Rock Mech Rock Eng
DOI 10.1007/s00603-015-0863-2

ORIGINAL PAPER

Modeling of Shales in Salt-Hydrocarbon Systems

Maria A. Nikolinakou[1] · Peter B. Flemings[2] · Michael R. Hudec[1]

Received: 28 September 2015 / Accepted: 30 September 2015
© Springer-Verlag Wien 2015

Abstract We model the stress–strain response of shale wall rocks to large deformations associated with the emplacement of salt bodies. We further identify the implications of these stress changes for hydrocarbon exploration. We model the mudrocks as porous elastoplastic materials. We employ both static and evolutionary approach for the modeling of salt systems and show that while the static one can model actual geologic geometries, only the evolutionary approach can provide a detailed description of the stress changes associated with the emplacement of salt. Hence, the evolutionary approach can register the overall stress history of the shale wall rocks, which is essential for predicting the present-day state of stress, porosity, and pore pressure. More generally, the evolutionary approach can provide useful insights for understanding Earth processes related to salt-hydrocarbon systems.

Keywords Shales · Forward modeling · Salt diapir · Poro-elastoplasticity · Wellbore stability

✉ Maria A. Nikolinakou
mariakat@mail.utexas.edu

Peter B. Flemings
pflemings@jsg.utexas.edu

Michael R. Hudec
michael.hudec@beg.utexas.edu

1 Bureau of Economic Geology, The University of Texas at Austin, 10100 Burnet Road, Building PRC-130, Austin, TX 78758, USA

2 Jackson School of Geosciences, The University of Texas at Austin, 10100 Burnet Road, Building PRC-130, Austin, TX 78758, USA

1 Introduction

During the last two decades, understanding the stress, material behavior, and pore pressure in shales around salt bodies has become increasingly important. The energy industry routinely drills near salt (Beltrão et al. 2009; Meyer et al. 2005; Seymour et al. 1993), because a significant number of hydrocarbon reservoirs around the world are found in layers dipping away from salt diapirs.

Salt is a viscous material that cannot sustain deviatoric stresses. Under differential loading, it flows, changes shape, and eventually relaxes to an isotropic (uniform) stress state (Urai and Spiers 2007). Therefore, emplacement of a salt body and its viscous relaxation process may cause significant deformation of the surrounding sediments, perturb their state of stress, and create local overpressures (Dusseault et al. 2004; Seymour et al. 1993). As a result, drilling near salt is particularly challenging, and problems leading to additional expense or even abandonment are common (Bradley 1978; Dusseault et al. 2004; Meyer et al. 2005; Seymour et al. 1993; Willson et al. 2003).

Historically, salt and the evolution of its cross section to the present-day geometry have been studied using kinematic restorations (Rowan and Ratliff 2012). This approach aims to explain the present geologic section through a sequence of plausible past sections; however, it does not model the constitutive response of the wall rocks, and hence, it cannot provide any prediction on their state of stress. Similarly, large-strain numerical studies (Albertz and Beaumont 2010; Chemia et al. 2009; Goteti et al. 2012; Gradmann et al. 2009) have focused on the rheological evolution of salt systems without modeling the geomechanical response of the sediments.

Geomechanical analyses of salt systems are now increasingly used to model the stress field and pore pressure around salt (Koupriantchik et al. 2004; Mackay et al. 2008; Nikolinakou et al. 2014a; Orlic and Wassing 2013; van-der-Zee et al. 2011). Because they model the shale response to salt loading, they can improve the design of economic well paths, ensure borehole stability, and minimize the risk of wellbore fracturing and formation fluid influxes. Latest advances in this field include the use of coupled poro-elastoplastic analyses to predict the transient pore pressure and stress changes around salt (Nikolinakou et al. 2012) and three-dimensional simulations of actual salt structures, combined with poro-elastic formulations (van-der-Zee et al. 2011).

There are two major types of geomechanical analyses: static and evolutionary. The static approach is the most commonly used and is built using the present-day salt geometry. The stress relaxation within the salt is the source of sediment loading (Fredrich et al. 2007). The evolutionary approach, on the other hand, models the evolution of the salt cross section to its final geometry. In this approach, stresses within the sediments develop not only because of sedimentation but also because of the loading from the moving salt (Nikolinakou et al. 2014a).

In this paper, we first review the merits and pitfalls of static analyses using an example salt from the Gulf of Mexico. Then, we discuss a new approach of evolutionary salt modeling. Our results highlight the fact that forward modeling can provide a detailed understanding of the stress history of shales close to salt diapirs; this is critical for predicting stress, porosity, and pore pressure in the wall rocks and, more generally, for understanding Earth processes related to salt systems.

