Journal of Structural Geology 63 (2014) 27–49

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Fold and fabric relationships in temporally and spatially evolving slump systems: A multi-cell flow model

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ARTICLE INFO

Article history:
Received 2 December 2013
Received in revised form
14 February 2014
Accepted 19 February 2014
Available online 4 March 2014

Keywords:
Slump folds
Foliation
Mass Transport Complex
Dead Sea

ABSTRACT

Folds generated in ductile metamorphic terranes and within unlithified sediments affected by slumping are geometrically identical to one another, and distinguishing the origin of such folds in ancient lithified rocks is therefore challenging. Foliation is observed to lie broadly parallel to the axial planes of tectonic folds, whilst it is frequently regarded as absent in slump folds. The presence of foliation is therefore often considered as a reliable criterion for distinguishing tectonic folds from those created during slumping. To test this assertion, we have examined a series of well exposed slump folds within the late Pleistocene Lisan Formation of the Dead Sea Basin. These slumps contain a number of different foliation types, including an axial–planar grain-shape fabric and a crenulation cleavage formed via microfolding of bedding laminae. Folds also contain a spaced disjunctive foliation characterised by extensional displacements across shear fractures. This spaced foliation fans around recumbent fold hinges, with kinematics reversing across the axial plane indicating a flexural shear fold mechanism. Overall, the spaced foliation is penecontemporaneous with each individual slump where it occurs, although in detail it is pre, syn or post the local folds. The identification of foliations within undoubted slump folds indicates that the presence or absence of foliation is not in itself a robust criterion to distinguish tectonic from soft-sediment folds. Extensional shear fractures displaying a range of temporal relationships with slump folds suggests that traditional single-cell flow models, where extension is focussed at the head and contraction in the lower toe of the slump, are a gross simplification. We therefore propose a new *multi-cell flow model* involving coeval second-order flow cells that interact with neighbouring cells during translation of the slump.

1. Introduction

A perennial problem when working in ancient deformed sedimentary rocks is clearly separating and distinguishing structures generated within unlithified “soft-sediment” from those folds and fabrics that developed during subsequent deformation of the fully lithified rock (e.g. Elliot and Williams, 1988; Maltman, 1984, 1994a,b,c; Debacker et al., 2006; Ortner, 2007; Waldron and Gagnon, 2011). A particularly perplexing issue relates to determining the origin of folds that are widespread features in a range of both tectonic and sedimentary environments. The presence of axial planar cleavage in tectonic folds, compared to its absence in soft-sediment folds, has been quoted in older texts as a robust and reliable criterion for distinguishing tectonic folds from slump folds (e.g. Potter and Pettijohn, 1963). As such, Webb and Cooper (1988, p.470) note that “characteristic slump related features include .... tight to isoclinal folds with no related cleavage”. Indeed, a number of recent text books, including that of Fossen (2010, p.239), perpetuate this view and note that soft-sediment folds “generally lack the axial planar cleavage so commonly associated with folds formed under metamorphic conditions.”

However, the counter-argument that cleavage, which is defined as “the ability of a rock to split or cleave into more or less parallel slices”, or foliation, defined as “any fabric-forming planar or curviplanar structure” (Fossen, 2010, p.244–245) may in fact form apparently axial–planar fabrics to sedimentary slump folds has also long been suggested and debated (e.g. Williams et al., 1969; Corbett, 1973; Woodcock, 1976a,b,; Tobisch, 1984; McClay, 1987; Farrell and Eaton, 1988; Maltman, 1994c). Two principle models have been proposed to explain how such sedimentary fabrics may develop with apparent axial–planar relationships to slump folds (see Maltman, 1981; Tobisch, 1984; Elliot and Williams, 1988). In

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http://dx.doi.org/10.1016/j.jsg.2014.02.007
0191-8141/

the first interpretation, the authors of some text books (e.g. Price and Cosgrove, 1990, p. 455) claim that cleavages that appear to be axial–planar with respect to sedimentary slump folds may actually be later and reflect mimetic growth of minerals during subsequent diagenesis of the sediment. This view is supported in a more recent text book, where Passchier and Trouw (2005, p.245) compare folds formed in tectonically deformed rocks with those generated in soft-sediments and note that “an obvious difference is that no axial plane cleavage should be present (in slump folds), but diagenetic foliation may have formed, parallel to bedding and axial planes”.

A second interpretation has proposed that sub-horizontal foliations that are apparently axial–planar to flat-lying recumbent slump folds are actually created by compaction of the sediment during subsequent burial and lithification (see discussion in Maltman, 1994c; McClay, 1987, p.12). The horizontal compaction fabric is thus fortuitously parallel to the axial plane of the recumbent slump fold. Consequently, both interpretations described above invoke a phase of subsequent foliation development that is parallel to the axial plane of the earlier slump fold. Maltman (1994d, p.153) summarised this dilemma for the relationship between slump folds and adjacent fabrics by noting “As yet, there is no good record of a slump fold with an axial–plane foliation that definitely formed through slumping rather than consolidation, but the question remains open”.

