Numerical modeling of the displacement and deformation of embedded rock bodies during salt tectonics - a case study from the South Oman Salt Basin

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Abstract

Large rock inclusions are embedded in many salt bodies and these respond to the movements of the salt in a variety of ways, including displacement, folding and fracturing. One mode of salt tectonics is downbuilding, whereby the top of a developing diapir remains in the same vertical position, while the surrounding overburden sediments subside. We investigate how the differential displacement of the top salt surface caused by downbuilding induces ductile salt flow and the associated deformation of brittle stringers, by an iterative procedure to detect and simulate conditions for the onset of localization of deformation in a finite element model, in combination with adaptive remeshing. The model setup is constrained by observations from the South Oman Salt Basin, where large carbonate bodies encased in salt form substantial hydrocarbon plays.

The model shows that, depending on the displacement of the top salt, the stringers can break very soon after the onset of salt tectonics and can deform in different ways. If extension along the inclusion dominates, stringers are broken by tensile fractures and boudinage at relatively shallow depth. Spacing of the boudin-bounding faults can be as

26 close as 3-4 times the thickness of the stringer. In contrast, salt shortening along the
27 inclusion may lead to folding or thrusting of stringers.

28 ***Introduction***

29 Large rock inclusions encased in salt (so-called rafts, floaters or stringers) are of broad
30 economic interest. Understanding when and how those rock bodies break and redistribute
31 fluids is of practical importance because the inclusions can contain overpressured fluids
32 or hydrocarbons and are therefore exploration targets but also pose drilling hazards
33 (Williamson et al., 1997; Koyi, 2001; Al-Siyabi, 2005; Schoenherr et al., 2007a;
34 Schoenherr et al., 2008, Kukla et al., subm). In addition, stringers are also relevant for the
35 planning and operation of underground caverns and waste disposal facilities. The
36 influence of stringer deformation is of importance for the understanding of the diagenetic
37 evolution and hence reservoir properties of stringer plays (Schoenherr et al., 2008;
38 Reuning et al., 2009). The study of stringers has also contributed to our understanding of
39 the internal deformation mechanisms in salt diapirs (Talbot and Jackson, 1987; Talbot
40 and Jackson, 1989; Talbot and Weinberg, 1992; Koyi, 2001; Chemia et al., 2008).
41 Stringer geometries and associated deformation were studied in surface piercing salt
42 domes (Kent, 1979; Reuning et al. 2009) and in mining galleries in salt (Richter-
43 Bernburg, 1980; Talbot and Jackson, 1987, Geluk, 1995; Behlau and Mingerzahn, 2001).
44 Additionally, recent improvements in seismic imaging allow the visualization and
45 analysis of large-scale 3D stringer geometries (van Gent et al, 2009; submitted). All these
46 studies reveal highly complex stringer geometries, such as open to isoclinal folding, shear
47 zones and boudinage over a wide range of scales and give valuable insights into the
48 processes occurring during salt tectonics. However, most salt structures have undergone a
49 combination of passive, reactive and active phases of salt tectonics (Mohr et al., 2005,
50 Warren 2006, Reuning et al., 2009) which complicates the interpretation of stringer
51 geometries. Besides the complexity of the internal structural geology, extensive

dissolution by groundwater can lead to a structural reconfiguration of the inclusions (Talbot and Jackson, 1987; Weinberg, 1993). The interpretation of the early structural evolution of brittle layers in salt giants (Hübscher et al., 2007) hence remains difficult. Results from analogue modelling have shown that stringers form in the ductile salt mass from the earliest stages until the end of halokinesis (Escher and Kuenen, 1929; Zulauf and Zulauf, 2005; Callot et al., 2006; Zulauf et al., 2009). During this evolution, the embedded inclusions undergo stretching, leading to boudinage and rotation. It was also suggested (Koyi, 2001) that the inclusions sink in the diapir due to negative buoyancy, moving downwards as soon as diapir growth and salt supply are not fast enough to compensate for this.

In numerical models, salt is often treated as relatively homogeneous material. The few studies that have addressed the evolution of stringers within the salt, focus on the rise and fall of viscous stringers during salt diapir growth (Weinberg, 1993; Koyi, 2001; Chemia et al., 2008). To our knowledge, no numerical study yet has investigated the brittle deformation of individual stringers during the initial phases of salt tectonics.

