Texas at Austin, 10100 Burnet Road, Building PRC-130, Austin, TX 78758, USA
[b] Department of Geological Sciences and Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, 10100 Burnet Road, Building PRC-130, Austin, TX 78758, USA

ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form 10 June 2016
Accepted 20 June 2016
Available online 23 June 2016

Keywords:
Salt weld
Stress near salt
Salt-weld seal
Salt diapirism modeling
Wellbore stability

ABSTRACT

We simulate welding of the source layer of a salt diapir with a forward finite-element model and study stresses and deformation in the salt layer and the diapir, as well as in their adjacent sediments. Welded salt layers are abundant in mature salt basins, where most or all of the salt has withdrawn into diapirs. However, there is little understanding of the stress field in these layers and their adjacent sediments. We show that salt flow along the source layer leads to significant stress anomalies inside the layer and in adjacent sediments. In the source layer, salt pressure becomes higher than overburden stress in nearly welded areas and becomes lower than overburden stress in adjacent thicker areas. When the source layer welds, stresses increase significantly in sediments near the weld tip, which helps compaction of these sediments and possibly their fracturing and faulting. Our model illustrates that all sediments overlying the weld experience this stress increase and the associated material changes as the weld tip propagates along the weld. We present natural examples fitting our predictions and discuss the importance of our results for the exploration, characterization, and production of reservoirs near welded salt layers.

1. Introduction

Horizontal salt welds, also known as primary welds, develop by complete or almost complete withdrawal of salt from a source layer into diapirs (Jackson and Talbot, 1991) (Fig. 1a). Several studies have documented geologic attributes of these welds and their importance to hydrocarbon exploration (Hoetz et al., 2011; Jackson et al., 2014; Maione, 2001; Peel, 2014; Rowan et al., 2012; Wagner, 2010). For instance, Hoetz et al. (2011) studied the data from wells drilled through horizontal welds and found a consistent reduction in the porosity of sediments near the welds. Maione (2001) also reported steeply dipping faults in sediments above salt welds in the East Texas Basin. However, there is little understanding of the linkage between these attributes and the welding process. Because the stress field near the welds determines these structural attributes, understanding the linkage requires identifying the stress field near a welding salt layer and the controls that the welding process has on the field.

To our knowledge, only one study has considered stresses near salt welds (Hoetz et al., 2011). The authors simulated a source-layer weld with a simplified model representing the overburden as a rigid sediment block sitting on a horst in a sea of salt (the "brick in a bathtub" model in their terminology). With analytical and numerical calculations, they showed that vertical stress increases remarkably at the base of the sediment block where the block is supported by the horst. However, in their simplified analysis, the authors studied only the vertical stress; further, because they assumed no limit for sediment strength (i.e., purely elastic behavior), they overestimated the stress increase at the weld. In addition, they simulated only the present geometry of the weld. As a result, their study fails to provide the history of stresses and possible irreversible material changes in sediments that could have occurred in the past during weld development.

Drilling results, along with analytical and numerical models, have shown that horizontal stress is high near vertical flanks of diapirs with a thick source layer in extensional or passive-margin basins (Dusseault et al., 2004; Heidari et al., 2016; Nikolinakou et al., 2014) (Fig. 1b). However, it is not clear whether this horizontal stress remains high after the source layer of the diapirs thins and welds. The high horizontal stress in diapir-flank sediments results from high horizontal pressure from the diapir pushing laterally against the sediments (Dusseault et al., 2004). Heidari et al. (2016) showed that the source layer of a salt diapir contributes to the high salt pressure in the diapir. They showed that the salt in the source layer is overpressured relative to the salt in the diapir and that the salt flow from the source layer into the diapir transmits this overpressure to the latter, increasing its own salt pressure. The magnitude of the transmitted overpressure

* Corresponding author.
E-mail addresses: mahdiheidari@utexas.edu (M. Heidari), mariakat@mail.utexas.edu (M.A. Nikolinakou), michael.hudec@beg.utexas.edu (M.R. Hudec), pflemings@jsg.utexas.edu (P.B. Flemings).

