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Fault patterns within sediment layers overlying rising salt structures: A numerical modelling approach

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ABSTRACT

Faulting of sediments overlying structures caused by salt movement is a widespread phenomenon and important for hydrocarbon production, because the faults facilitate hydrocarbon migration to and from the reservoir or may compartmentalize the reservoir. A major problem in mapping the intensity of deformation is that many faults and fractures are below the seismic resolution, and that the seismic data may appear dimmed and distorted owing to escaping gas. Another major problem is that the salt displacement causing the deformation is often only reflected in the overlying fracture patterns and hence not directly observable. This study uses a numerical spring-slider model, including vertical as well as horizontal movements of the substrata (the salt). The model demonstrates how the fracture patterns in the sediments above salt structures are controlled by the salt kinematics. The modelling experiments show that concentric faults develop when only vertical salt movements are involved, whereas radial faulting dominates when even small levels of horizontal movements are included. A case study from the southern Danish Central Graben illustrates that the fault structures in the cover-sediments characterizes the salt movement. The analysis and prediction of the systematics of these small scale faults, which are too small to be recognized on seismic data, is important when the fluid migration and hence hydrocarbon production from fields related to salt-structures is to be optimized.

1. Introduction

Salt tectonics is defined as the deformation of sediments during the flow of salt. The subject has received increasing interest, mainly due to the fact that salt tectonics have influenced sediment deposition and deformation within many of the world's hydrocarbon provinces (Hudec and Jackson, 2007). Furthermore, the fault distribution associated with salt structures may influence the production of hydrocarbons due to segmentation of reservoirs (Stewart, 2006). Three-dimensional (3D) seismic data acquired above salt structures successfully display detailed fault patterns (Brown, 1986; Bacon et al., 2007; Cartwright and Huuse, 2005; Stewart, 2006, 2007), but the understanding of the dynamic relations between salt movement and the generation of fault patterns is generally based on analogue modelling (e.g. Alsop, 1996), numerical modelling (e.g. Poliakov et al., 1996), a few field studies of faults at the top of the structure (Davison et al., 1996) or along the margins of a rising diapir (Alsop et al., 2000). However, the links between salt movement and the surrounding fracture patterns are far from completely understood. Another critical element relates to seismic imaging problems of the fault patterns caused by gas leakage from the reservoirs, which reduces the seismic resolution.

Analogue modelling of salt structure kinematics and the associated deformation of the overburden has been performed as early as 1926 (Torrey and Fralich, 1926) and continues until present. Although the majority of the experiments performed were focused on the evolution of cross-sections (e.g. Vendeville and Jackson, 1992a,b; Koyi et al., 1993; Alsop, 1996), map-views of the faulted surface have also been analysed in experiments (Torrey and Fralich, 1926; Parker and McDowell, 1955; Withjack and Scheiner, 1982; Yamada et al., 2005). A general pattern in the analogue models is that experiments where vertical movements are dominating (e.q. an indentor moving vertically) concentric fractures dominate, whereas horizontal displacements induce radial fractures.

Numerical modelling of salt tectonics accelerated in the 1990's and its utility increased dramatically due to improving numerical techniques and increasing computing power (e.g. Poliakov et al., 1993; Daudré and Cloetingh, 1994; Gemmer et al., 2004; Ismail-Zadeh et al., 2004; Albertz and Beaumont, 2010). A major benefit of numerical modelling compared to analogue modelling is that it is

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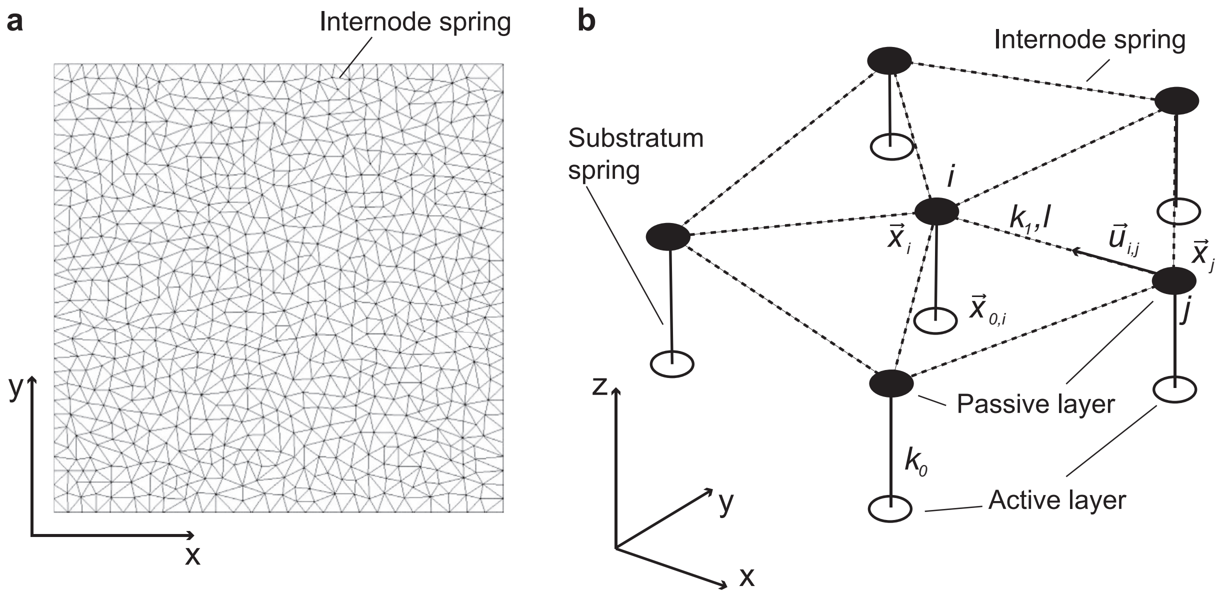

