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Seismogenic slump folds formed by gravity-driven tectonics down a negligible subaqueous slope

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ABSTRACT

The Late Pleistocene Lisan Formation contains superb examples of soft-sediment deformation generated during gravity-driven slumping and failure down extremely gentle (<1°) slopes towards the palaeo-Dead Sea Basin. Following a previously established framework, portions of individual slumps are broadly categorised into coherent, semi-coherent, and incoherent domains, reflecting increasing deformation and disarticulation of sediment. We present new structural data collected from each of these (overlapping) domains that demonstrate how the orientation of fold hinges and axial planes becomes more dispersed as slumps become increasingly incoherent. Such patterns are the reverse to that typically encountered in lithified rocks where increasing deformation results in clustering of linear elements towards the flow direction, and may reflect greater heterogeneity and disarticulation within slumps. Use of folds to determine palaeoslopes should therefore be limited to those from coherent slumps, where the opportunity for hinge dislocation and rotation is more limited. Within coherent and semi-coherent slumps, folds are reworked to create classic Type 1, 2 and 3 refold patterns during a single progressive deformation perhaps lasting just a matter of minutes. It is noteworthy that slump folds are typically lacking in smaller parasitic folds, implying that instantaneous development and/or limited viscosity contrasts have hindered the formation of second order folds. As deformation intensifies within semi-coherent to incoherent slumps, some fold hinges rotate towards the flow direction to create sheath folds. However, many fold hinges do not rotate into the flow direction, but rather roll down-slope to form a new category of *spiral folds*. Extreme deformation may also generate semi-detached fold trains in which the short limbs of verging fold pairs are relatively thickened resulting in en-echelon *X folds*. The hinges of the sheared fold pair are reduced to apophyses, although these can still be used to infer original fold vergence. As observations are from a thin slumped system over a relatively small area, the variation in structural style from coherent to incoherent is attributed to increasing deformation.

1. Introduction

Most text books concerning structural geology and sedimentary processes to some degree neglect structures generated during gravity-driven soft sediment deformation, which occurs prior to the complete lithification of sediments (see Maltman, 1984). This may reflect the fact that this topic spans structural geology, sedimentary systems, and surficial processes associated with slope failure, and perhaps therefore does not fit neatly into any of these categories. In addition, structures generated in soft-sediments will become increasingly difficult to recognise as these become lithified, and possibly undergo subsequent phases of tectonism as hard rocks (see for example, Debacker et al., 2006; Ortner, 2007; Waldron and Gagnon, 2011). Despite these complications, the study of deformation in sediments is growing in importance as the resulting structures affect porosity and permeability of the lithified rock, with obvious implications for fluid flow associated with hydrocarbons and aquifers (e.g., Hurst et al., 2011). In addition, the study of structures within slump sheets is also important as large-scale systems of gravity-driven deformation associated with slope failure are increasingly recognised on high resolution seismic surveys of continental margins where Mass Transport Complexes (MTCs) are imaged (e.g., Bull et al., 2009; Butler and Paton, 2010; Gardner et al., 1999; Jackson, 2011; Lee et al., 2007). The direct analysis of smaller scale structures at outcrop will therefore help with interpretation of these features, which not only are important in hydrocarbon exploration, but also present significant hazards where modern slope failures can threaten hydrocarbon infrastructure and pipelines (e.g., Locat and Lee, 2002; Mason et al., 2006).

Although failures in modern subaqueous settings can occur on exceptionally low angle slopes of as little as 0.25° (e.g., Field et al., 1982), evidence from the older geological record is frequently interpreted to suggest that more significant slopes are necessary (e.g., Allen, 1982; Lewis, 1971; see Garcia-Tortosa et al., 2011). Detailed studies of modern or relatively recent subaqueous slope failures, which are now exposed at outcrop, can therefore provide further detailed information on the controls and geometries associated with gravity-driven slump systems.

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Finally, the investigation of gravity-driven slump folds and systems is important as it provides wider ranging benefits relating to the analysis of structures (and in particular folds) in other settings where an understanding of flow is important such as salt glaciers (e.g., Aftabi et al., 2010), sub-glacial shear zones (e.g., Lesemann et al., 2010), snow slides (e.g., Lajoie, 1972) and metamorphic shear zones (e.g., see review and references in Druguet et al., 2009).

Deformation within non-cohesive or poorly lithified soft-sediments is largely achieved via independent particulate flow (Knipe, 1986). Relationships between the ratio of pore fluid pressure and cohesive strength of the sediment (due to grain weight) determine the exact nature of the structures that form in the sediment (Knipe, 1986; Ortner, 2007). When fluid pressure is lower than grain weight then hydroplastic deformation develops, leading to primary sedimentary features such as bedding being modified via folds and shears that resemble ductile structures in metamorphic rocks. When fluid pressure is equal to grain weight then sediment liquefies to form laminar flow, in which primary sedimentary features such as bedding are destroyed. When fluid pressure is greater than grain weight then sediment fluidizes to form turbulent flow, in which primary sedimentary features including bedding are destroyed. Increases in pore fluid pressure are achieved by high permeability fluid-rich sediments being overlain by low permeability sediments that act as a seal to prevent fluid escape. Increases in fluid pressure are also temporarily triggered by seismic activity that may ultimately result in fluid pressure exceeding the tensile strength of the surrounding sediment, leading to sedimentary dykes catastrophically injecting into areas of lower pressure and intruding the overlying sequence.

