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Cycles of passive versus active diapirism recorded along an exposed salt wall

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Although it has long been recognised that passive salt diapirism may encompass sub-ordinate cycles of active diapirism, where sedimentary overburden is periodically shed off the roof of the rising salt, there has been very little study of this process around exposed salt (halite) diapirs. However, the Late Miocene-Pliocene Sedom salt wall, on the western side of the Dead Sea Basin, presents an opportunity for detailed outcrop analysis of diapiric salt and the associated depositional and deformational record of its movement during both passive and active phases of diapirism. The sub-seismic scale record of diapirism includes sedimentary breccia horizons interpreted to reflect sediments being shed off the crest of the growing salt wall, together with exceptional preservation of rotated unconformities and growth faults. Areas of more pronounced dips directed towards the salt wall are capped by unconformities, and interpreted to represent withdrawal basins within the overburden that extend for at least 1500 m from the salt margin. Elsewhere, broad areas of upturn directed away from the salt extend for up to 1250 m and are marked by a sequence of rotated unconformities which are interpreted to bound halokinetic sequences. The margins of the salt wall are defined by steep extensional boundary faults that cut upturned strata, and have enabled rapid and active uplift of the salt since the Holocene. The Sedom salt wall therefore charts the transition from passive growth marked by withdrawal basins, growth faults and unconformities, to more active intrusion associated with major boundary faults that enable the rapid uplift of overburden deposited on top of the salt to ~100 m above regional elevations in the past 43 ka. Individual cycles of passive and active diapirism occur over timescales of <30 ka, which is up to an order of magnitude less than typically suggested for other settings, and highlights the dynamic interplay between salt tectonics and sedimentation in an environment undergoing rapid fluctuations in water level.

1. Introduction

It has long been recognised that the sedimentary overburden which surrounds salt structures provides a detailed record for the nature and timing of adjacent salt flow and diapirism (e.g. Trusheim, 1960). However, owing to the extreme aridity required to preserve halite at the earth's surface, the study of salt tectonics suffers from a "scarcity and poor quality of field exposures" (Ringenbach et al., 2013). In recent decades, much of the research effort on salt tectonics has therefore focussed on physical modelling (e.g. Hudec and Jackson, 2011; Dooley et al., 2015), numerical modelling (e.g. Fuchs et al., 2014, 2015) and numerous studies involving the interpretation of seismic sections through salt-influenced basins (e.g. Archer et al., 2012; Jackson et al., 2014, 2015). However, the often steep attitude of bedding adjacent to salt structures, coupled with complications associated with stratigraphic facies changes, and increased faulting and fluid flow concentrated along salt margins, can hinder seismic analysis (see Davison et al., 2000a, b). Direct observations on salt and the adjacent overburden have been largely restricted to a few areas such as the Zagros Mountains (e.g. Talbot, 1979, 1998; Aftabi et al., 2010) which are complicated by ongoing orogenesis, or underground mine workings that, owing to their economic drivers, are focussed on the salt itself rather than the surrounding overburden (e.g. Schofield et al., 2014; Burliga, 2014). Although modelling, seismic

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interpretation and mine studies each generate important information regarding salt tectonics, they suffer from a collective weakness to deliver detailed (sub-seismic scale) structural and sedimentary observations from overburden surrounding the salt. Our scientific motivation is therefore to provide a detailed analysis of the evolution of a diapiric salt wall based on direct observations of outcrops of halite and adjacent sediments. The outcrop study of halite-rich structures is important because salt diapirs dominated by, or containing other evaporitic minerals such as gypsum may display different seismic attributes (e.g. Vargas-Meleza et al., 2015) and/or structural architectures. This point has recently been emphasised by Butler et al. (2015) who note that "shallowly buried gypsum need not form a weak layer within sedimentary successions, which may be important when considering mobilization of evaporite successions soon after their deposition".

Diapiric salt that cross cuts the adjacent sedimentary overburden may either form broadly cylindrical bodies termed salt stocks where the cross sectional ratio is <2, or linear salt walls defined as where the ratio is >2 (Hudec and Jackson, 2011, p.31). Active salt diapirism may simply be defined as "diapir rise by arching, uplifting, or shouldering aside it's roof" (Hudec and Jackson, 2011, p269). Halokinetic active diapirism is driven by overburden load, causing diapiric salt to be pressurised and exert an upward force on its roof. If this buoyancy force is greater than the strength of the roof, then the roof is pushed up as the diapir actively rises (Hudec and Jackson, 2011, p269) (Fig. 1a). Active diapirs are typically marked by: i) stratigraphic units being lifted above their regional elevations on the diapiric crest, ii) normal faulting and grabens forming in sediments over the diapiric crest,