Fig. 1. The spring-slider mesh. a: shows the mesh of inter-node springs in the passive layer in an unstructured grid built from Delaunay triangulation. The unstructured grid differs from the regular grid used by Malthe-Sørenssen et al. (1998a), and helps to greatly reduce the grid dependency of the fracture pattern orientation. b: The principles for the arrangement of the internode springs, substratum springs, passive and active layers, as well as the values used during modelling (see text for further details).

possible to compute variations in strain and stress in time and space as opposed to the often purely qualitative kinematic results of analogue experiments.

The previous numerical model experiments have mostly been based on continuum mechanics for predicting the visco-plastic flow of the salt and the sediment overburden. We take a new approach and model fracture patterns in the sediment overburden using a discrete spring-slider numerical model. The dynamics of the spring-slider model operates in a thin sediment layer overlying the salt structure, and the kinematics of the salt is simply imposed as a boundary condition for the modelling process. The strength of the spring-slider model approach associates to how fracture propagation is simulated in a simple and yet physically consistent manner. Fault and fracture propagation is driven by stress concentrations arising along the edges of failure planes, and the spring-slider model includes this first-order effect because the yielding of one spring transmits and concentrates stress on neighbouring springs. This inherent communication between springs leads to fracture growth and fusion in ways that resemble the behaviour of fractures in natural brittle materials (Malthe-Sørenssen et al., 1998a).

The vertical and horizontal movements imposed onto a sediment succession overlying salt are reflected in the shape of the interface between the salt and the overlying sediments. The dynamics of the deformation is however not fully understood: is the surface simply moving up and down due to lateral movement of salt internally in the salt structure (vertical simple shear), or is there an expansion of the structure similar to the inflation of a balloon (i.e. local extension parallel to the surface horizon)? It has previously been shown that spring-slider models can reproduce the fracture pattern in a glacier during a sub-glacial volcanic eruption due to vertical movements of the substrata (Malthe-Sørenssen et al., 1998b). The model does not include variations in strength, temperature nor the influence of syn-deformational sediment loading. This is chosen in order to keep the model as simple as possible. The spring-slider model may be used for analysing a variety of different salt settings, as e.g. the extension structures created during gravity induced thin skinned extension of the cover sediments at passive margins (Brun and Fort, 2011) or in intracratonic basins (Clausen et al., 2012). However, the objective of this paper is to study how the kinematics of a salt-sediment interface influences the generation of fractures and faults above salt pillows and diapirs.

2. The numerical model

The numerical spring-slider model used here is based on the substrate supported spring network model defined by Meakin (1987) and Malthe-Sørenssen et al. (1998a). The 2-D spring network model was used by Malthe-Sørenssen et al. (1998a) to simulate extensional clay fractures. However, in order to investigate the influence of salt structures, we have introduced vertical movements, so that the attachment point of a substratum spring can also be moved in the z direction (vertically) similar to the model of Malthe-Sørenssen et al. (1998b), which was applied to the problem of glacial collapse over a subglacial volcano.

The model involves a number of nodes arranged in a thin layer (the passive layer) and the nodes are mutually connected by springs (inter node springs). Each node is also connected to the substratum (the active layer) by another spring (substratum spring) (Fig. 1). The strength of the connection between the passive and the active layer is expressed by the effective substrate attachment force constant $\mathbf{k} = k_0/k_1$, where k_1 is the spring constant of the inter node springs and k_0 the spring constant of the substratum springs (Malthe-Sørenssen et al., 1998a). The $\mathbf{k}$ value thus constrains the relative strength of the coupling between the active layer and the passive layer, but cannot be related directly to rheological properties of materials involved.

A model run is performed by moving the substratum (the active layer) in increments according to the given boundary conditions in a number of time steps. The deformation of the active layer is transmitted to the passive layer via the substratum springs and the passive layer is deformed by stretching the inter node springs. After each time step, the grid is relaxed so that the net force on each node is minimized (Malthe-Sørensen et al., 1998a). The net force is calculated from