2 Geomechanical Static Approach

2.1 General

The geomechanical static approach is the most commonly used in the energy industry, which in turn has developed a number of elaborate three-dimensional static tools. It is built using observed present-day salt geometries and an assumed initial stress field. Most published studies assume idealized salt shapes (Fredrich et al. 2007; Luo et al. 2012; Nikolinakou et al. 2012; Orlic and Wassing 2013; Sanz and Dasari 2010), but a few studies use geometries devised on the basis of seismic information (Henk 2005; Koupriantchik et al. 2004; Nikolinakou et al. 2013). The driving mechanism for the static analyses is the stress relaxation within the salt. The salt stress changes cause deformation of the salt mass, which in turn loads the wall rocks. The mode of deformation can vary depending on the initial stress state and the form of the salt. For example, stresses within salt bodies with comparable horizontal and vertical dimensions (ideally, spheres) converge to an isotropic value that lies between the overburden value and that of the initial horizontal stresses (e.g., Nikolinakou et al. 2012). In a typical non-compressional setting, this causes loading at the flank and unloading above and/or below the salt. On the other hand, stresses within long, shallow salt bodies converge to the value of the overburden, because no arching mechanism can develop to support any stresses not transmitted through the salt (e.g., Nikolinakou et al. 2013). This loads the sediments laterally and causes little interaction with the sediments below salt.

Therefore, the major contribution of the static approach is that it can provide a first-order understanding of the stress perturbations within the shale wall rocks, based on the present-day salt geometry. However, it cannot account for stress or pore pressure changes that result from the evolution of the salt geometry to its current shape. Moreover, static results depend on the assumed initial stress field, which is usually not well understood.

2.2 Example: the Mad Dog Salt

The geomechanical modeling of the Mad Dog field (Nikolinakou et al. 2013) is a case study that illustrates the benefits of the static approach.

The Mad Dog salt is part of the larger Sigsbee salt canopy located in the deepwater northern Gulf of Mexico. It is found in the Green Canyon about 190 miles southwest of New Orleans (Fig. 1). The studied part of the canopy measures 20 km in horizontal extent and 0.1–4 km in vertical thickness (Fig. 2). The top of the salt is locally less than 1 km below the seafloor (Fig. 2). We built a plane strain model within the finite-element package ABAQUS© (ABAQUS 2009). We modeled the salt as a solid viscoelastic material (Fredrich et al. 2007; Sanz and Dasari 2010) and the sediments as solid

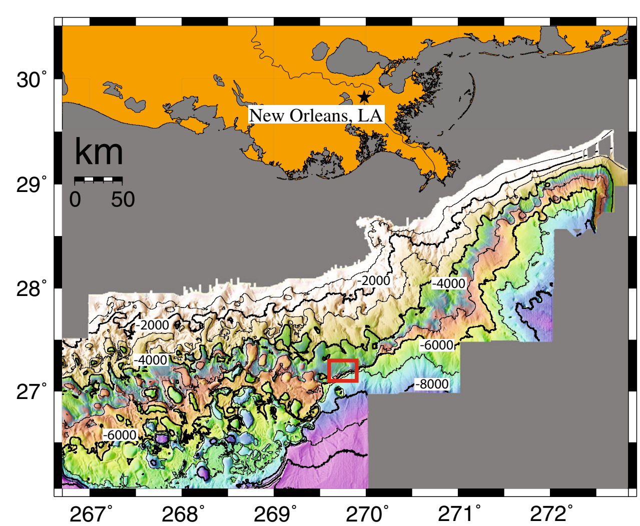


Fig. 1 Location of the Mad Dog Field, Gulf of Mexico (Merrell 2012)