The aim of this study is to report the first results of a study aimed at contributing to our understanding of brittle stringer dynamics during downbuilding. We use the finite element method (FEM) to model the deformation and breaking of brittle layers embedded in ductile, deforming salt bodies.

Geological Setting

The study area is situated in the south-western part of the South Oman Salt Basin (SOSB), in the south of the Sultanate of Oman (Fig. 1). The SOSB is late

77 Neoproterozoic to early Cambrian in age and is part of a salt giant consisting of a belt of
78 evaporitic basins, from Oman to Iran (Hormuz Salt) and Pakistan (Salt Range) and
79 further to the East Himalaya (Mattes and Conway Morris, 1990; Allen, 2007).

80 The SOSB is an unusual petroleum-producing domain. Self-charging carbonate stringers
81 embedded into the salt of the SOSB represent a unique intra-salt petroleum system with
82 substantial hydrocarbon accumulations, which has been successfully explored in recent
83 years (Al-Siyabi, 2005; Schoenherr et al., 2008, Grosjean et al., 2009;). However,
84 predicting subsurface stringer geometries and reservoir quality remains a major
85 challenge. The SOSB strikes NE-SW and has a lateral extension of approximately 400
86 km x 150 km. Its western margin is formed by the “Western Deformation Front” (Fig. 1),
87 a structurally complex zone with transpressional character (Immerz et al., 2000). The
88 eastern margin is the so-called “Eastern Flank” (Fig. 1), a structural high (Amthor et al.,
89 2005).

90
91 The eastward- thinning basin fill overlies an Early Neoproterozoic crystalline basement
92 and comprises late Neoproterozoic to recent sediments with a total thickness of up to 7
93 km (Heward, 1996; Amthor et al., 2005; Al-Barwani and McClay, 2008). Oldest deposits
94 of the basin are the Neoproterozoic to Early Cambrian age (~800 to ~530 Ma) Huqf
95 Supergroup (Gorin et al., 1982, Hughes and Clark, 1988; Burns and Matter, 1993;
96 Loosveld et al., 1996; Brasier et al., 2000; Bowring et al., 2007). The lower part of the
97 Huqf Supergroup comprises continental siliciclastics and marine ramp carbonates of the
98 Abu Mahara- and Nafun-Group (Fig. 2), which were deposited in a strike-slip setting and
99 later in a period of relative tectonic quiescence with broad, regional subsidence (Amthor
100 et al., 2005). During end Buah-times (~550,5 to 547,36 Ma, Fig. 2) an uplift of large
101 basement blocks led to segmentation of the basin and to the formation of fault-bounded
102 sub-basins (Immerz et al., 2000; Grotzinger et al., 2002, Amthor et al., 2005). Basin
103 restriction during Ediacaran times led to first Ara-salt sedimentation within these fault-
104 bounded sub-basins at very shallow water depths (Mattes and Conway Morris, 1990;
105 Schröder et al, 2003; Al-Siyabi, 2005). Periods of differential subsidence in the SOSB led

106 to transgressive to highstand conditions which caused growth of isolated carbonate
107 platforms. In total six carbonate- to evaporite (rock salt, gypsum) sequences of the Ara
108 Group were deposited, termed A0/A1 to A6 from bottom to top (Mattes and Conway
109 Morris, 1990) (Fig. 2). Bromine geochemistry of the Ara Salt (Schröder et al., 2003;
110 Schoenherr et al., 2008) and marine fossils in the 20-200 m thick carbonate intervals
111 (Amthor et al., 2003) clearly indicate a seawater source for the Ara evaporates.
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113