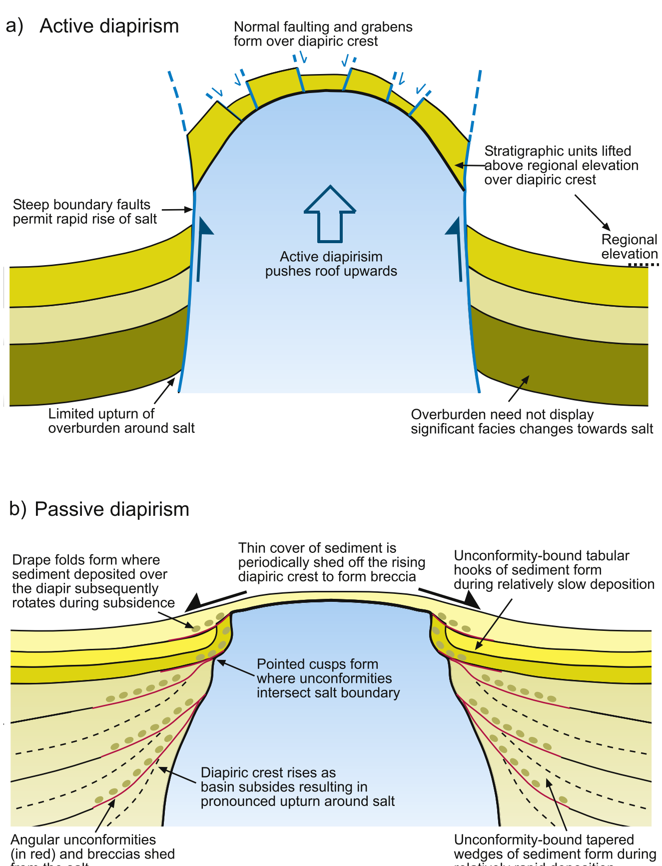

Fig. 1. Schematic cartoons illustrating typical features of a) active salt diapirism and, b) passive salt diapirism.

iii) large boundary faults permitting the relative rise of salt along the diapiric flanks, and iv) a lack of significant facies change in surrounding sediments (e.g. Nelson, 1991; Schultz-Ela et al., 1993; Rowan, 1995, p.204) (Fig. 1a).

Passive salt diapirism is defined as "syndepositional growth of a diapir whose exposed crest rises as sediments accumulate around it" (Hudec and Jackson, 2011, p.275). In passive diapirism, the diapir crest can be occasionally buried, but the diapir repeatedly breaks through the thin temporary roof strata. The base of the salt continues to subside with the basin as it fills with sediment, while the crest of the diapir keeps pace with sedimentation in a 'downbuilding' process (e.g. Vendeville and Jackson, 1991; Hudec and Jackson, 2011 p.275) (Fig. 1b). Passive diapirs are typically associated with: i) pronounced areas of bedding upturn, ii) sedimentary facies changes, and iii) unconformities and breccia horizons within overburden around the flanks of the diapir (Fig. 1b). There is therefore a distinct stratigraphic and sedimentological record of salt movement during passive diapirism. Criteria for recognising passive and active diapirs have been previously summarised by Jackson et al. (1994), Rowan (1995) and Davison et al. (2000a, b).

Bedding upturn and folding noted above is attributed to the shearing of rocks and sediments around the diapir as the salt rises and/or the sediments sink, and may be generated via the passive rise or active piercement of salt (Bornhauser, 1969; Alsop et al., 2000; Davison et al., 2000a, b; Rowan et al., 2003). Drape folding is specifically created where sediments are deposited directly over the flanks of a growing salt diapir, and are subsequently rotated into steeper attitudes as the sediments sink around the salt during passive diapirism (Schultz-Ela, 2003; Rowan et al., 2003; Giles and Rowan, 2012) (Fig. 1b). Drape folding is therefore a near surface process that occurs by "rotation of beds in and below the bathymetric scarp" marking the passive diapir (Rowan et al., 2003, p.753). Rowan et al. (2003, p.753) note however, that "passive diapirism actually entails cycles of small-scale active diapirism as the salt periodically inflates and lifts a thin cover during times of slow sedimentation" (see also Hearon et al., 2014, p.58; Salazar et al., 2014). Davison et al. (1996a, p.8) suggest that this cover will typically be <50 m in thickness. Given that cycles of both passive and active diapirism may therefore occur, the question becomes one of determining the relative components of each, and the contribution that each makes to the deposition and deformation of sediments during the growth of an individual diapir.

There are very few outcrop-based studies of the structural and sedimentological effects of salt diapirs, where halite is actually exposed at the earth's surface. The classic work of Rowan et al. (2003) and Giles and Rowan (2012) on La Popa in Mexico is in an area that has suffered subsequent contraction and lacks halite exposures. The preliminary work of Li et al. (2014) in a newly recognised salt tectonic province in NW China records a very thin (<50 m wide) salt wall where halite is exposed at the surface, but which is overprinted by a regional fold and thrust belt. The recent studies of halokinetic sequences in the Sivas Basin in Turkey (Ringenbach et al., 2013; Callot et al., 2014), together with the work of Poprawski et al. (2014) in northern Spain are marked by evaporites being dominated by gypsum (rather than halite) and also suffer from salt-related structures being overprinted by later regional contraction. Despite this welcome surge in recent publications focussing on outcrop studies of salt tectonics, there still remains a lack of detailed work on exposures of halite-dominated diapirs that have not suffered overprinting by contraction and orogenesis.

As discussed by Alsop et al. (2015) the Sedom salt wall on the western margin of the exceptionally arid Dead Sea Basin (Fig. 2a, b) receives <50 mm precipitation per year and has the advantage over many areas in that a) halite and surrounding clastic overburden are