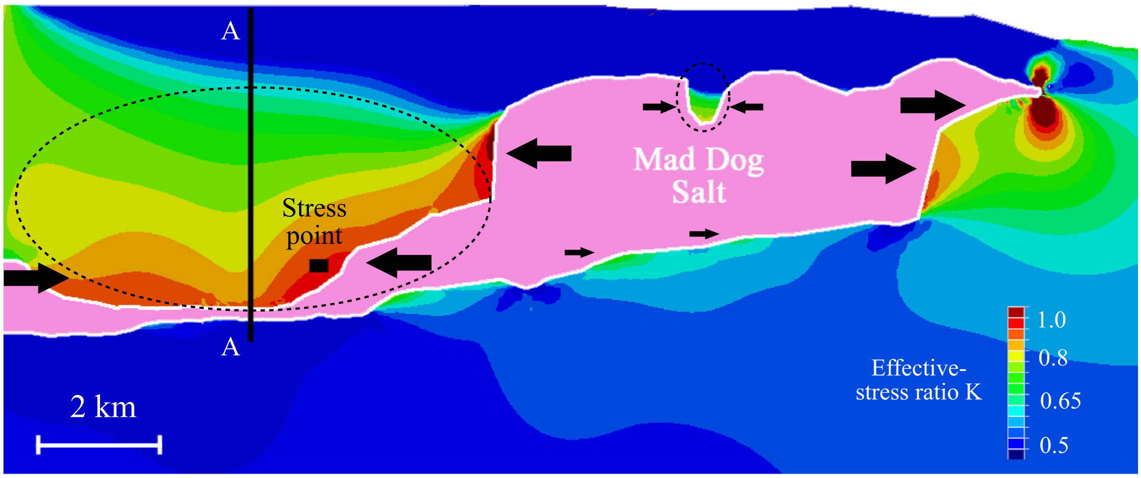


Fig. 2 Static analysis of the Mad Dog field: Horizontal-to-vertical effective stress ratio, K, within the wall rocks, illustrating elevated horizontal stresses in the minibasins (*circled areas*) and in front of the salt body (Nikolinakou et al. 2013)

elastic and assumed a geostatic initial stress field, with $K_0 = 0.5$ (initial horizontal effective stresses equal half the value of the effective overburden). Pore pressures are assumed hydrostatic. More details about the model can be found in Nikolinakou et al. (2013).

Because this salt body is much longer than the thickness of the overlying sediments, no arching mechanism can develop to support any fraction of the overburden, and hence, the final isotropic stress within the salt has to be equal to the vertical overburden value. This means that the salt horizontal stress is also equal to the overburden value. In non-compressional regions, such as the Mad Dog area in the Gulf of Mexico, the regional horizontal stress is a fraction of the vertical overburden stress; therefore, the salt stress is higher than the regional horizontal stress. As a result, the salt is horizontally loading the wall rocks, and so the sediments experience a lateral stress increase as in typical thrust geologic settings (Fig. 2). Consequently, the horizontal stress is significantly elevated within minibasins and in front of the salt, and it has a value close to the vertical stress (Fig. 3). On the other hand, stress perturbations below the salt body are notably smaller, since the salt stress is equal to the overburden stress.

The case study illustrates that a long and shallow salt geometry would indicate elevated lateral stresses in minibasins and close to vertical (or in general inclined) salt faces. This has several implications for drilling in those areas: (a) high leak-off values; (b) decrease in differential (shear) stresses, therefore lower risk of shear failure; and (c) overpressures under undrained or partly drained conditions. In addition, because the salt stress equals the vertical overburden stress, a sudden decrease in horizontal stresses is expected at horizontal salt-sediment boundaries; this results in a sharp drop in least principal stress when exiting a flat salt base.

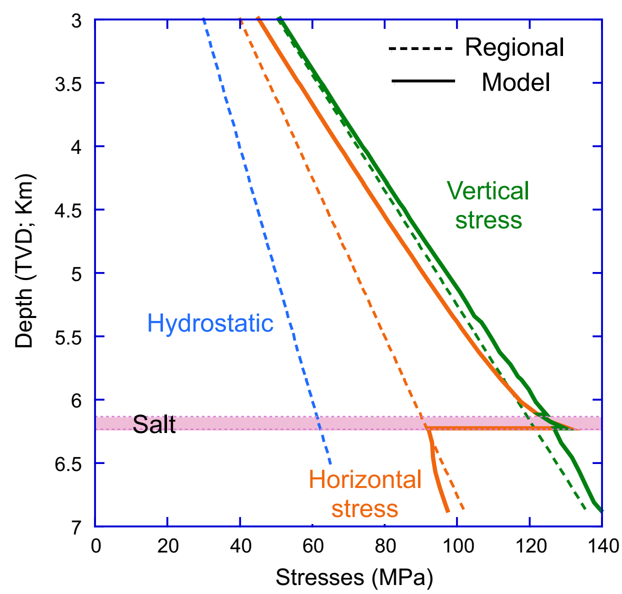


Fig. 3 Vertical stress profile through the minibasin on the *left* of the Mad Dog salt (section A–A in Fig. 2). *Dashed lines* plot regional stresses and *solid lines* show near-salt stresses. The location of the salt is also *highlighted*. The horizontal stress is elevated and converges to the value of the vertical stress, throughout the depth of the minibasin (Nikolinakou et al. 2013)

3 Geomechanical Evolutionary Approach

3.1 General

The strength of shales, as well as their response to external loading, is a function of their loading history since deposition (Terzaghi et al. 1996) and their diagenetic history (Laubach et al. 2010). The stress history is especially critical in near-salt environments that are associated with significant geologic deformations. Hence, the current strength and stress state of the salt wall rocks will be more closely predicted when the development of the salt diapir is modeled concurrently with basin sedimentation.