114 Subsequent deposition of continental siliciclastics on the mobile Ara Salt led to strong
115 salt tectonic movements. Differential loading formed 5-15 km wide clastic pods and salt
116 diapirs, which led to folding and fragmentation of the carbonate platforms into isolated
117 stringers floating in the Ara Salt. Early stages of halokinesis started with deposition of the
118 directly overlying Nimr Group, derived from the uplifted basement high in the Western
119 Deformation Front and the Ghudun High. This early halokinesis was controlled by pre-
120 existing faults and formed asymmetric salt ridges and mini-basins (Al-Barwani and
121 McClay, 2008). During deposition of the massive Amin Formation the depositional
122 environment changed from proximal alluvial fans to a more distal fluvial-dominated
123 environment, whereas the existing salt ridges acted as barriers until salt welds were
124 formed (Hughes-Clark, 1988; Droste, 1997). Further salt ridge rises and/or shifts of
125 accommodation space during deposition of the Mahwis. Formation led to formation of
126 several listric growth faults in the post-salt deposits. Salt dissolution during Mahwis and
127 lower Ghudun-times formed small 1-2 km wide sub-basins on the crest of selected salt
128 ridges. The end of salt tectonics is marked by the lower Ghudun group, because salt ridge
129 rise could not keep pace with the rapid sedimentation of this formation (Al-Barwani and
130 McClay, 2008). Extensive near-surface dissolution of Ara Salt affected especially the
131 Eastern Flank during the Permo- Carboniferous glaciations, forming the present-day
132 shape of 'stacked' carbonate platforms without separating salt layers (Heward, 1996).

133 In Carboniferous times reactivated basement faults led to movement of a number of salt
134 ridges forming new, point-sourced diapirs. This renewed downbuilding changed into
135 compressional salt diapirism during Cretaceous time (Al-Barwani and McClay, 2008).
136 This complex sequence of salt tectonics led to present-day variable salt thicknesses from

a few metres up to 2 km in the SOSB.

Salt-tectonics in the study area

The salt tectonic evolution of the study area was studied from seismic lines supplied by PDO Exploration (Fig. 3). Here the deposition of the Nimr Group on the mobile Ara substrate led to early downbuilding and the formation of first generation Nimr minibasins and to small salt pillows on the flanks around the pods. Ongoing siliciclastic sedimentation made the pods sink deeper into the salt and caused further salt flow (cf. Ings and Beaumont 2010). The first salt pillows evolved into salt ridges due to vertical rise and lateral thinning of the salt body. Ongoing salt squeezing promoted the active rise of salt ridges with listric growth faults forming above or on their flanks. The growth fault created locally new accommodation space which led to differential loading during deposition of the Amin conglomerates. This differential loading formed a second generation 'pod' on the top of an existing salt ridge. The new evolving pod developed two new ridges. The growth faults in the SW of the study area, located on the flanks of the salt ridge, were associated with growth of the existing salt ridge. Small sub-basins formed by salt dissolution were of minor importance in the study area. The end of the salt tectonics is indicated by the Ghudun layer with lateral constant thickness.

Geomechanical modelling of salt tectonics

Geomechanical modelling of geological structures is a rapidly developing area of research. The numerical techniques allow incorporation of realistic rheologies, complex geometries and boundary conditions, and are especially useful for sensitivity analyses to explore the system's dependence on variations in different parameters. The disadvantages are numerical problems with modelling localization of deformation, with poorly known

initial conditions and controversy on the appropriate rheologies.

In addition to simplified analytical models which serve well to elucidate some critical problems (Lehner, 2000; Fletcher et al., 1995; Triantafyllidis and Leroy 1994), most work is based on numerical techniques, usually applying finite elements, (Last, 1988; Van Keken, 1993; Podladchikov et al. 1993; Poliakov et al. 1993, Woidt & Neugebauer 1980; 1994; Ismail-Zadeh et al. 2001; Daudré & Cloetingh 1994; Kaus & Podladchikov 2001; Schultz-Ela and Walsh, 2002; Schultz-Ela and Jackson, 1993; Gemmer et al., 2004; Ings and Beaumont 2010).

Almost all work to date has been in 2D, concentrating on forward modeling of systems at different scales, and incorporating different levels of complexity in different part of the models. For example, some models try to incorporate realistic two-component rheology of the salt, while others use simple, temperature independent rheology. Other models focus on a detailed description of the stress field in applied studies of hydrocarbon reservoirs around salt domes, but only consider small deformations. Overburden rheology is in some cases modelled as frictional-plastic with attempts to consider localized deformation, while other models assume linear viscous overburden. Although most models produce results which are in some aspects comparable with the natural prototypes, it is at present unclear how the combination of simplifications at different stages of the modelling might produce realistic-looking results. Therefore, numerical modelling of salt tectonics is a rapidly evolving field which in recent years has started to produce quite realistic results; however much remains to be done until the full complexity of salt tectonic systems is understood.

