Research Article

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Modeling of stringer deformation and displacement in Ara salt after the end of salt tectonics

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Abstract: The present work considers numerical models of large rock inclusions (stringers) are embedded in many salt bodies. The study has been made to investigate the influence of salt tectonic process, such as downbuilding, on the deformation and displacement of stringers. In this research, the focus has been on establishing numerical models of the deformation and displacement of stringer embedded in salt (at rest) after occurrences of salt tectonics. The problem of influence of eventual tectonic processes at larger stage is addressed on the development of stringers. The numerical model is based on finite element method in combination with adaptive remeshing. The results show that the stringers experience minor sinking and the differential stress in salt and the differential stress in the stringer decrease during the period after salt tectonics. The change of stress of reservoir will influence drilling process and oil or gas production.

Keywords: stringer, deformation, displacement, salt tectonics, internal stress, fragments

1 Introduction

Salt tectonics is strongly related to hydrocarbon reservoirs in sedimentary basins worldwide. Large rock inclusions encased in salt (so-called rafts, floaters or stringers) are of broad economic interest [1]. It is important to understand when and how those inclusions break and redistribute salt flow. As oil and gas reservoirs, the inclusions containing hydrocarbon hold potential drilling hazards [2–7]. The evolution of stringers also strongly relates to the inter-

nal deformation mechanisms in salt diapirs [8–12]. In the previous research, the results of a study of the dynamics of brittle inclusions in salt during downbuilding process were presented [1]. The FEM package ABAQUS and remeshing technique are used to model the brittle deformation and displacement. Although the model is simplified, it offers a practical method to explore complex stringer motion and deformation, including brittle fracturing and disruption. According to these modeling results, stringers can break very soon after the onset of salt tectonics (~10 m top-salt minibasin subsidence) and are broken by tensile fractures. Redistribution of salt flow can lead to a series of boudinage in the later stage. While horizontal salt extensions cause tensile fracture, vertical components of the salt flow dominates bending and rotation of stringers. The aim of this study is to contribute to our understanding on the deformation and displacement of stringer embedded in salt (at rest) after occurrences of salt tectonics. The location and internal stress of stringer strongly relates to the potential operational hazard risks and wellbore stability. The model geometry considered is the same as introduced in Li *et al.* [1], but employed for making calculation of subsequent after the occurrence of salt tectonics stops.

2 Geological Setting

Based on the geological background, the study area is located in the southwest of the South Oman Salt Basin (SOSB), in the south of the Sultanate of Oman (Figure 1). The SOSB is from late Neoproterozoic to early Cambrian and is an evaporative basin belt from Oman to Iran (Hormuz Salt) and Pakistan (Salt Range) and further to the East Himalaya [13, 14]. The SOSB is an unusual petroleum-producing domain. Self-charging carbonate stringers embedded into the salt of the SOSB represent a unique intra-salt petroleum system that contains large amount of hydrocarbon accumulations. It has been successfully explored in recent years [4–6, 15] (Figure 2).

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Figure 1: Southern Oman with three major salt basins which developed during the Late Proterozoic and which are known from elsewhere in the Middle East. Neoproterozoic assemblage of clastics, carbonate and salt sequences [7].

As introduced in Reuning *et al.* [12] and Li *et al.* [1], the geochronology was adopted from Al-Husseini [16]. The lithostratigraphy of the lower Huqf Supergroup was adapted from Allen [14] and Rieu *et al.* [17]. The lithostratigraphy of the upper Huqf Supergroup and the Haima Supergroup was adapted from Boserio *et al.* [18], Droste [19], Blood [20] and Sharland *et al.* [21]. The lithostratigraphic composite log on the right (not to scale) shows the six carbonate to evaporate sequences of the Ara Group, which are overlain by siliciclastics of the Nimr Group and further by the Mahatta Humaid Group. Sedimentation of the siliciclastics on the mobile evaporate sequence led to strong halokinesis, which ended during sedimentation of the Ghudun Formation [22].

