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Upslope-verging back thrusts developed during downslope-directed slumping of mass transport deposits

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ABSTRACT

While much research has recently been focussed on downslope-verging systems of gravity-driven fold and thrust belts within mass transport deposits (MTDs), rather less attention has been paid to back thrusts, which are defined as displaying the opposite vergence to the main transport direction in thrust systems. A fundamental question arises over whether back thrusts in downslope-verging MTDs record actual movement back upslope. In order to address this issue, we have examined exceptional outcrops of Pleistocene fold and thrust systems developed in MTDs around the Dead Sea Basin. Back thrusts can be interpreted in terms of a '*downslope-directed underthrust model*', where material moves down slope and is driven into the footwall of the back thrust, resulting in the 'jacking up' of the largely passive hangingwall. Our data support this underthrust model and include the observation that stratigraphic units may be markedly thickened (up to 250%) in the footwall of back thrusts. This thickening is a consequence of pure shear lateral compaction as the 'wedge' of sediment is driven into the footwall to create an underthrust. In addition, back thrusts may be rotated as new back thrusts form in their footwalls, ultimately resulting in overturned thrusts. The observation that steeper back thrusts typically accommodate less displacement than gently-dipping back thrusts suggests that steepening occurred during back thrusting, and is therefore a consequence of 'footwall wedging'. Contrary to some recent interpretations, we demonstrate that back thrusts can develop in gravity-driven systems and cannot therefore be used to distinguish different emplacement mechanisms for MTDs.

1. Introduction

While much research has recently been focussed on downslope-verging systems of gravity-driven fold and thrust belts within mass transport deposits (MTDs), rather less attention has been paid to back thrusts developed within such systems. Although this may be partially due to back thrusts being apparently absent from some seismic sections across MTD's from offshore Namibia (e.g. Butler and Paton, 2010; Scarselli et al., 2016) or offshore Brazil (e.g. Reis et al., 2016), they are undoubtedly imaged and well-developed in other settings, such as the Storegga Slide in the North Sea, where oppositely verging thrusts create 'pop-up' blocks in the MTD (e.g. Bull et al., 2009, p.1146) or back thrusts in the Niger Delta (e.g. Corredor et al., 2005; Morley et al., 2011; Jolly et al., 2016). Back thrusts are also imaged on detailed seismic sections through mass movement induced fold and thrust belts in unconsolidated lacustrine sediments (e.g. Schnellmann et al., 2005). The presence of back thrusts observed in outcrop studies of thrust systems in orogenic belts (e.g. Butler, 1987) and gravity-driven slump systems (e.g. Farrell, 1984; Strachan and Alsop, 2006; Garcia-Tortosa et al., 2011) is, however, long established and indisputable. Indeed, more than a quarter of all thrusts recorded by Garcia-Tortosa et al. (2011) in a gravity-driven slump system from California are back thrusts.

Despite the widespread occurrence of back thrusts in slump systems and MTDs, the geometry and mechanics of these apparently anomalous structures, that verge back up the regional slope, have not been discussed in detail. Farrell (1984, p.733), working on slump sheets, noted that "folds associated with upslope propagating faults will verge upslope" and that "faults which propagate in the opposite direction to the bulk transport direction are

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analogous to back thrusts in orogenic belts". Back thrusts have previously been defined in text books as those thrusts that "travel with the opposite sense" (i.e. towards the hinterland) (e.g. Ghosh, 1993, p.445), while more recently, Fossen (2016, p. 474) defines a back thrust as a "Thrust displacing the hangingwall toward the hinterland, i.e. opposite to the general thrusting direction". A simple question then arises over whether back thrusts in downslope-verging slump systems record actual movement back upslope (i.e. opposite to the general thrusting direction). Interpreting the mechanism by which back thrusts have developed within MTDs is clearly critical when evaluating and distinguishing models of sediment deformation. Indeed, Myrow and Chen (2015, p. 641) note that "Thrusting of parts of brittle deformed beds took place in multiple orientations, although, in many cases, this was nearly oppositely oriented which is evidence against slope-generated gravity-driven transport and consistent with seismic deformation". A follow-up question may then be posed over the role that thrust geometries play in distinguishing different triggers and mechanisms of sediment deformation.

Slumps and MTDs are developed across a range of scales and settings and nearly all are considered to be gravity-driven. Although movement of material up the regional slope may be locally achieved by slumping off distinct palaeo-highs, tilted fault blocks and pre-existing structural culminations (e.g. Alsop and Marco, 2011), this mechanism fails to account for the more general development of back thrusts in otherwise downslope-verging and gravity-driven fold and thrust systems.