Many studies have examined folds and faults formed during hydroplastic deformation of soft-sediment from the stand-point of guidelines established in the geometric analysis of metamorphic rocks over many decades (Fossen, 2010; Ramsay, 1967; Ramsay and Huber, 1987; Turner and Weiss, 1963). Whilst these undoubtedly provide a valuable framework, an analysis of soft sediment deformation in modern settings, where the gravity-driven component of deformation and direction of slope failure are unambiguous, also presents an opportunity to re-evaluate (and challenge) some of these assumptions. Our study therefore aims to explore and address a number of factors and fundamental questions pertaining to slump folding associated with slope failure including:

i) How can gravity-driven slumping occur down exceptionally gentle (<1°) slopes?
ii) How do classical refold patterns form almost instantaneously within slumps?
iii) Why do some fold hinges rotate and others roll during slumping?
iv) What structural patterns are defined by overall slump fold hinges and axial planes as deformation intensifies?
v) Why do axial surfaces in some slump folds define en-echelon patterns as they step across weaker units?
vi) Why do small-scale parasitic folds rarely develop around slump folds?
vii) How representative and useful are structures formed in recent slumps when interpreting those preserved in the geological record?

The purpose of this paper is therefore to address the fundamental questions noted above. We stress however that we are by no means the first to consider some of the basic issues such as how slumping occurs on very low angle slopes (see for example the earlier work of Field et al., 1982; Garcia-Tortosa et al., 2011) and how structures evolve as deformation intensifies within slumps (e.g., Woodcock, 1976a,b, 1979). The Late Pleistocene Lisan Formation exposed on the western shore of the Dead Sea does however provide superb examples of soft sediment deformation associated with slope failure, and this unique opportunity permits perhaps unrivalled excavation and 3-D examination of the resulting slump geometries.

2. Soft sediment deformation

2.1. A theoretical framework for the description of kinematics in slumps

Gravity-driven slumps related to slope failure have been hypothetically modelled as flow cells marked by extension in the upslope regime that is broadly balanced by contraction in the lower downslope or toe area of the slump (e.g., Collinson, 1994; Elliot and Williams, 1988; Farrell, 1984; Farrell and Eaton, 1987; Hansen, 1971; Lewis, 1971; Martinsen, 1989, 1994; Martinsen and Bakken, 1990; Smith, 2000; Strachan, 2002, 2008). Slope failure is considered to initiate at a single point and generates a compressive wave that spreads downslope and an extensional wave that propagates upslope (Farrell, 1984) (Fig. 1a). Subsequent translation of the slumped mass results in compressional folds and thrusts at the downslope toe of the system, whilst the head is marked by extensional

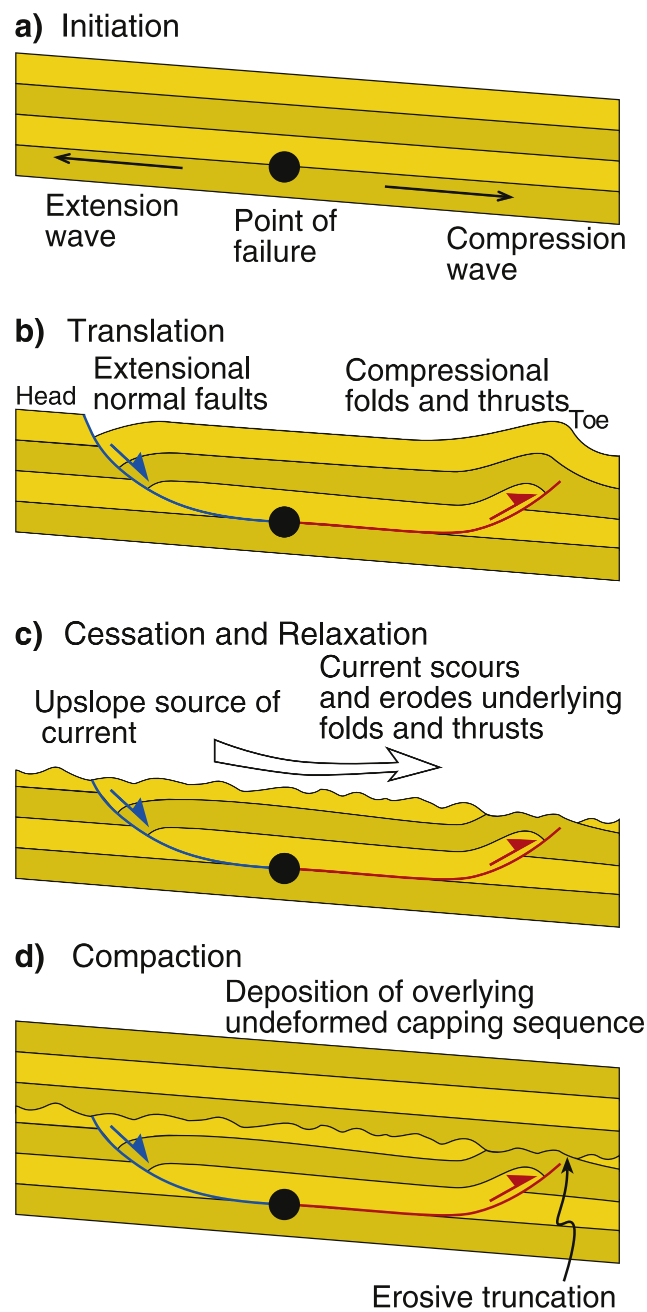

Fig. 1. Schematic cartoons illustrating the initiation (a), translation (b), cessation and relaxation (c), and subsequent compaction (d) of a hypothetical slump sheet.