The eastwards-thinning basin covers an Early Neoproterozoic crystalline basement and contains Late Neoproterozoic–Recent sediments with a total thickness

of up to 7 km [22–24]. The oldest deposits in the basin are the Neoproterozoic–Early Cambrian age (c. 800–530 Ma) Huqf Supergroup [25–30]. The lower part of the Huqf Supergroup is continental siliciclastics and marine ramp carbonates of the Abu Mahara and Nafun Group (Figure 3). These rocks were deposited in a strike-slip setting and later associated with extensive regional settlement [24]. With the deposition of the terminal Nafun Group sediments (c. 550.5–547.36 Ma, Figure 3), an uplift of large basement blocks led to the division of the basin and to the formation of fault-bounded sub-basins [31, 32]. The Nimr group finished forming characteristic pods in the study area at about –520 Ma. The purpose here is to model the stringer deformation and displacement after salt tectonics (from –520 Ma to 0 Ma) and to investigate the redistribution of differential stress in stringers and long-term salt rheology after the end of salt tectonics. Detailed knowledge of the

Figure 2: Seismic cross section of an Ara salt diapir, exemplarily showing interpreted stringer occurrences and faults [4, 7].

Figure 3: Chronostratigraphic summary of rock units in the subsurface of the Interior Oman (modified from [12], reprinted by permission from GeoArabia). The modeled part of the stratigraphy is signed with a brown box on the right side of the figure.

internal stresses in the stringers could have significant implications for example, for structural interpretation and assessment of drilling risks.

3 Setting up the models

3.1 Model set-up

As introduced in Li *et al.* [1], the model considers that the SW-dipping basement has a width of 18 km. The salt initially has a thickness of up to 1600 m and thins towards the NE (600 m). The carbonate stringer with a length of 12 km and a height of 80 m is located 360 m above the basement. Further details of model parameter values are given in Table 1. The passive downbuilding of the Haima pod is strongest in the center of the model and volume of salt remains constant during deformation. These pods are assumed to accumulate and subside in the center. Simplified model set-up is shown in Figure 4

The model assumes that the rheology of salt may be described by a power-law relationship between the differ-

Figure 4: Simplified model set-up [1].

ential stress and strain rate:

$$\dot{\epsilon} = A (\Delta\sigma)^n = A_0 \exp\left(-\frac{Q}{RT}\right) (\sigma_1 - \sigma_3)^n \quad (1)$$

where $\dot{\epsilon}$ is the strain rate, $(\sigma_1 - \sigma_3)$ differential stress, A_0 a material parameter, Q the activation energy, R the gas con-

Table 1: Values of parameters considered in the model.

Parameter	Value
Width of salt body (W)	18000m
Height of salt body (H)	1600m
Stringer thickness (h)	80m
Stringer length (l)	12000m
Salt density	2040kg/m ³
Stinger density	2600kg/m ³
Salt rheology	$A=1.04 \times 10^{-14}$ $\text{MPa}^{-5} \text{s}^{-1}$, $n=5$
Salt temperature	50°C
Stringer elastic properties	$E=40\text{GPa}$, $\nu=0.4$
Basement elastic properties	$E=50\text{GPa}$, $\nu=0.4$
Basement density	2600kg/m ³
Calculation time	6.3Ma

stant ($R=8.314 \text{ Jmol}^{-1} \text{K}^{-1}$), T temperature, and n the power law exponent.

The two main deformation mechanisms in salt, under the stress conditions and temperatures of active diapirism are pressure solution creep, with $n = 1$ and dislocation creep, with n around 5 [33]. As argued in Urai *et al.* [33] and Li *et al.* [1], the rheology can be simplified to $n = 5$ with the appropriate material parameters for the salt at rest. The parameters measured for Ara rock salt in triaxial deformation experiments are: $A_0 = 1.82 \times 10^{-9} \text{ s}^{-1}$, $Q=32400 \text{ Jmol}^{-1}$, $n = 5$ [33, 34]. The elastic properties of stringer and basement included Young's modulus E and Poisson's ratio ν .

In the previous work, deformation of the salt section was applied by a vertical displacement of the top salt boundary, simulating the down-building of overburden sediments into the salt and formation of a salt pillow. The commercial finite element modelling package ABAQUS has been employed for modelling deformation of stringers. This method incorporates effects of power law creep and elastoplastic rheology and employs adaptive re-meshing techniques. (1) Displacement of top salt. In the model, the displacement of the top salt is achieved by applying a pre-determined displacement field. At this stage of the modelling horizontal motion at this boundary (the equivalent of a fully coupled salt–sediment interface) is not allowed. (2) Iterative scheme for stringer breaking. A strongly simplified, iterative procedure is adopted in ABAQUS to detect the onset of conditions of fracturing and model the subsequent break-up of the stringers. (3) Adaptive remeshing of the model. The built-in adaptive remeshing routines are used in ABAQUS to create new elements while mapping the stress and displacements of the old mesh on this new one.