In order to distinguish back thrusts from downslope-directed fore thrusts, *a priori* knowledge of the general direction of thrust transport is required, which, in the case of gravity-driven MTDs, is considered downslope. While this direction may be relatively simple to ascertain in modern or recent basins, it becomes increasingly debateable in ancient settings. We have therefore chosen to analyse a recent MTD system around the Dead Sea Basin in which there is no dispute about downslope directions and consequently what constitutes a downslope-directed fore thrust or upslope-verging back thrust (e.g. Alsop et al., 2016a) (Fig. 1). Our research focuses on some fundamental questions regarding back thrusts in gravity-driven MTDs, including:

i) Do back thrusts typically form in the central or downslope toe regions of MTDs?
ii) What controls the development of back thrusts in gravity-driven MTDs?
iii) What are the displacement patterns along back thrusts?
iv) When do back thrusts form within the thrust sequence?
v) How do back thrusts in MTDs compare to those in lithified rocks?
vi) Do back thrusts in gravity-driven MTDs record movement back upslope?

2. Geological setting

The Dead Sea Basin is a pull-apart basin developed between two left-stepping, parallel fault strands that define the sinistral Dead Sea Fault (Garfunkel, 1981; Garfunkel and Ben-Avraham, 1996) (Fig. 1a). The Dead Sea Fault has been active since the Miocene (Nuriel et al., 2017) and during deposition of the Lisan Formation in the late Pleistocene (70-15 ka) (Haase-Schramm et al., 2004). The Lisan Formation comprises a sequence of alternating aragonite-rich and detrital-rich laminae on a sub-mm scale that are thought to represent annual varve-like cycles (Begin et al., 1974). Varve counting, combined with isotopic dating, suggests that the average sedimentation rate of the Lisan Formation is ~1 mm per year

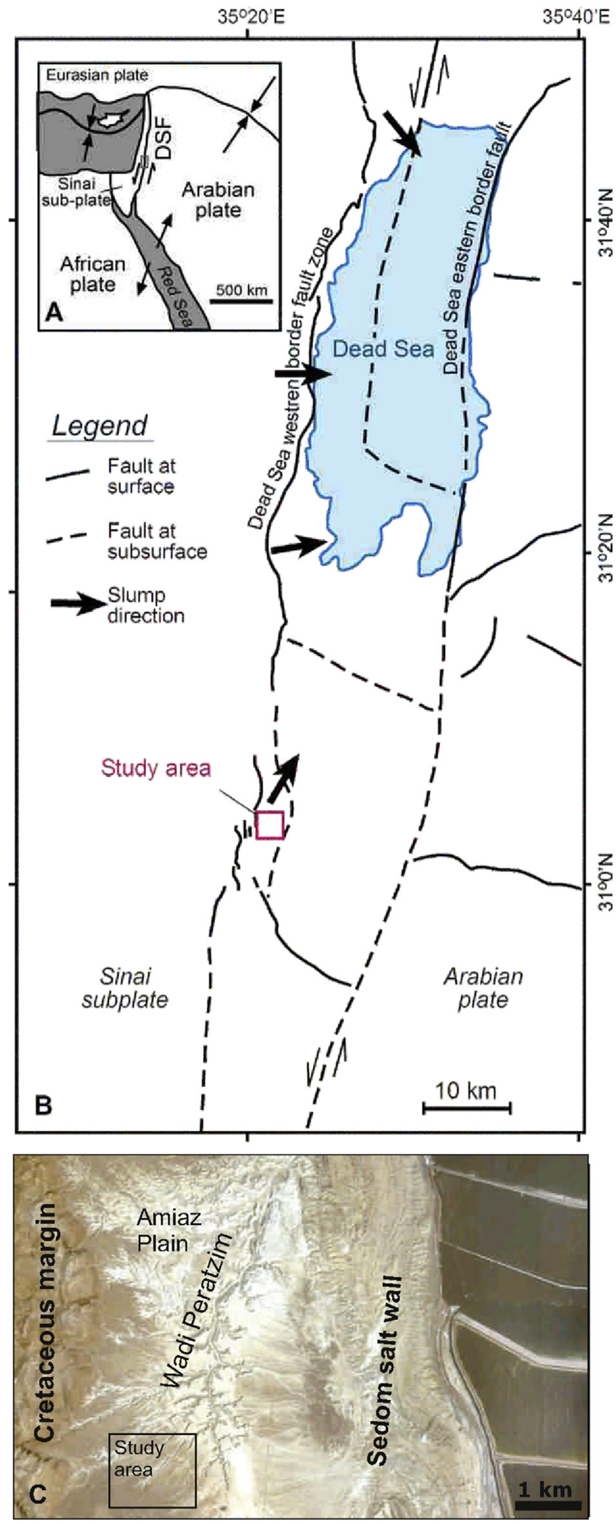

Fig. 1. a) Tectonic plates in the Middle East. General tectonic map showing the location of the present Dead Sea Fault (DSF). b) Map of the current Dead Sea showing the position of localities referred to in the text. The arrows within the Lisan Formation represent the direction of slumping in MTD's that forms a semi-radial pattern around the Dead Sea Basin. c) Image of the light-coloured Lisan Formation at Wadi Peratzim, with the brownish Cretaceous margin to the west and the Sedom salt wall to the east. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)