Geomechanical evolutionary models can simulate such development and can provide a powerful tool to simulate and understand how stresses redistribute in the wall rocks near salt. The major benefits of evolutionary models are (a) stresses within the basin develop as a function of both the depositional process and the loading from the salt, and no horizontal-to-vertical stress ratios need to be assumed (i.e., uniaxial strain deposition); and (b) the current strength and deformation characteristics of mudrocks are estimated based on the accumulated strain history. On the other hand, evolutionary models require longer preparation and run times and greater computational power, and they rarely match the present-day geometry observed in seismic sections.

3.2 Example: a Rising Salt Diapir

The evolutionary modeling of a rising salt diapir (Nikolinakou et al. 2014a) illustrates that forward models can provide a detailed understanding of the stress history of sediments close to salt diapirs.

We built a drained, axisymmetric model of a salt diapir (Fig. 4) within the finite-element program Elfen® (Rockfield 2010). We simulated sedimentation by aggrading the top of the model 400 m every half million years. We modeled the salt as a solid viscoplastic material (Munson and Dawson 1979) and the shales as porous elastoplastic materials, using the SR3 critical state formulation from the Elfen® material library. The density and strength of shales vary as a function of porosity, and hence, they are updated because of both sedimentation and of salt diapir rise. More details about this study can be found in Nikolinakou et al. (2014a).

The salt diapir grows in the lateral (radial) direction and increases its radius as it moves upwards, expanding in the circumferential direction (Fig. 5). This subjects the sediments to radial shortening, which increases the horizontal stress, and to circumferential extension, which decreases substantially the hoop stress (Fig. 6). Because stresses within the salt are nearly isotropic, the principal stresses in the shales next to salt rotate, such that they become perpendicular and tangential to the contact with salt.

Simulating the evolution of a salt diapir reveals four important changes in the stress field within the adjacent shales:

(a) The horizontal (radial) stress is not necessarily a fraction of the overburden, and it can be higher than the overburden value, because of the lateral push from the salt (Fig. 6b).

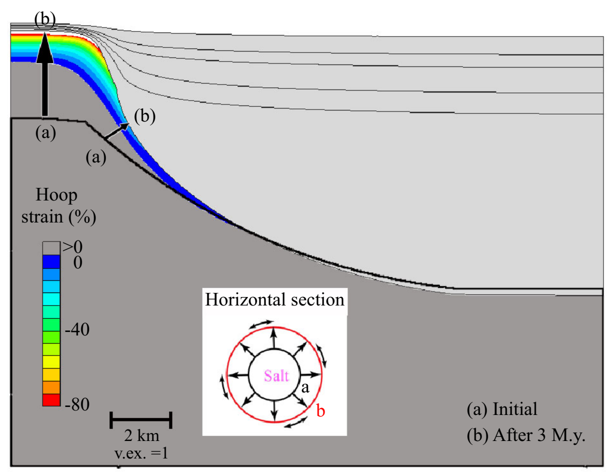


Fig. 5 Vertical section showing salt geometry at beginning of simulation and after 3 m.y. of sedimentation. Contours show extensional hoop strain and *inset* map-view sketch illustrates deformation of horizontal dome sections, after Nikolinakou et al. (2014a)

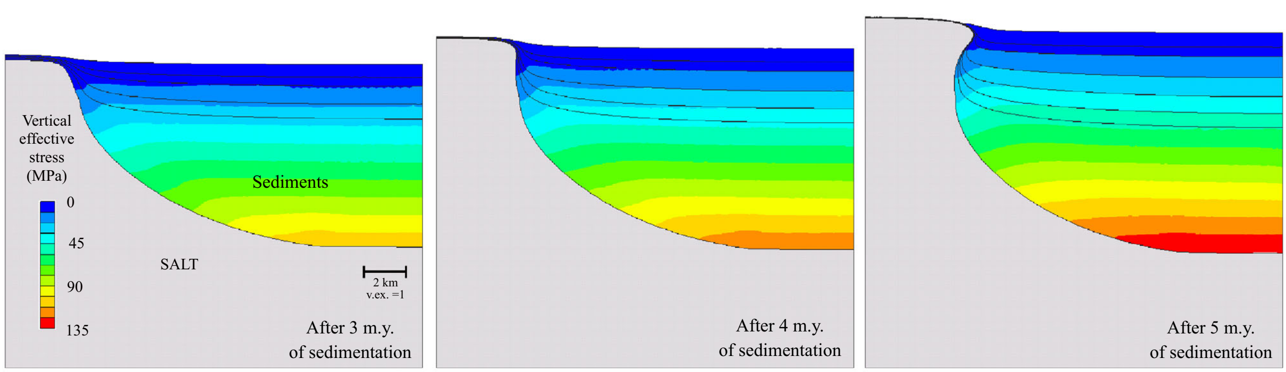


Fig. 4 Evolutionary analysis of a salt diapir: vertical sections predicted by the numerical model after 3, 4, and 5 m.y. of sedimentation. Contours illustrate changes in vertical stress due to sedimentation and simultaneous salt movement (after Nikolinakou et al. 2014a)

