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Distinguishing thrust sequences in gravity-driven fold and thrust belts

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ABSTRACT

Piggyback or foreland-propagating thrust sequences, where younger thrusts develop in the footwalls of existing thrusts, are generally assumed to be the typical order of thrust development in most orogenic settings. However, overstep or 'break-back' sequences, where later thrusts develop above and in the hangingwalls of earlier thrusts, may potentially form during cessation of movement in gravity-driven mass transport deposits (MTDs). In this study, we provide a detailed outcrop-based analysis of such an overstep thrust sequence developed in an MTD in the southern Dead Sea Basin. Evidence that may be used to discriminate overstep thrusting from piggyback thrust sequences within the gravity-driven fold and thrust belt includes upright folds and forethrusts that are cut by younger overlying thrusts. Backthrusts form ideal markers that are also clearly offset and cut by overlying younger forethrusts. Portions of the basal detachment to the thrust system are folded and locally imbricated in footwall synclines below forethrust ramps, and these geometries also support an overstep sequence. However, new 'short-cut' basal detachments develop below these synclines, indicating that movement continued on the basal detachment rather than it being abandoned as in classic overstep sequences. Further evidence for 'synchronous thrusting', where movement on more than one thrust occurs at the same time, is provided by displacement patterns on sequences of thrust ramp imbricates that systematically increases downslope towards the toe of the MTD. Older thrusts that initiate downslope in the broadly overstep sequence continue to move and therefore accrue greater displacements during synchronous thrusting. Our study provides a template to help distinguish different thrust sequences in both orogenic settings and gravity-driven surficial systems, with displacement patterns potentially being imaged in seismic sections across offshore MTDs.

1. Introduction

Piggyback or foreland-propagating thrust sequences, where younger thrust imbricates develop in the footwalls of existing thrusts, are generally assumed to be the typical order of thrust development in most tectonic settings (e.g. Boyer and Elliot, 1982; Morley, 1988; Fossen, 2016, p.359). However, Boyer (1992, p. 377) notes that such foreland-propagating systems "have taken on the role of an axiom in the study of thrust kinematics" while Butler (2004, p.2) challenges "the dogma of simple foreland-propagation". An alternative overstep thrust sequence, where later thrusts develop in the hangingwalls of earlier thrusts, may also develop (e.g. Elliot and Johnson, 1980, p. 90; Boyer and Elliot, 1982; Park, 2013, p.16). Such overstep thrust sequences are considered to be particularly relevant to gravity-driven mass transport deposits (MTDs), where retrogressive slope failure encourages the locus of deformation to migrate upslope, while thrusting is still directed downslope. Overstep thrust sequences have been interpreted to develop during cessation of movement in MTDs for more than 30 years since the application of the 'dislocation model' to slumps by Farrell (1984), but no outcrop detail has been provided (see Farrell, 1984; Martinsen and Bakken, 1990).

Suggestions of overstep thrust sequences imaged in seismic data from the offshore Norwegian margin were described by Ireland et al. (2011, p. 34) who noted that "Thrusts probably propagated retrogressively based upon the observation that fold amplitudes decrease upslope". Working with seismic sections from the Orange Basin of offshore Namibia, de Vera et al. (2010, p.230) also suggested that local areas of overstep thrusting develop due to truncation of underlying structures by overlying thrusts, although an overall piggyback system of thrusting is considered to operate. In a further seismic example across a fold and thrust system developed offshore Borneo, Totake et al. (2017) recognised that "upper imbricate sheets appear to be younger than underlying sheets, creating a similar structure to break-backward imbricate structure" (i.e. overstep thrusting).