Methods

While the above interpretation (Figure 3) serves to illustrate the most important profiles, it is important to keep in mind that the SOSB salt tectonics (Al-Barwani & McClay, 2008) is strongly non-plane strain and for a full understanding a 3D analysis and modelling is required. So the models presented here are the first step towards full

understanding of stringer dynamics in this complex system.

In this study we used the commercial finite element modelling package ABAQUS for our modelling, incorporating power law creep, elastoplastic rheologies and adaptive remeshing techniques.

Model setup

To capture and explore the essential elements of the system, a simplified, generic model (Fig. 4) was defined, based on the SW-part of the interpreted seismic line, between the two major salt highs (cf. Fig. 3).

The model with SW-dipping basement has a width of 18 km. The dip angle is 3.2°. The salt initially has a thickness up to 1600 m and thins towards the NE to 600 m. The carbonate stringer with a length of 12 km and a thickness of 80 m is located 360 m above the basement (Table 1). The passive downbuilding of the Haima pod is strongest in the centre of the model and volume of salt remains constant during deformation, while the Haima pods accumulate and subside in the centre. In this simple model, we start with a sinusoidal shape of top salt, increasing in amplitude over time.

The duration and rate of deformation was estimated using thickness variations of the overlying siliciclastic layers. The interpreted seismic line (Fig. 3) indicates that the Nimr group, forming the characteristic pods in our study area, has the highest lateral thickness variations. This suggests that the main salt deformation took place during the deposition of the Nimr group. Therefore a deformation time of ~6.3Ma (2×10^{14} s) was used.

An important tool to validate the models is to compare the calculated differential stress with results of subgrain size piezometry using core samples of SOSB Ara salt samples (Schoenherr et al, 2007a). Table 1 lists a number of key properties of the model.

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220

221 Table 1: boundary conditions, input parameter

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=1.04×10 ⁻¹⁴ MPa ⁻⁵ s ⁻¹ , n=5
Salt temperature	50°C
Stringer elastic properties	E=40Gpa, v=0.4
Basement elastic properties	E=50Gpa, v=0.4
Basement density	2600kg/m ³
Calculation time	6.3 Ma

222

223

224 The rheology of salt was described by a power-law relationship between the differential
 225 stress and strain rate:

226

227 (1)

228

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

230

231 where $\dot{\varepsilon}_{DC}$ is the strain rate, $(\sigma_1 - \sigma_3)$ is differential stress, A_0 is a material parameter, Q is
 232 the activation energy, R is the gas constant ($R=8.314 \text{ Jmol}^{-1}\text{K}^{-1}$), T is temperature, and n
 233 is the power law exponent.

234

235 The two main deformation mechanisms in salt under the stress conditions and
 236 temperatures of active diapirism are pressure solution creep, with $n = 1$ and dislocation

creep, with $n =$ around 5 (Urai et al., 2008). As argued in Urai et al., 2008, under active diapirism deformation occurs at the boundary of these two mechanism and therefore rheology can be simplified to $n = 5$ with the appropriate material parameters. Here we used parameters measured for Ara rock salt in triaxial deformation experiments: $A_0=1.82\times10^{-9}\text{MPa}^{-5}\text{s}^{-1}$, $Q=32400\text{ Jmol}^{-1}$, $n = 5$ (Schoenherr et al., 2007b, Urai et al., 2008). Under the differential stresses observed within the salt in our models this results in an effective viscosity η_{eff} of $2.5\times10^{19}\text{Pa s}$ to $7.3\times10^{20}\text{Pa s}$ during active deformation.

In order to simplify the models we used a constant temperature of 50°C for the whole salt body. This simplification is justified by the relatively small total thickness of the salt layer which would result only in small temperature and rheological differences if a realistic temperature gradient was applied.