3.2 Modeling of stringer sinking in Ara salt after the end of salt tectonics

Through the calculation of displacement and deformation of stringers, the result of the final configuration of Ara salt can be achieved. According to the geological setting and the chronostratigraphic chart (Figure 3), the Nimr group finish forming the characteristic pods in the study area at around -520 Ma . The purpose to model the stringer deformation and displacement after salt tectonics (from -520 Ma to 0 Ma) is to investigate the redistribution of differential stress in stringers and long-term salt rheology due to the end of salt tectonics.

The result of the final configuration of Ara salt section is shown with elongated, already broken and physically isolated stringer fragments embedded in salt. The details are presented in Figure 4, adapted from Li *et al.* [1]. During salt tectonics, the deformation of stringer and salt flow changes the internal stress of stringer. When the stress exceeds failure criterion, the stringer is fractured into fragments. In the final configuration of salt section, a series of isolated stringer fragments exists. This figure also illustrates the geometry of model evolution and the location of the 1st, 2nd, 3rd, 4th and final configuration of the breakages. The displacements of the mid node on the initial top salt for each step are at depths of 10m, 60m, 180m, 350m and 500m. The time period is 6.3Ma. At the end of salt tectonics (-520Ma), the salt deformation is stopped on the model and only the gravitational loading is applied on the salt section and the stringer fragments to investigate their deformations and displacements. The model is 2D plain strain. The boundary conditions are zero displacement perpendicular to the boundary at the bottom and at the sides. The top salt surface is kept to be zero displacement. This post-tectonics setup is simulated about a time span of 520 Ma.

4 Result

Figure 5 shows the deformed mesh and the sequence of breaks in the stringer together with the displacement of top salt during downbuilding. The first break in the stringer occurs slightly upslope from the center of the model, in the region where the downward movement of the top salt surface with respect to the sloping basement is fastest. After the break, the two stringer fragments move apart and the velocity field of the salt is redistributed. Figure 6 shows the contour of the differential stress $\sigma_1 - \sigma_3$ in salt after the end of tectonics (-520Ma , -519.9Ma , -519Ma , -509Ma

Figure 5: The geometry of model evolution and the location of the 1st, 2nd, 3rd, 4th and final configuration of the breakages. The displacements of the mid node on the initial top salt for each step are 10m, 60m, 180m, 350m and 500m. Position of the break indicated by the grey arrow. Salt is shown in blue. Dotted line shows the position for initial top salt [1].

and today). The age we choose is based on the trend of result change. It can be seen that when salt tectonics just stops (–520Ma) the differential stress inside the salt is between c. 600 kPa and c. 1.4 MPa. This agrees well with the differential stress of c. 1.0 MPa in Ara salt measured from subgrain-size data [5]. This suggests that our model and the boundary conditions chosen are internally consistent. The result at the first 0.1 year, the first one year and the first ten years are provided. When salt tectonics stops (–520 Ma), an approximately 0.1Ma period of stress relaxation in the salt around the stringer fragments is observed from 1 MPa down to 0.5MPa as well as a second, smoother phase of relaxation down to 0.25MPa from –519.9 Ma to –519Ma, Then the stress relaxation down to 0.20 MPa is shown from –519 Ma to –509 Ma. Finally, the stress relaxation down to 0.1 MPa is shown from –509 Ma to –250 Ma and down to 0.05MPa at 0Ma. This result shows that stress decreases

rapidly at the beginning stage after salt tectonics stops and gradually descends in the later period. The expectation of the stress in salt is essential to be investigated because it is strongly related to drilling and underground storage construction engineering.

Figure 7 shows the contour of the differential stress $\sigma_1 - \sigma_3$ in stringer fragments after the end of tectonics. The average differential stress decreases inside the stringer fragments from 30 MPa to 25 MPa in 0.1Ma from –520Ma to –519.9Ma and down to 20MPa during 1Ma from –519.9Ma to –519Ma. From –519Ma to –509 Ma, the differential stress relaxation continues and the stress goes down to 18MPa. Finally, the stress relaxation down to 17.5 MPa is shown from –509 Ma to –250 Ma and down to 17MPa at 0Ma. The result also shows stress decreases rapidly at the beginning stage after salt tectonics stops and gradually descends in the later period. After salt tectonics, the stringer

Figure 6: The contour of the differential stress $\sigma_1 - \sigma_3$ in salt after the end of tectonics (–520Ma, –519.9Ma, –519Ma, –509Ma, –250Ma and today).