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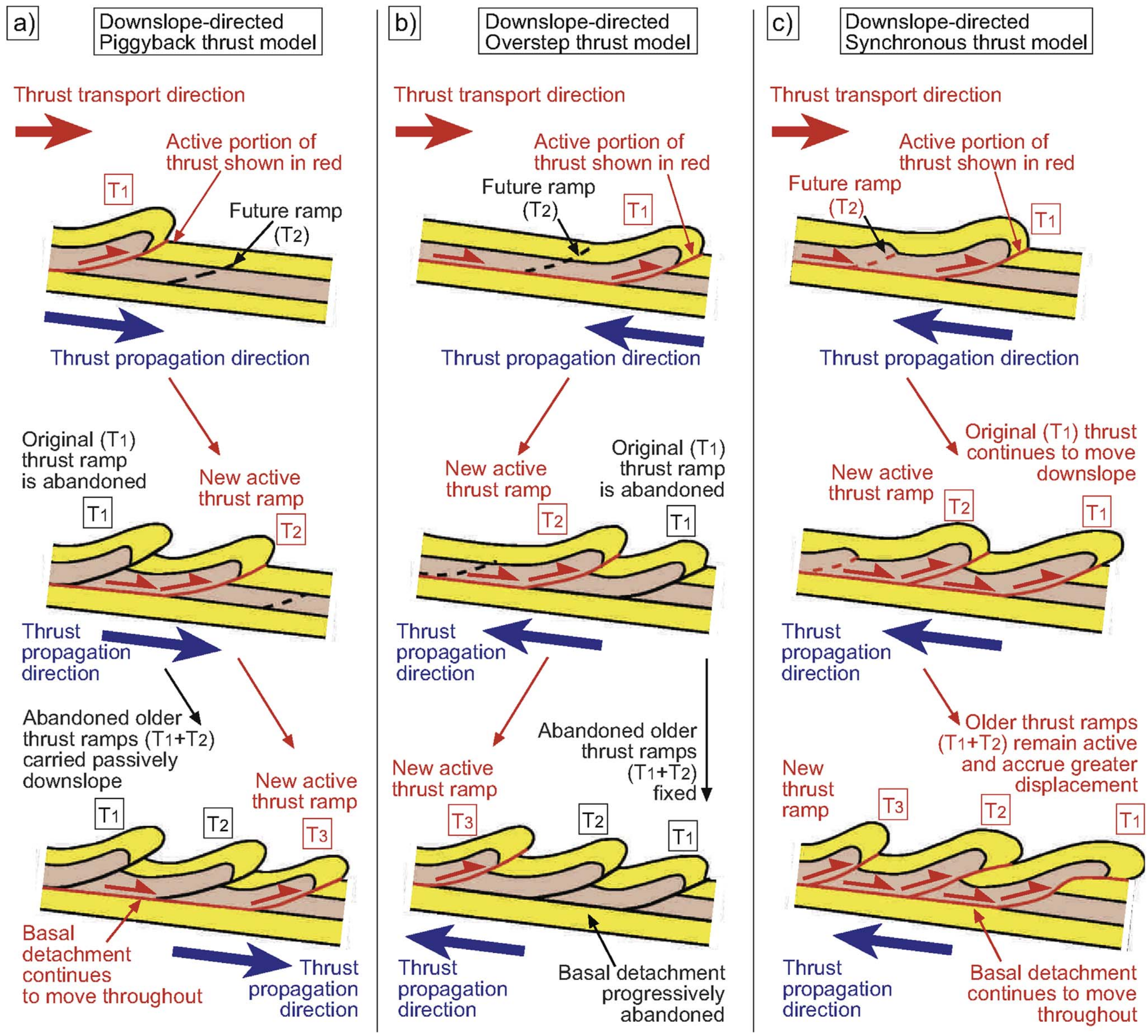

Fig. 1. Schematic illustrations of sections across a) piggyback, b) overstep and c) synchronous thrust sequences in a downslope-directed mass transport deposit (MTD). In c), a thrust system that initiates in an overstep sequence subsequently undergoes continued synchronous thrusting. In each case, thrusts (T) are numbered in the order of development (T1, T2, etc.) and are shown in red where active and black where inactive, while the direction of thrust transport (large red arrow) and overall thrust propagation (blue arrow) are also highlighted. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Gross age relationships of gravity-driven fold and thrust belts may be discernible on seismic sections where the ages of strata within, and overlying, an MTD may be determined (e.g. Bull et al., 2009; Morley et al., 2011; Peel, 2014; Reis et al., 2016; Cruciani et al., 2017). Overlying strata that display onlap relationships onto structures and bathymetry created by the MTD are particularly useful in bracketing the timing of thrust movement (e.g. Frey-Martinez et al., 2005; Jolly et al., 2016; Scarselli et al., 2016). A number of seismic studies tentatively interpret piggyback sequences within gravity-driven fold and thrust belts based on "increasing (thrust) dips back up the regional slope" (de Vera et al., 2010, p.229), or " back rotation and straightening of inner, older thrust ramps" (Scarselli et al., 2016, p.168), with older thrusts considered to be steepened-up by new thrusts forming in their footwall. However, despite improvements in seismic imaging, the resolution still does not typically permit detailed cross-cutting relationships between individual thrusts and folds within imbricate sequences to be clearly determined. Indeed, some authors stress that numbering of thrusts on seismic sections does "not imply a sequence of formation" (Butler and Paton, 2010, p.7), while Frey-Martinez et al. (2006, p.591) stress that it is not possible to give a definitive direction of thrust propagation. Thus, within many natural gravity-driven systems associated with MTDs, there remains significant uncertainty as to the order of development of thrust sequences.

Field-based studies of ancient MTDs may provide further information about styles of deformation (e.g. Woodcock, 1976a, b; 1979; Ortner and Kilian, 2016; Korneva et al., 2016) and the sequence of thrust development (e.g. Lucente and Pini, 2003; Sharman et al., 2015; Sobiesiak et al., 2017), although they may be complicated by the effects of later regional tectonism that frequently masks original relationships generated during MTD emplacement. In addition, although such outcrop-based work enables small-scale details to be ascertained (e.g. Gibert et al., 2005; Garcia-Tortosa et al., 2011; Basilone, 2017), it is sometimes limited by the nature and extent of good exposures, with Ireland et al. (2011, p 34) noting only "rare opportunities to study the geometry of internal deformation (within) submarine landslides". Martinsen and Bakken (1990, p.162) examined onshore exposures of Carboniferous