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Research paper

Physical modelling of sub-salt gliding due to fluid overpressure in underlying sedimentary strata

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ABSTRACT

The Gulf of Mexico and the offshore Campos and Santos basins of Brazil provide good examples of sub-salt detachments, by shearing in the presence of overpressure.

We have developed new physical models of such situations, including layers of ductile silicone putty, which simulated an evaporite, and fluid overpressure in porous brittle layers. We studied two configurations, in which the maximal overpressure was either beneath a single ductile layer of silicone (simulating salt), or between two such layers of silicone (simulating an evaporite sequence).

The results of our analogue modelling showed that detachment faults appeared and persisted at the bases of the ductile layers, even though some ductile deformation occurred simultaneously within these layers. For models where maximal overpressure was between two ductile layers, detachment occurred mainly at the base of the upper silicone layer.

On comparing our models with structures in the Gulf of Mexico or offshore Brazil, we find strong similarities, which lead us to suspect that detachment is indeed possible at the base of an evaporite sequence in nature. This conclusion has strong implications, not only for the understanding of petroleum systems, but also for better management of petroleum production in sedimentary basins.

1. Introduction

Salt basins worldwide have provided some of the most prospective hydrocarbon reserves. The best known so far are probably those in the Gulf of Mexico, where recent activity has led to a large number of discoveries, and the South Atlantic basins of offshore Brazil. However, others exist in West Africa, the North Sea, the Gulf of Suez, the Red Sea, the Persian Gulf, the Zagros Mountains of Iran and Iraq and the north Caspian area. Many such basins display overpressure at depth, in part because of the low permeability of the salt and in part because of compaction or generation of hydrocarbons.

Salt tectonics have become increasingly important for petroleum exploration, because of their role in hydrocarbon generation and accumulation. Therefore many studies have focussed on salt tectonics and especially on the shapes resulting from salt mobility (e.g. Chapple, 1978; Davis and Engelder, 1985; Butler et al., 1987; Treloar et al., 1992; Dixon and Liu, 1992; Weimer and Buffler, 1992; Cobbold et al., 1995; Letouezey et al., 1995; Sans and Vergés, 1995; McGuinness and Hossack, 1993; Akrout et al., 2011). However, these studies have assumed that deformation was facilitated by the ductile behaviour of salt layers.

In contrast, more recent work on the Gulf of Mexico (e.g. Harrison and Patton, 1995; Hudec and Jackson, 2006; Hudec and Jackson, 2009) has indicated that salt layers have slid over other sedimentary strata, by detaching close to their bases. Furthermore,

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this area has become of importance for hydrocarbon exploration. Seismic profiles and oil wells have provided good evidence for detachments, at the bases of salt layers or just below them, in response to stress of gravitational or tectonic origin. Furthermore there is evidence for fluid overpressure beneath the salt, suggesting a possible link between detachment and overpressure.

So far, physical modelling of salt tectonics has involved silicone putty as a ductile layer (for example, Cobbold et al., 1989; Cobbold and Szatmari, 1991; Vendeville and Jackson, 1992; Koyi, 1997; Ge et al., 1997; McClay et al., 1998; Gaullier et al., 2000; Brun and Fort, 2004; Fort et al., 2004; Gaullier and Vendeville, 2005; Vendeville, 2005). Independently of that, new techniques involving pore fluids in porous brittle sands have been developed at Géosciences-Rennes (Cobbold and Castro, 1999; Cobbold et al., 2001; Mourgues and Cobbold, 2003, 2006a; 2006b; Zanella et al., 2014). One of the objectives has been to study the role of overpressure in creating detachment levels (e.g. Cobbold et al., 2004).

In this paper, we describe some new modelling of the effects of fluid pressure on detachment, especially beneath ductile layers (Akrout, 2011). Thus we have studied 4 configurations, in which detachment occurred, either within ductile silicone, or as a result of overpressure within sand (Fig. 1). In the presence of silicone layers, maximal overpressure was initially beneath a single one of them or between two such layers (Fig. 2).