http://dx.doi.org/10.1016/j.tecto.2016.06.027
0040-1951/

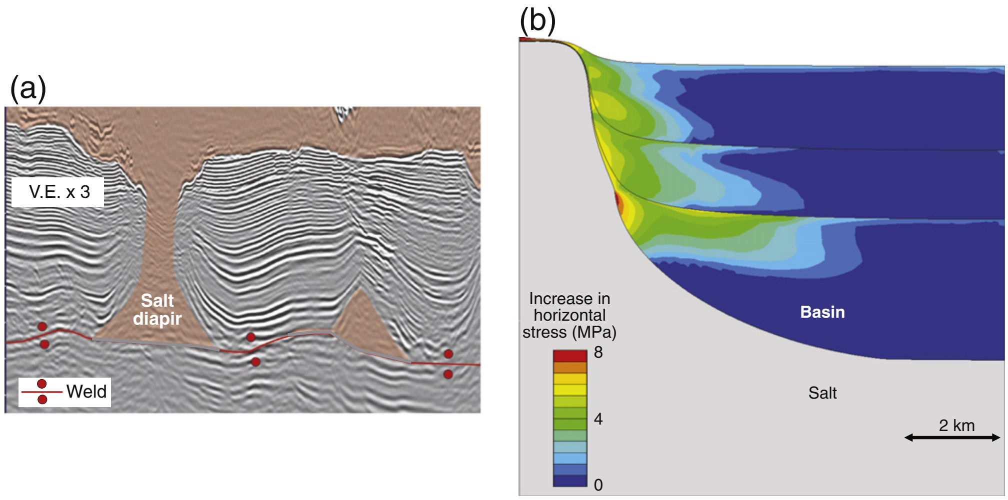

Fig. 1. Diapirs with welded and thick source layers. (a) A salt diapir with a largely welded source layer in Gulf of Mexico. Seismic data courtesy of CGG. (b) Increase in horizontal stress near a salt diapir with a thick source layer relative to regional (far-salt) value, obtained from a numerical model (Nikolinakou et al., 2014). High horizontal stress in diapir-flank sediments results from salt pressure, which is equal to salt overburden stress plus additional overpressure from salt source layer.

depends on the salt-pressure dissipation along the source layer, which changes with the source-layer thickness and geometry (Langlois and Deville, 2014). To quantify this dissipation and therefore the salt pressure in the diapir as the source layer thins and welds, one needs to simulate the salt flow along with the evolution of the source-layer geometry.

Many hydrocarbon prospects lie near salt diapirs with a welded source layer. Changes in stresses and structural attributes of sediments near welds are important for the exploration and production of these prospects. Stresses have direct control of the stability of wellbores and therefore of the planning of safe and economic drilling operations (Dusseault et al., 2004; Luo et al., 2012). The porosity of sediments affects the productivity of reservoirs, and the existence of faults impacts the migration and trapping of hydrocarbons. The geomechanical analysis of welding can thus also help better exploration, characterization, and production of reservoirs near welded salt layers.

In this study, we use a forward evolutionary finite-element model to investigate the impact of source-layer welding on stresses in the salt layer and diapir, as well as in their adjacent sediments. Our model, using realistic geometries of a salt-basin system, allows us to study stresses for a spectrum of source-layer thicknesses ranging from thick to thin to, finally, welded. We use more realistic poroelastic–plastic rheology for sediments (Albertz and Sanz, 2012; Gray et al., 2014), thereby taking into account their finite strength. Our model also allows us to monitor stresses through the entire process of welding and thereby identify possible irreversible stress-related features in sediments.

2. Numerical model

We use a plane-strain finite-element model to simulate the rise of a salt wall and the subsequent welding of its source layer under progressive sedimentation. The model is built within Elfen® (Rockfield, 2010) and analyzed using a finite-deformation, quasistatic, explicit, Lagrangian formulation with automated adaptive remeshing to handle excessive distortion of elements during large deformations (Peric and Crook, 2004; Thornton et al., 2011). A new mesh of elements is generated once a set of predefined criteria for element distortion is exceeded in any region in the model (Perić et al., 1999). The program also uses a regularization method to eliminate the dependency of results on the element size distribution in strain-softening regions.

Salt is represented as a viscoplastic material (Munson, 1997) with a constant density of 2.1 g/cm^3 (Fig. 2) and a viscosity that decreases with depth because of ground-temperature gradient. Sediments are represented by a critical-state poroelastic–plastic material model, SR3 (Crook et al., 2006). SR3 maintains the advantages of a traditional Mohr–Coulomb model to define sediment failure under shear stress and also takes into account material inelastic behavior under isotropic stresses (Muir Wood, 1990). Our model considers compaction of sediments with depth and the resulting increase in their density (Fig. 2). The input parameters used for salt and sediments in our model are given in Appendix A. The sediment parameters in our model reflect the behavior of a mudrock (Rockfield, 2010). Mudrocks are very common in most passive margin systems, which are of particular interest in salt tectonics (Boggs, 2010). For the sake of simplicity, only one rock type is used in the model.

Our model initiates with a flat salt layer having 3 km thickness and 60 km breadth (Fig. 3a). Sediments are deposited with a slope of 2° toward the center of the model and the final sediment thickness of 18 km. Sedimentation is simulated by progressive deposition of sediment

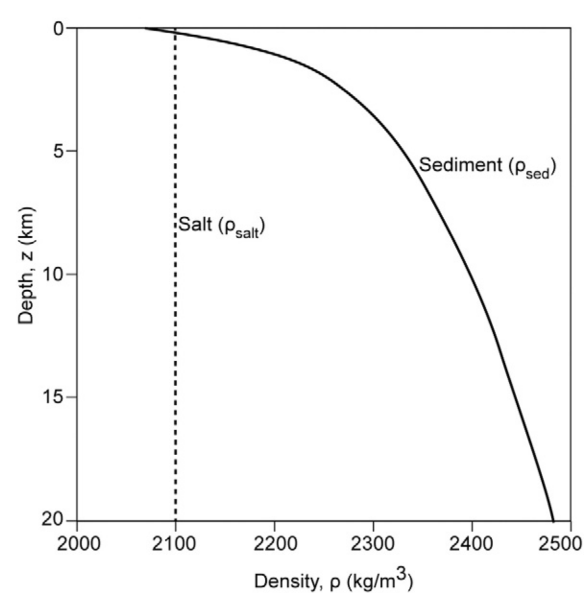

Fig. 2. Density profiles of salt and sediments. With depth, salt has a constant density, but sediments increase in density because of compaction.