The mechanical properties of the stringers used in the models are based on those of typical carbonate rocks in the SOSB. The elastic properties are relatively well known, but the fracture strength was determined experimentally on small samples. It therefore remains difficult to extrapolate these results to the scale of 10-100 m, which is relevant for the models presented here. At that scale additional, less well known properties, like small scale fracture density, have a strong influence on the fracture strength.

In our models we take a conservative approach and assume that the large scale fracture strength is close to that of an undamaged carbonate rock. We therefore chose a Mohr-Coulomb fracture criterion with a cohesion of 35MPa, a tensile strength of 25MPa and a friction angle of 30 degrees and the elastic properties $E = 40\text{ GPa}$ and a Poisson ratio of $\nu = 0.4$. If we consider a thickness of the combined salt and sediment cover above the stringer of around 1000m we obtain an absolute vertical stress of about 25MPa and therefore, assuming hydrostatic pore pressure, an effective vertical stress of about 15MPa. Given these stress condition the relevant failure mechanism for the stringer is tensile. We have therefore used a test comparing the minimum principal stress in the stringer with the tensile failure strength to determine if the stringer is breaking during a given time step.

Displacement of top salt

Our models are constrained by the displacement of the top Ara salt over time as shown by the sediment package above. One approach to develop a model with the correct displacement would be forward modelling and progressive deposition of sediment (Ings and Beaumont 2010, Gemmer et al., 2004, 2005), and adjusting the model to produce the observed displacement. However, this would be very time-consuming and probably produce non-unique solutions. We therefore chose for a modelling strategy where the displacement of the top salt is achieved by applying a predetermined displacement field. At this stage of the modelling we do not allow horizontal motion at this boundary, (the equivalent of a fully coupled salt-sediment interface). The model is validated against differential stress measured in the salt using subgrain size piezometry. We keep the total vertical load on the top salt surface constant by applying a displacement boundary condition on the top of the model as discussed; together with a constant total upwards load at the bottom of the model. The right and left sides of the model are constrained not to move horizontally but are free to move vertically.

As discussed before, in the initial models presented above we start with a sinusoidal shape of top salt, increasing in amplitude at constant rate over a time interval of $\sim 6.3\text{Ma}$ (2×10^{14} s). In future work the model can be easily adapted to include the results of 2D or 3D palinspastic reconstruction of the overburden (Mohr et al., 2005).

Iterative Scheme for Stringer Breaking

One of the main challenges of the current study is to model the breaking of the brittle layers embedded in salt which deforms in a ductile manner. Full description of the opening and propagation of a fracture and its filling with the ductile material is beyond the capabilities of current numerical modelling. Therefore, we adopted a strongly simplified, iterative procedure in ABAQUS to detect the onset of conditions of fracturing and model the subsequent breakup of the stringers.

For this purpose an initial model is set up with the material properties in a gravity field. The model is then run, i.e. the salt body is deformed, and the stresses in the stringer are

monitored. If the stresses in a part of the stringer exceed the defined failure criterion, the simulation is stopped, the stringer is ‘broken’ by replacing the material properties of one column of elements in the stringer by those of salt (Figure 14) and the simulation is continued until the failure criterion is exceeded again in another part of the stringer. This procedure is repeated until the final deformation of the salt body is reached while the stress in no part of the stringer is exceeding the failure criterion.

Adaptive remeshing of the model

The model contains material boundaries which in the standard FEM, need to be located at an element boundary. Therefore deformations of the model in the model also require the deformation of the FEM mesh.

The heterogeneous deformation of the salt body around the stringers leads locally to high strains which therefore result in local strong distortions of the FEM mesh. However, if the distortion of the mesh becomes too large, it can cause numerical instabilities and inaccuracy. This process limits the maximum achievable deformation of a FEM model with a given mesh.

To overcome these limitations we have used the built-in adaptive re-meshing routines of ABAQUS to create new elements while mapping the stress and displacements of the old mesh on this new one. Since in our model the mesh needs to deform to follow the moving material boundaries, this would lead to mesh distortions which will eventually become too large. After a certain amount of deformation, a new mesh is built according to the new locations of the material boundaries and the field variables are mapped from the old to the new mesh. Then the calculation is continued using the new mesh until another re-meshing step is needed.