Table 2: Time, stress relaxation and differential stress in the model result.

Time (Ma)	Relaxation (MPa)	Differential Stress (MPa)
–520.0	0.0	1.0
–519.9	0.5	0.5
–519.0	0.25	0.25
–509.0	0.15	0.1
–250.0	0.1	0.05
0.0	0.1	0.0

almost does not sink because the differential stress in salt is very low and salt flows slowly. If the salt flows faster, the stringer can sink and rotate obviously and it will also influ-

ence the internal stress of stringer. However, the stringer remains location and the result is in good agreement with the seismic interpretation and real situation. The stress in salt and stringer can not be easily measured with different laboratory methods. The forecast of stress through numerical calculations can be an effective way and useful for engineering design.

5 Discussion

In model studies of the present work it is assumed that salt rheology follows a power law with the same exponent n . The density of the stringer and the geometry change of the stringer relate to the gravity of the stringer, and it affects

Figure 7: The contour of the differential stress $\sigma_1\text{--}\sigma_3$ in stringer fragments after the end of tectonics (–520Ma, –519.9Ma, –519Ma, –509Ma, –250Ma and today).

the differential stress $\Delta\sigma$. Results clearly demonstrate that stringers do not significantly sink over geologic times. In addition, seismic data shows that the location of stringers in Ara salt are still in the upper part or mid part of the salt body after long time >500Ma [1, 12]. Moreover, as the part of the Zechstein in the Northern Netherlands, salt tectonics effectively stopped since the Palogene [35, 36]. It has shown that many of the 30-to-80-m-thick Zechstein 3 intra-salt stringers broke up during salt tectonics and are still embedded in the middle to upper salt section as separate fragments of 100 m- to 1000 m-scale [37, 38]. The phenomenon shows that the long-term rheological behavior of the salt is, at least in some cases, quite different from what is expected from laboratory derived rheological parameters. Through investigating the stringer sinking in salt body, the geological process can be inferred and the long-term salt rheology can be evaluated. One thing needs to be mentioned, in the research an important precondition is that salt tectonics is inactive after tectonics ceases.

The episodes of uplift and subsidence of the regions are not taken into consideration. If the region has episodes of uplift and subsidence, the change of temperature due to change of location or depth of salt, the stringer sinking and deformation will be influenced [39–44]. Furthermore, the statement on long-term rheological behavior may be considered valid only if the regions have not undergone changes in deep heat flow. If the changes in deep heat flow influences the regions, salt rheology will decrease and salt can flow easily and the stringer will descend faster.

Another important point is that the internal stress of stringer and salt is strongly relevant to drilling and oil or gas development. Ara stringer fragments have experienced complex movements within the salt tectonically and can hold exceptionally high or low fluid pressures. Squeezing salts and intrasalt brine pockets will lead to drilling hazards, and the stringer fragments and associated pressure kicks or losses represent the most hazardous obstructions when drilling through the salt basin [37, 45].

The determination of the internal stress in stringer and salt is critical to prevent from the drilling hazards. Since the measurement of stress in rock salt is difficult in laboratory experiments, the inversion of gravitational sinking of stringer in salt at rest is an effective way to forecast the stress distribution and provide reference for engineering design.

6 Conclusion

In the study, the deformation and displacement of the stringer in Ara salt at rest after relaxation of stresses is modeled from tectonic movement. After salt tectonics, stress relaxation occurs both in salt and stringer fragments. Dislocation creep in salt leads to minor sinking and deformation of in the time span of 520Ma. Almost no displacement of stringer fragments is caused by rapid stress relaxation from 1 Ma to approximately 0.1 Ma around stringer fragments, after salt tectonics stopped. Due to the stress redistribution in salt, the differential stress in stringer fragment also decreases about 15MPa. It is concluded that the stringer has suffered minor sinking in a time span of 520Ma after changes in differential stress in salt and internal stress in stringer. Last but not least, stringer can be expected more sinking distance and deformation when the regions have undergone changes in deep heat flow or episodes of uplift and subsidence during the last 500Ma. The simulation of gravitational sinking of stringer fragments in rock salt can predict internal stress of stringer and salt for structural interpretation and assessment of drilling risks.

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