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Sedimentary and structural controls on seismogenic slumping within mass transport deposits from the Dead Sea Basin

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ABSTRACT

Comparatively little work has been undertaken on how sedimentary environments and facies changes can influence detailed structural development in slump sheets associated with mass transport deposits (MTDs). The nature of downslope deformation at the leading edge of MTDs is currently debated in terms of frontally emergent, frontally confined and open-toed models. An opportunity to study and address these issues occurs within the Dead Sea Basin, where six individual slump sheets (S1–S6) form MTDs in the Late Pleistocene Lisan Formation. All six slumps, which are separated from one another by undeformed beds, are traced towards the NE for up to 1 km, and each shows a change in sedimentary facies from detrital-rich in the SW, to more aragonite-rich in the NE. The detrital-rich facies is sourced predominantly from the rift margin 1.5 km further SW, while the aragonite-rich facies represents evaporitic precipitation in the hyper saline Lake Lisan. The stacked system of MTDs translates downslope towards the NE and follows a pre-determined sequence controlled by the sedimentary facies. Each individual slump roots downwards into underlying detrital-rich layers and displays a greater detrital content towards the SW, which is marked by increasing folding, while increasing aragonite content towards the NE is associated with more discrete thrusts. The MTDs thin downslope towards the NE, until they pass laterally into undeformed beds at the toe. The amount of contraction also reduces downslope from a maximum of ~50% to <10% at the toe, where upright folds form diffuse 'open-toed' systems. We suggest that MTDs are triggered by seismic events, facilitated by detrital-rich horizons, and controlled by palaeoslope orientation. The frequency of individual failures is partially controlled by local environmental influences linked to detrital input and should therefore be used with some caution in more general palaeoseismic studies. We demonstrate that MTDs display 'open toes' where distributed contraction results in upright folding and shortening rather than distinct thrusts. Such geometries may account for some of the contraction that is apparently missing when balancing seismic sections across large off shore MTDs.

1. Introduction

The study of mass transport deposits (MTDs) has been facilitated by improved seismic resolution and has shown on a large scale that sedimentation can influence where subsequent slope failure occurs (e.g. Rowan et al., 2004; Morley et al., 2011; Peel, 2014; Armandita et al., 2015). However, traditional models of slumping generated on a small scale typically tend to assume a layer-cake stratigraphic template, although more recent works suggest that slumps may be generated due to slope instabilities associated with rapid sedimentation and associated facies changes (e.g. Odonne et al., 2011). The coarse grain size and thick beds in such settings are not conducive to structural analysis as they typically lack the refined stratigraphy and precise markers necessary for detailed correlation of structures within individual slump sheets. Despite the differences in scale, the outcrop study of well-exposed slump systems is important as it provides further details and constraints on large-scale MTDs that are imaged seismically offshore (e.g. Worrall and Snelson, 1989; Morley and Guerin, 1996; Frey-Martinez et al., 2005; Bull et al., 2009; Morley et al., 2011; Jackson, 2011).

Traditional models of slumping associated with MTDs assume that the amount of extension in the upslope 'head' region of a slumped mass should be balanced by the amount of contraction in the downslope 'toe' within the same sheet (Farrell, 1984, see also Alsop and Marco, 2014) (Fig. 1a). However, such equilibria are in reality rarely observed, with significant amounts of contraction required to balance large-scale slumps or MTDs missing from seismic sections (e.g. Butler and Paton, 2010; de Vera et al., 2010). Such disparities could be attributed to out of section movement during gravity spreading (see discussion in Alsop and Marco, 2011), or lateral compaction of sediments at the leading edge of MTDs