Results

Figure 5 illustrates the simplified model setup, drawn to scale. Figure 6 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 up-slope from the centre 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. In Figure 6 the maximum vertical displacements are given relative to the initial datum. The second and third break also occur in the central region of the model whereas the fourth break is located in the right part of the model where the salt layer above the stringer is significantly thinner than in the left part. The length of the boudins can be as small as 3-4 times the thickness of the stringer. In this model, the regions where most intense folding or thrusting of the stringers is expected with increasing displacement, i.e. in the areas of horizontal shortening near the side boundaries of the model, do not contain stringers, so only minor folding and rotation of the stringers occurs around the ends of the boudins.

As described above, the Mohr-coulomb criterion and the values of the minimum principal stress (Figure 6) were used as a criterion for failure in the stringer. If the criterion is exceeded, the stringer is broken at the location where the stress exceeds the breaking strength as shown in Figure 7.

We observe (Figure 8) that there is a stress shadow, i.e. an area where the differential stress is smaller than in the surrounding region, in the salt underneath the stringer at the location of the future break with a stress increase after the stringer breaks and the salt on the two sides is in communication. In Figure 7, we can also see that the fracturing condition is reached due to both extension and bending of the stringers. There is no further fracturing of the stringer between the 4th break shown in Figure 5, i.e. after the displacement in the centre of the top salt has reached 310m, and the end of the simulation which is at a central top salt displacement of 500m.

The salt flow around stringers leads to an extension which is dependent on the flow patterns in the salt and length of the stringer fragments (Ramberg, 1955). Therefore, if the length of stringer is small enough, the stress can not exceed the failure strength so that no further fracturing takes place.

Figure 9 shows contours of the differential stress $\sigma_1 - \sigma_3$ in the model. It can be seen

that the differential stress inside the salt is between ~600kPa and ~1.4MPa. This agrees well with the differential stress of ~1MPa in Ara salt measured from subgrain size data (Schoenherr et al., 2007a). This suggests that our model and the boundary conditions chosen are internally consistent.

Comparison of stress orientations during the different stages of model evolution (Figure 9) shows how principle stress orientations change due to the breaking of the stringer (Figure 10). This is visible in the central part of the model. In step 1, the stress orientation changes at the breaking part. On the top of the stringer, we can see that the orientation of the principal stresses rotates by up to 90°. The same evolution can be observed in other steps (Figure 11). Before the break in the stringer occurs it can be seen in Figure 12 that the flow pattern in the salt is organized in such a way that there is a particularly strong horizontally diverging flow above the region of the stringer where the break will happen. It is also noticeable that flow in the salt layer between the basement and the stringer has a much lower velocity than above, as expected for the dominantly Couette flow in this region. After the stringer has been broken into two separate fragments the flow pattern is reorganized as shown in Figure 13. There is now a strong flow through the gap between the two stringer fragments which are moving apart, leading to bending moments and rotation of the stringers. Due to this movement there is now also a more rapid flow of the salt in the relatively thin layer between the stringer and the basement rock.

Discussion

We presented an approach to numerically model the deformation and breakup of brittle layers embedded in ductile salt. While full and comprehensive treatment of boudinage is a very complex process, this approach is reasonably practical and seems to describe many of the critical processes in the development of salt stringers. Although the basic principles for the onset of boudinage have been recognized for a long time, much less is known of the evolution of a set of boudins after their initial formation. The details of the evolution of the boudin-neck and the evolution of pore pressure in the stringers (e.g. Schenk et al., 2007) are also not yet captured. Therefore the calculations are regarded as strongly conservative considering the high strength assigned to the stringers. Considering the

evidence for overpressures in many carbonate stringers in the SOSB, in reality the stringers probably failed much earlier than in this model (Kukla et al., *subm.*).