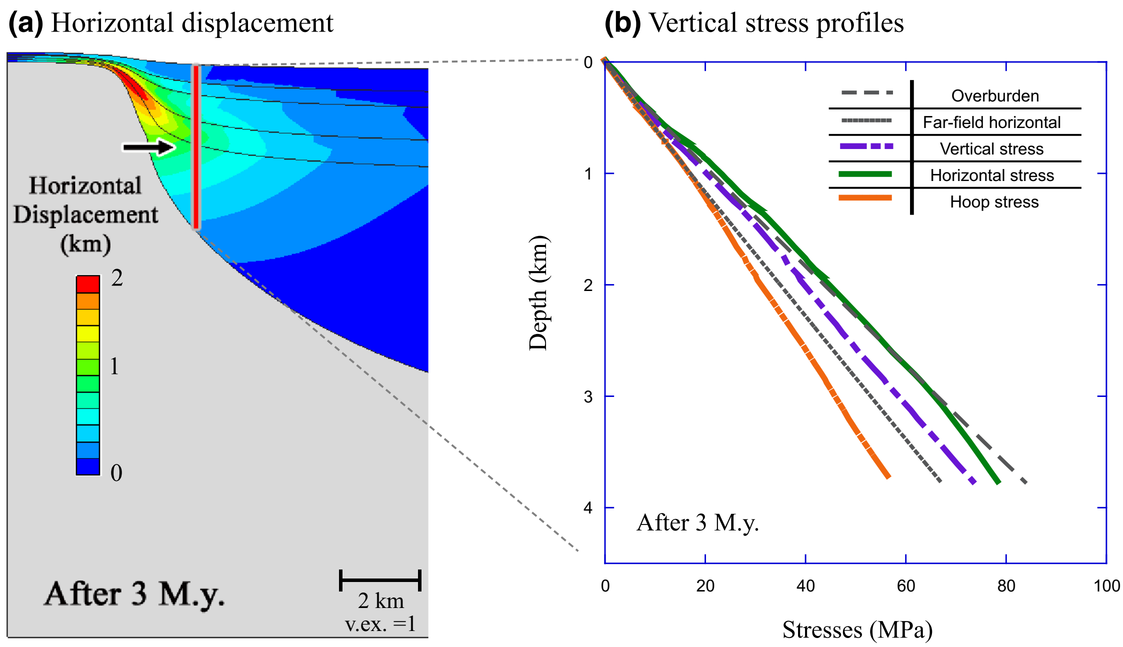
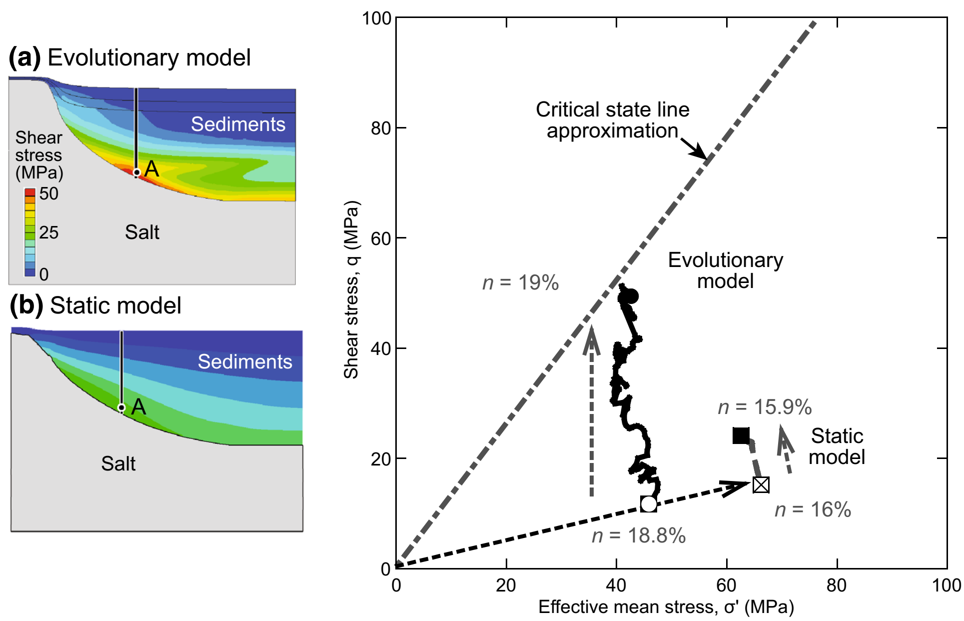