The objectives and the results are somewhat comparable to those in a recent publication on numerical (finite element) modelling of sub-salt detachments, resulting from overpressure (Luo et al., 2015). However, our physical models are more variable and more three-dimensional.

2. Natural examples of salt detachments

2.1. Gulf of Mexico (Figs. 3–5)

The Gulf of Mexico (Fig. 3) is a wide area of regional salt tectonics and also one of the most prolific hydrocarbon provinces. Gravitational gliding has been responsible for up-dip extension and down-dip shortening (Fig. 4). The most prominent normal faults are of Jurassic to Early Cretaceous age and detach in the Jurassic salt. The petroleum industry has been aware of the mobility of the salt since 1970 (Schultz-Ela and Jackson, 1993).

There is a variety of models for the emplacement of allochthonous salt in the Gulf of Mexico. All involve detailed structural analyses of the geometry, evolution and fault patterns. There are several deep-water contractional fold belts associated with salts tectonics, such as the Mississippi Fold Belt (Wu et al., 1990; Weimer and Buffler, 1992), Atwater thrust belt (Peel et al., 1995) and Perdido Fold Belt.

Wu et al. (1990) and Weimer and Buffler (1992) suggested that a fold belt may have formed at the basin–ward edge of a regional detachment on the Jurassic salt. Huber (1989) considered well-documented thrust faults, occurring on the upper continental slope, which are related to allochthonous salt sheets, include the Ewing Bank thrust. Glacier Models of allochthonous salt-sheet emplacement have thrust faults, which accommodate

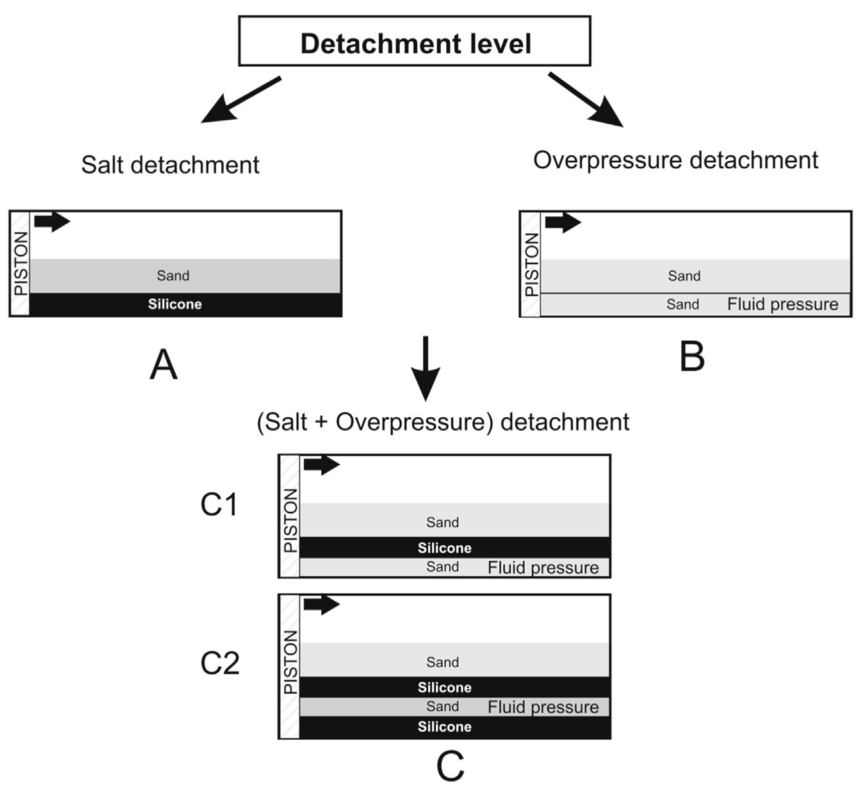

Fig. 1. Four kinds of physical modelling of detachments. A. Detachments involving ductile layers (silicone). B. Fluid overpressure in purely brittle sediment (sand). C1. Maximal overpressure beneath a single ductile layer. C2. Maximal overpressure between two ductile layers.