The carbonate stringers embedded in the salt are modeled as brittle elastoplastic material while the salt is modelled as non-newtonian viscous fluid ($n=5$). This is in contrast to previous studies that have used viscous material for both the salt and the embedded rock bodies (Weinberg, 1993; Koyi, 2001; Chemia et al., 2008). In the numerical model of the sinking anhydrite blocks on salt diapirs (Koyi, 2001), the anhydrite is given a 10^4 times higher viscosity than the salt, however, both materials are considered as Newtonian ($n=1$) viscous fluids. In contrast, the analogue model presented in the same paper uses a Mohr-Coulomb material, i.e. sand, as an analogue for the anhydrite stringers. In the model of (Chemia et al., 2008), the salt is again considered to be Newtonian, however the anhydrite is treated as non-Newtonian fluid with a power-law rheology ($n=2$). In addition, the overlaying sediments are also modelled as non-Newtonian viscous material, but with a power-law exponent $n=4$. Chemia et al, 2009 have demonstrated the influence of non-newtonian salt rheologies on the internal deformation of a salt diapir containing heavy inclusions such as anhydrite bodies.

One key difference in the outcome of the simulations of the deformation of the rock bodies embedded in salt between our work and previous numerical studies is that we allow for breaking of the (brittle) stringers in our work whereas most previous numerical studies have tended to produce folding or pinch-and swell of the (viscous) stringers. From the results of the simulations presented in this work (Figures 5-12), it can be seen that the stringers deform in different ways depending on the local stress and strain conditions. In the central part of the model where the laterally diverging flow patterns in the salt cause extension of the stringer, the stringers are broken by tensile fractures and boudinaged. The spacing of the boudin-bounding faults can be as close as 3-4 times the thickness of the stringer. Interpretations of seismic data (Figure 3) indicate that the stringers in the Ara salt are indeed broken and boudinaged underneath the Haima pod, in agreement with the model. However, the stringers are also interpreted as folded. This is also in agreement with observations in salt mines (Borchert and Muir, 1964) and 3D seismic observations of stringers in salt in the Central European Basin where resolution of the seismic is much

better (Strozyk et al., this volume). This might be an effect of the mechanical properties assumed for the stringers. In this study the stringers are treated as elastoplastic, whereas in nature they show a combination of brittle and ductile behaviour. When the brittle stringer in our models is stretched, the stress change will result in failure of the stringer and boudinage. Under compressive loading the model shows shortening, bending and under suitable salt flow conditions thrusting may also occur (Leroy and Triantafyllidis 2000). Progressive salt deformation may lead to complex combinations of these effects, for example to boudinage followed by overthrusting.

In future work, we will attempt to include the ductile behaviour of the stringer into the model by considering visco-plastic material properties for the stringers in addition to the current elasto-plastic material.

Conclusions

We presented first results of a study of the dynamics of brittle inclusions in salt during downbuilding. Although the model is simplified, it offers a practical method to explore complex stringer motion and deformation, including brittle fracturing and disruption.

Under the conservative conditions modelled here, stringers are broken by tensile fractures and boudinaged very early in downbuilding (~ 50 m top-salt minibasin subsidence) in areas where horizontal salt extension dominates. Ongoing boudinage is caused by reorganization of the salt flow around the stringers. Rotation and bending of the stringers is caused by vertical components of the salt flow. Flow stresses in salt calculated in the numerical model are consistent with those from grain size data. The model can easily be adapted to model more complex geometries and displacement histories.

Acknowledgements

We thank the Ministry of Oil and Gas of the Sultanate of Oman and Petroleum Development Oman LLC (PDO) for granting permission to publish the results of this study. We also thank PDO for providing the seismic data and Zuwena Rawahi, Aly

Brandenburg, Martine van den Berg and Gideon Lopez Cardozo for useful discussion.

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Figure caption:

Fig. 1: Overview map of the Late Ediacaran to Early Cambrian salt basins of Interior Oman (modified from Schröder et al., 2005 and Reuning et al., 2009, reprinted by permission from GeoArabia). The study area (marked by the yellow square) is located in the southwestern part of the South Oman Salt Basin. The eastward-thinning basin with sediment fill of up to 7 km is bordered to the west by the transpressional “Western Deformation Front” and to the east by the structural high of the “Eastern Flank”.