Fig. 6 Evolutionary analysis of a salt diapir: **a** vertical section with contours of horizontal displacement next to rising salt dome, after 3 m.y. of deposition; **b** stress profiles of horizontal, vertical, and hoop stresses along well next to salt, after Nikolinakou et al. (2014a)

Fig. 7 Contours showing shear stresses predicted by (**a**) evolutionary and (**b**) static model. Stress path (mean effective stress and corresponding shear stress) for point *A* near base of diapir. Evolutionary approach predicts much higher shear stress and stress state closer to critical state (Nikolinakou et al. 2014b)



(b) The hoop stress is the least principal stress and it decreases near the salt diapir (Fig. 6b). This increases the danger for circulation loss during drilling.

(c) The respective increase in radial and decrease in hoop stress result in high differential (shear) stresses near the diapir (Fig. 7). This increases the possibility of borehole breakouts.

(d) Because of the large increase in the radial stress, the mean stress increases near the upper parts of the diapir, leading to a porosity lower than the one predicted by uniaxial basin modeling.

4 Evolutionary vs. Static approach

In comparison to evolutionary analyses, static ones require shorter preparation and run times, and less computational power. More importantly, they can model specific present-day geometries of salt. However, they cannot account for stress perturbations due to the emplacement of the salt body.

In order to demonstrate the importance of forward modeling, we compare a static with an evolutionary model of a salt diapir (Nikolinakou et al. 2014b). The static model uses as present-day geometry the final salt shape of the evolutionary model. They both simulate the wall rock shales as poro-elastoplastic materials using the critical state formulation (Modified Cam Clay and SR3 respectively).

Because the static approach does not model the large deformations associated with the rise of the salt diapir, it predicts much smaller stress perturbations than the evolutionary one. In particular, it cannot capture the increase in horizontal stress and decrease in hoop stress that result from the increase in the salt radius and hence the circumferential expansion of the diapir. Consequently, the evolutionary approach predicts much higher shear stresses, especially above the diapir pedestal (Fig. 7).

The higher shear predicted by simulating the evolutionary model has major implications for borehole stability (Fig. 8). To avoid failure or collapse of the borehole during drilling, the mud weight must be higher than the formation pore pressure in order to avoid blowouts and lower than the least principal stress in order to avoid loss of circulation. In addition, the range of admissible borehole pressures is constrained to prevent compressive failure of the borehole (borehole wall breakouts; Zoback 2007). Along the vertical profile A (Fig. 7), the evolutionary model predicts a sudden decrease in the least principal stress, and high shear stresses; as a result, borehole compressional failure cannot be prevented above the salt pedestal (Fig. 8a). In contrast, the static model shows no notable changes in the least principal stress or in the admissible mud weight range with depth (Fig. 8b). In other words, the static approach is not able to predict the difficult drilling conditions above the salt pedestal.

5 Summary

We discuss the static and evolutionary approaches for the modeling of shale wall rocks in salt-hydrocarbon systems. We model shales as poro-elastoplastic materials. We show that static models can provide a first-order estimation of stress re-distribution around salt. However, evolutionary models offer a more complete estimation of the stress field near salt, as they capture stress changes both because of sedimentation and of the loading from the moving salt. We illustrate that the large deformations associated with the diapir rise lead to significant stress changes, including a least principal stress that decreases near the salt, and lower porosity values near the upper parts of the diapir.

Furthermore, we compare the static and evolutionary approach for the case of a salt diapir and show that the static model cannot account for stress changes owing to the salt emplacement, while the evolutionary one can provide a detailed description of the stress history of the wall-rock