Clearly the range of potential interpretations regarding slump fold and foliation relationships noted above is important because they can critically alter the fundamental understanding of the timing between sedimentation and deformation patterns. The interpretation of sedimentary environments and associated palaeogeographies, not to mention isotopic dating of intrusions that postdate *apparently* regional structures, are seriously flawed if the basic field relationships associated with recognition of soft-sediment deformation are incorrectly identified. Debate continues on the timing of regional deformation relative to lithification, with the possibility that pockets of overpressured sediment may remain unlithified for periods of time whilst surrounding areas are lithified and undergo “tectonic” deformation (e.g. Phillips and Alsop, 2000; Ortner, 2007; see Waldron and Gagnon, 2011). While regional deformation could strike at any stage within the spectrum of the continuing lithification process, resulting in a degree of ambiguity as to whether folds and foliations were forming in truly “soft-sediment”, the generation of slump folds requires the sediment to be unlithified *at the time of slumping* and thereby negates much of that debate.

In addition to the potential pitfalls in regional correlation and dating of deformation events outlined above, the study of foliation development and deformation in unlithified sediments, in general, is also significant because of the profound effects it may have on the permeability of the host sediment. This possibility has obvious implications for hydrocarbons and fluid flow (e.g. Hurst et al., 2011). Furthermore, the study and interpretation of fabrics associated with soft-sediment deformation is important for the recognition and understanding of ancient Mass Transport Complexes (MTC’s) that are increasingly interpreted from offshore seismic sections and are growing in economic significance (e.g. see review by Lee et al., 2007; Bull et al., 2009; Jackson, 2011). Understanding the development of cleavages and foliations is crucial because they are sub-seismic scale deformation that is “hidden” on seismic sections, but are important to the deformation analysis. As such, foliation may be a manifestation of lateral compaction, that could account for up to 40% “shortening” that is apparently absent, but is required to balance and restore regional cross sections in offshore MTC’s (e.g. see Butler and Paton, 2010). Finally, the study of foliation in sediment is of more general interest because it may be useful when interpreting folds and fabrics in other settings and environments where flow occurs such as subglacial shear zones (e.g. Lesemann et al., 2010; Pisarska-Jamroży and Weckwerth, 2012 and references therein) or salt flows (e.g. Aftabi et al., 2010).

Central to many of these arguments is the basic issue as to whether foliations can indeed form genuine axial–planar fabrics to slump folds created during soft-sediment deformation. To address this fundamental problem, we have therefore undertaken a detailed study involving observations of both foliations and slump folds in an attempt to better understand their geometry and relationships to one another. The aim of this contribution is therefore to clarify if a) foliations can form axial–planar to slump folds, and if so, b) the nature and kinematic significance of such fabrics in models of slump systems. In particular we raise a number of important questions including:

i) What are the different types of foliations and lineations that may form around slump folds?
ii) What are the relative timing relationships between foliations and slump folds?
iii) What are the kinematics associated with sedimentary foliation development?
iv) What relationship, if any, does the orientation of foliation have with the slope?
v) Can foliation–bedding relationships be used to distinguish sedimentary and tectonic folds?
vi) How can the development of foliation be incorporated into models of flow within slumps?

Although a number of authors have previously described apparent axial–planar fabrics from slump folds (e.g. Williams et al., 1969; Bell, 1981; Tobisch, 1984), the detailed relationships are frequently hindered by the analyses being undertaken in ancient rocks that have experienced subsequent diagenesis and tectonism (see Elliot and Williams, 1988). These younger events may alter, mask, or even entirely overprint the original relationships, creating ambiguity in these interpretations. Many of these issues about ambiguity from overprinting are absent from the late-Pleistocene Lisan Formation developed around the Dead Sea Basin. Superb preservation, coupled with the option of 3-D excavation in these largely unlithified sediments, allows us to examine a range of fold-related structures such as grain-shape fabrics, crenulation cleavage, spaced foliations and intersection lineations that normally are restricted to analysis in classical metamorphic rocks (e.g. Turner and Weiss, 1963; Ramsay, 1967; Ramsay and Huber, 1987).

2. Soft-sediment deformation

Over the past 40 years, gravity-driven slumps of unconsolidated sediment have typically been modelled in terms of deformation cells translating downslope (e.g. Hansen, 1971; Lewis, 1971; Farrell, 1984). These systems are marked by extension in the upslope portion of the slump that is broadly balanced by contraction in the downslope or toe area of the slump (e.g. Farrell, 1984; Farrell and Eaton, 1987; Elliot and Williams, 1988; Martinsen, 1989, 1994; Martinsen and Bakken, 1990; Smith, 2000; Debacker et al., 2001; Strachan, 2002, 2008; Gilbert et al., 2005; Garcia-Tortosa et al., 2011) (Fig. 1). Within such models, translation of the slump-sheet occurs along some form of underlying detachment or failure surface with extension at the head accommodated by normal faults and fractures, while folds are considered to be one of the primary manifestations of contraction in the lower portion of the slump (e.g. see review in Alsop and Marco, 2011) (Fig. 1). Deformation associated with translation along the basal decollement is considered to be dominated by non-coaxial strain (e.g. Wetzler et al., 2010),