Fig. 2: Chronostratigraphic summary of rock units in the subsurface of the Interior Oman (modified from Reuning et al., 2009, reprinted by permission from GeoArabia). The geochronology was adopted from Al-Husseini (2010). The lithostratigraphy of the lower Huqf Supergroup was adapted from Allen (2007) and Rieu et al. (2007). The lithostratigraphy of the upper Huqf Supergroup and the Haima Supergroup was adapted from Boserio et al. (1995), Droste (1997), Blood (2001) and Sharland et al. (2001). The lithostratigraphic composite log on the right (not to scale) shows the six carbonate to evaporite 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 evaporite sequence led to strong halokinesis, which ended during sedimentation of the Ghudun Formation (Al-Barwani and McClay, 2008).

Fig. 3: (a) Un-interpreted seismic line crossing the study area. (b) Interpretation of the seismic line shown in a). The formation of salt pillows and ridges is caused by passive downbuilding of the siliciclastic Nimr minibasin leading to strong folding and fragmentation of the salt embedded carbonate platforms.

Fig. 4. Simplified model setup discussed in this paper (Fig. 3), not drawn to scale.

Fig. 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 50m, 190m, 290m, 310m and 500m. Given the sinusoidal shape of the prescribed displacement of the top salt surface this results in a total deformation amplitude between is twice as large, i.e. the height difference between the highest and lowest point of the top salt surface is 100m, 380m, 580m, 610m and 1000m in the respective time steps. Position of the break indicated by the grey arrow. Salt is shown in blue, carbonate stringer in red and pre-salt sequence in yellow. Dotted line shows the position for initial top salt.

Fig. 6. The minimum principal stress during the model evolution from step 1 to step 5. Dotted line shows the position for initial top salt.

Fig. 7. The minimum principal stress to cause tensile failure is exceeded in stringer in

step 1. Where the tensile strength is exceeded the stringer is broken at this spot. Dotted line shows the position for initial top salt.

Fig. 8. The differential stress in salt during the model evolution from step 1 to step 5. The differential stress is plotted here on the undeformed FEM mesh. The reason that it has not been plotted on the deformed mesh as all the other data presented is a limitation in the current version of the software used. The differential stress for step 5 is plotted on a partially deformed mesh here because the model has been re-meshed due to the large local deformations between steps 4 and 5.

Fig. 9. The stress orientations during the model evolution process from step 1 to step 5. Stress orientations around stringers are clearly visible. Minimum principal stress in stringer is horizontal. Dotted line shows the position for initial top salt.

Fig. 10. The stress orientations during the model evolution process in step 1. Stress orientation change at the breaking part is clearly visible. Minimum principal stress in stringer is horizontal. Dotted line shows the position for initial top salt.

Fig. 11. The stress orientations during the model evolution process in step 3. Stress orientations around stringers are clearly visible. Minimum principal stress in stringer is horizontal. Dotted line shows the position for initial top salt.

Fig. 12. The velocity gradient in salt localizes at the position of the future break in stringer. The part beneath the stringer has very small flow. Blue arrow points to stringer. Grey arrow indicates location of future break. Dotted line shows the position for initial top salt.

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760

761 Fig. 13. A strong flow through the gap between the separating stringer fragments
762 develops. A significant flow can also be observed in the relatively thin salt layer
763 between the stringer and the basement. Dotted line shows the position for initial top
764 salt.

765

766

767 Fig. 14 Breaking of a stringer and subsequent separation of the fragments.

768 a) The minimum principal stress is used to detect tensile failure in stringer in step1. If
769 tensile strength is exceeded, the stringer is broken in this location.

770 b) After the first break, the salt flows inside the fractured part. The minimum principal
771 stress in stringer decreases. Meanwhile with the further displacement on the top, the
772 minimum principal stress around stringer also decreases.

773 c) With the further displacement of the top surface, the two stringers continue moving
774 apart.

775 d) The two stringers continue moving apart and the minimum principal stress decreases
776 in the salt.

777

778

779

1km

Minimum Principal Stress

Minimum Principal Stress

Strength (25MPa)
exceeded

Differential stress in salt

1km

Stress orientation changes
at the breaking part

Minimum In-Plane Principal Stress
Maximum In-Plane Principal Stress
Out-of-Plane Principal Stress

Stress orientation changes
around the stringer

Stringer

Stringer Fragments

Basement

a)

b)

c)

d)