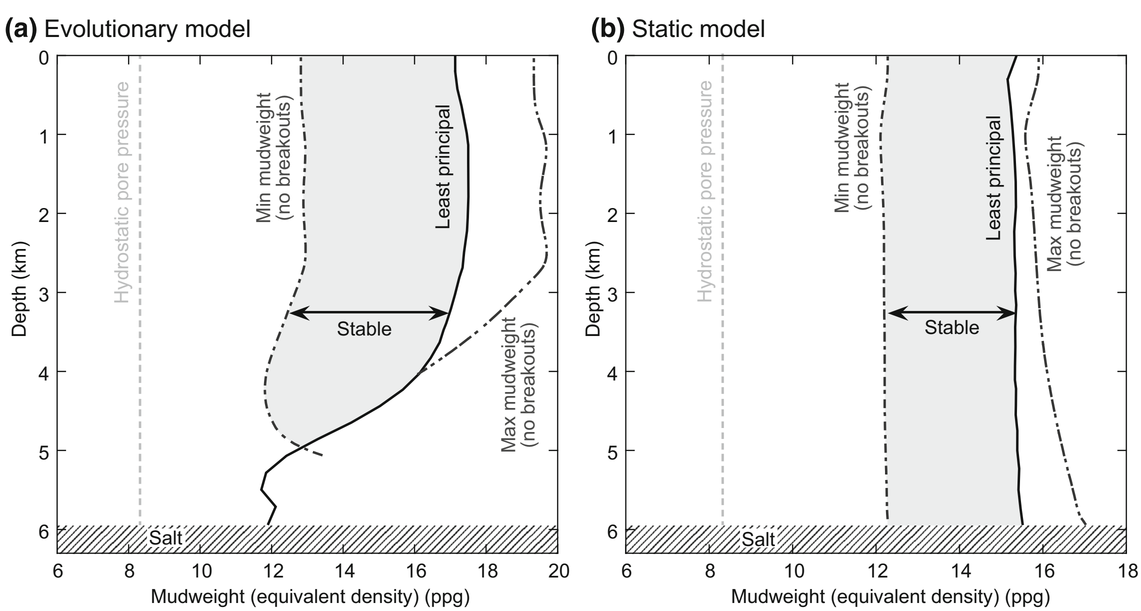


Fig. 8 Mud weights predicted along well *A* (Fig. 7). Evolutionary model predicts sudden decrease in least principal stress and borehole collapse above salt base. Static model, in contrast, shows no notable change in the range of stable mud weights. (Nikolinakou et al. 2014b)

shales. This is essential for understanding how the material has compressed to its current volume, and therefore for predicting more efficiently the current strength and anisotropy characteristics of the shales.

Acknowledgments The discussed research projects were funded by the Applied Geodynamics Laboratory consortium and the University of Texas at Austin (U. T.) GeoFluids consortium. AGL is supported by the following companies: Anadarko, Apache, BHP Billiton, BP, CGG, Chevron, Cobalt, ConocoPhillips, Ecopetrol, ENI, ExxonMobil, Fugro, Global Geophysical, Hess, Ion, KNOC, McMoRan, Maersk, Marathon, Murphy, Nexen, Noble, Pemex, Petrobras, PGS, Repsol, Samson, Saudi Aramco, Shell, Statoil, Talisman, TGS, Total, Western Geco, and Woodside. U. T. GeoFluids is supported by the following companies: Anadarko, BHP Billiton, BP, Chevron, Conoco-Phillips, ExxonMobil, Hess, Murphy Oil, Repsol, Schlumberger, Shell, Statoil, and Total. The author received additional support from the U. T. Jackson School of Geosciences. This publication was authorized by the Director, Bureau of Economic Geology.

References

ABAQUS (2009) Abaqus user guide and help documentation, Version 6.9, SIMULIA company

Albertz M, Beaumont C (2010) An investigation of salt tectonic structural styles in the Scotian Basin, offshore Atlantic Canada: 2. Comparison of observations with geometrically complex numerical models. Tectonics 29:TC4018. doi:10.1029/2009TC002540

Beltrão RLC, Sombra CL, Lage ACVM, Fagundes Netto JR, Henriques CCD (2009) Challenges and new technologies for the development of the pre-salt cluster, Santos Basin, Brazil. Paper presented at the Offshore Technology Conference, Houston, Texas, 4–7 May 2009

Bradley WB (1978) Borehole failure near salt domes. Paper presented at the Society of Petroleum Engineers Annual Fall Technical Conference and Exhibition, Houston, Texas, 10/01/1978

Chemia Z, Schmeling H, Koyi H (2009) The effect of the salt viscosity on future evolution of the Gorleben salt diapir, Germany. Tectonophysics 473:446–456. doi:10.1016/j.tecto.2009.03.027

Dusseault MB, Maury V, Sanfilippo F, Santarelli FJ (2004) Drilling around salt: risks, stresses, and uncertainties. Paper presented at the 38th US Rock Mechanics and Geomechanics Symposium, Houston,TX, 5–9 June 2004

Fredrich JT, Fossum AF, Hickman RJ (2007) Mineralogy of deepwater Gulf of Mexico salt formations and implications for constitutive behavior. J Petrol Sci Eng 57:354–374. doi:10.1016/j.petrol.2006.11.006

Goteti R, Ings SJ, Beaumont C (2012) Development of salt minibasins initiated by sedimentary topographic relief. Earth Planet Sci Lett 339(340):103–116. doi:10.1016/j.epsl.2012.04.045