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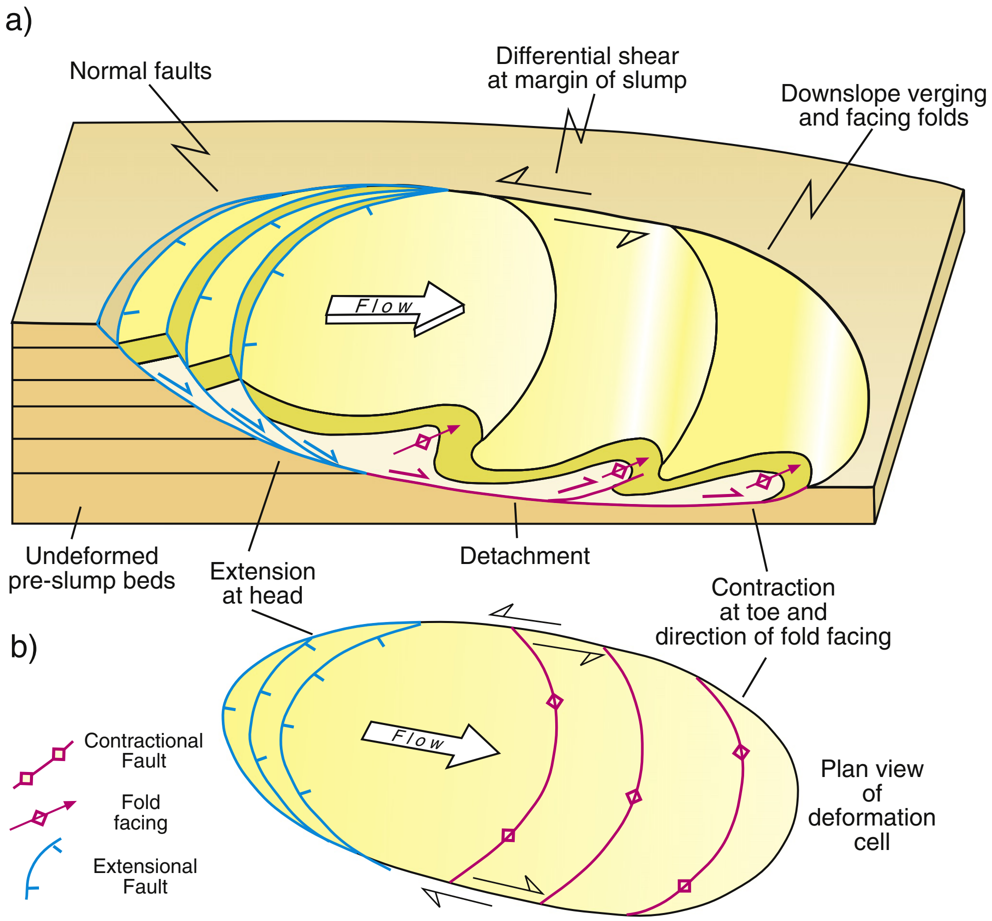

Fig. 1. a) Schematic 3-D cartoon and b) plan view of a slump deformation cell illustrating a typical slump-related fold and fault system overriding undeformed horizontal pre-slump beds. The slumped mass flows downslope (towards the right) along a basal detachment and is marked by extension at the (upper) head of the slump and contraction associated with folds and thrusts at the toe. Folds typically verge and face upwards in the downslope direction.

that may create structures and fabrics that are below the resolution of the seismic imaging (e.g. Butler and Paton, 2010; de Vera et al., 2010).

The main aims of this work are therefore to discuss a) the stratigraphic and sedimentological influences that collectively form environmental controls on styles of deformation in slump sheets, and b) the nature of deformation at the leading downslope toes of slump sheets. This paper addresses a number of basic questions relating to these aims including:

i) Does the amount of slump sheet translation sequentially vary up through a sequence?
ii) Do slumps reworked by multiple seismic events display different amounts of translation?
iii) Do slumps maintain a constant flow direction up through a sequence of several slumps?
iv) Does the thickness and spacing between individual slump sheets vary downslope?
v) How does the thickness and extent of sediment caps vary above slump sheets?
vi) Does the amount of contraction vary towards the downslope toe of each slump?
vii) What structures mark the leading edge of slump sheets?
viii) Does lithological variation control structural style within slump sheets?
ix) What factors control the timing and frequency of slumps?

The Late Pleistocene Lisan Formation outcropping on the western margin of the Dead Sea Basin is an ideal place to study these issues as individual slumps are superbly exposed allowing them to be easily correlated and traced. The recent investigation of drill cores taken from the depocentre of the Dead Sea reveals that the stratigraphic thickness of the Lisan Formation is three times greater than its onshore equivalent, largely due to the input of transported sediment and disturbed layers (Marco and Kagan, 2014). The slump systems observed onshore ultimately may form part of these larger MTDs that feed into the deep basin. The quality of onshore outcrop is perhaps unparalleled and this permits greater detailed analysis of MTD slump systems than otherwise possible. In addition, lateral facies changes are observed within slumps, making them an especially good analogue for larger-scale marine MTDs which frequently are associated with variable sedimentary input (e.g. Peel, 2014).

2. General slump patterns

Gravity-driven slumps of poorly lithified or ‘soft-sediments’ (e.g. Maltman, 1984) deform by particulate flow (e.g. Knipe, 1986), with the ratio of pore fluid pressure and cohesive strength of the sediment (due to grain weight) controlling the nature of the resulting structures (e.g. Knipe, 1986; Ortner, 2007). If pore fluid pressure is equal to, or greater than, the cohesive strength of the sediment, then bedding is effectively destroyed as the sediment either liquefies or fluidises, respectively. However, where pore fluid pressure is marginally less than the cohesive strength of the sediment, it deforms by hydroplastic deformation, which preserves primary features such as bedding, and this enables slump folds and shears to be defined. An increase in pore fluid pressure therefore provides an effective mechanism by which to