Gradmann S, Beaumont C, Albertz M (2009) Factors controlling the evolution of the Perdido Fold Belt, northwestern Gulf of Mexico, determined from numerical models. Tectonics 28:TC2002. doi:10.1029/2008tc002326

Henk A (2005) Pre-drilling prediction of the tectonic stress field with geomechanical models. First Break 23:53–57. doi:10.3997/1365-2397.2005021

Koupriantchik D, Meyers AG, Hunt S (2004) 3D geomechanical modelling towards understanding stress anomalies causing wellbore instability. Paper presented at the Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium (NARMS), Houston, Texas, June 5–9, 2004

Laubach SE, Eichhubl P, Hilgers C, Lander RH (2010) Structural diagenesis. J Struct Geol 32:1866–1872. doi:10.1016/j.jsg.2010.10.001

Luo G, Nikolinakou MA, Flemings PB, Hudec MR (2012) Geomechanical modeling of stresses adjacent to salt bodies: 1. Uncoupled models AAPG. Bulletin 96:43–64. doi:10.1306/04111110144

Mackay F, Inoue N, Fontoura SAB, Botelho F (2008) Geomechanical effects of a 3D vertical salt well drilling by FEA. Paper presented at the The 42nd US Rock Mechanics Symposium (USRMS), San Francisco, California, June 29–July 2, 2008

Merrell MP (2012) Pressure and Stress at Mad Dog Field, Gulf of Mexico. The University of Texas at Austin, Austin

Meyer D, Zarra L, Rains D, Meltz B, Hall T (2005) Emergence of the Lower Tertiary Wilcox trend in the deepwater Gulf of Mexico. World Oil 226(5):72–77

Munson DE, Dawson PR (1979) Constitutive model for the low temperature creep of salt (with application to WIPP). SAND79-1853, Sandia National Laboratories, Albuquerque, NM

Nikolinakou MA, Luo G, Hudec MR, Flemings PB (2012) Geomechanical modeling of stresses adjacent to salt bodies: 2. poro-elasto-plasticity and coupled overpressures. Am Assoc Pet Geol Bull 96:65–85. doi:10.1306/04111110143

Nikolinakou MA, Merrell MP, Luo G, Flemings PB, Hudec MR (2013) Geomechanical modeling of the Mad Dog salt, Gulf of Mexico. Paper presented at the 47th US Rock Mechanics Symposium, San Francisco, CA, 23–26 June, 2013

Nikolinakou MA, Flemings PB, Hudec MR (2014a) Modeling stress evolution around a rising salt diapir. Mar Pet Geol 51:230–238. doi:10.1016/j.marpetgeo.2013.11.021

Nikolinakou MA, Hudec MR, Flemings PB (2014b) Comparison of evolutionary and static modeling of stresses around a salt diapir. Mar Pet Geol 57:537–545. doi:10.1016/j.marpetgeo.2014.07.002

Orlic B, Wassing BBT (2013) A study of stress change and fault slip in producing gas reservoirs overlain by elastic and viscoelastic caprocks. Rock Mech Rock Eng 46:421–435. doi:10.1007/s00603-012-0347-6

Rockfield (2010) ELFEN Forward Modeling User Manual. Rockfield Software Limited

Rowan MG, Ratliff RA (2012) Cross-section restoration of salt-related deformation: best practices and potential pitfalls. J Struct Geol 41:24–37. doi:10.1016/j.jsg.2011.12.012

Sanz PF, Dasari GR (2010) Controls on in situ stresses around salt bodies. Paper presented at the 44th US Rock Mechanics Symposium, Salt Lake City, UT June 27–30

Seymour KP, Rae G, Peden JM, Ormston K (1993) Drilling close to salt diapirs in the North Sea. Paper presented at the Offshore Europe, Aberdeen, UK, 09/07/1993

Terzaghi K, Peck RB, Mesri G (1996) Soil mechanics in engineering practice. Wiley, New York

Urai JL, Spiers CJ (2007) The effect of grain boundary water on deformation mechanisms and rheology of rocksalt during long-term deformation. In: Wallner M, Lux K, Minkley W, Hardy Jr H (eds) Proceedings of the 6th conference on the mechanical behavior of salt, 'SaltMech6', Hannover, Germany, 22–25 May 2007. Taylor and Francis, London

van-der-Zee W, Ozan C, Brudy M, Holland M (2011) 3D geomechanical modeling of complex salt structures. In: SIMULIA Customer Conference

Willson SM et al (2003) Wellbore stability challenges in the deep water, Gulf of Mexico: case history examples from the pompano field. Paper presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, 5–8 October 2003

Zoback MD (2007) Reservoir geomechanics, 1st edn. Cambridge University Press, Cambridge