Slide Stacking: A new mechanism to repeat stratigraphic sequences during gravity-driven extension

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ABSTRACT

Gravity-driven sliding of sediments down subaqueous slopes results in mass transport deposits (MTDs) recognised both in outcrop studies and from offshore margins where they may extend for 100’s km. While seismic sections may reveal the large-scale geometry of such features, they fail to capture some of the structural and stratigraphic detail necessary for a fuller understanding of the processes involved. Using the late Pleistocene Lisan Formation sediments exposed around the Dead Sea Basin as our case study, we show that interplay between bed-parallel translational slides and associated normal faults may result in stratigraphic repetition through a process we term ‘slide stacking’. This mechanism, where retrogressive slope failure results in slides cutting across earlier normal faults, produces repeated sequences with older over younger stratigraphic relationships more usually attributed to compressional (thrust) deformation. Slide stacking results in a ~25% attenuation of the upper sequence above the basal shear surface (BSS), which is itself associated with liquefaction and fluidised sediment. The displaced stratigraphy above the BSS is also marked by sedimentary rafts that are broken into blocks by normal faults and become increasingly separated from one another during downslope translation. The hangingwalls of synthetic listric faults form roll-overs that are progressively tightened towards the underlying BSS to create overturned anticlines that apparently verge upslope. The paradoxical situation therefore arises of contractional geometries, such as older over younger stratigraphic repetition across slides, and upslope-verging recumbent anticlines with locally overturned limbs being created during downslope-directed gravity-driven extension. The downslope margin of the slide stack displays earlier normal faults that created scarps where much of the sedimentary buttress, that would otherwise support the toe of the slide, was removed. Consequently, this leads to predominantly superficial and unrestrained downslope slipping, resulting in very localised contractional geometries that do not balance the overall extension, as in classical gravity-failure models. Localised deformation of the sedimentary sequence that unconformably overlies the slide stack indicates that downslope translation continued after the initial rapid slope failure, suggesting that the entire MTD remained inherently unstable. Slide stacking operates at km scales with stratigraphic repetition governed by the throw of earlier normal faults and the amount of downslope translation.

1. Introduction

The significance of submarine slides and their recognition in the geological record have been of interest to geologists for many decades with McCallien (1935) and Jones (1939) among the earlier workers who describe details of deformation associated with slumping and sliding of unconsolidated sediments. The onset of high-resolution seismic sections from offshore continental margins has enabled the recognition of large-scale slides that transfer sediment downslope to form mass transport deposits (MTDs) (e.g. Armandita et al., 2015; Reis et al., 2016; Scarselli et al., 2016; Jolly et al., 2016; Morley et al., 2011, 2017; Huhn et al., 2020; Steventon et al., 2019; Alves et al., 2022; Maduna et al., 2022; Assis et al., 2024; Olobayo and Huuse, 2024 for recent reviews). However, many details of slides are still not resolvable on such seismic profiles and analysis of sub-seismic scale deformation (typically <10 m, see Pei et al., 2019; Alves et al., 2022, p.364), has therefore developed at
outcrops (e.g. Woodcock, 1976a; b; Gibert et al., 2005; Garcia-Tortosa et al., 2011; Sharman et al., 2015; Korneva et al., 2016; Sobiesiak et al., 2017; Cardona et al., 2020; Rodrigues et al., 2020; Claussmann et al., 2023). The study of sub-aqueous slump and slide sheets is important not only for understanding of sediment movement in basins, but is also critical to infrastructure projects, such as pipelines and cables, that are vulnerable to hazards associated with downslope movement of sediment (e.g. Piper et al., 1999; Thomas et al., 2016; Mosher et al., 2010; Lin et al., 2010; Carter et al., 2014).

Outcrop studies focusing on the origins and evolution of subaqueous slides yield the most insightful results where a viable mechanism to trigger slides, such as seismic activity, is present. These studies are further enriched by clear stratigraphic controls and well-defined or easily inferred sedimentary basin geometries. Where such constraints are satisfied, as in the present study, our objective is to formulate new models for sedimentary slides that develop existing known relationships. It is important to clarify that our work does not aim to comprehensively review the phenomena of slides and slumps. However, it is worth noting that the terms slide and slump have been used in different ways by engineers and geologists (see a short review of this by Woodcock, 1979), and it is therefore prudent to highlight the main differences.

1.1. Key attributes and terminology of gravity-driven slump and slide sheets

Mass transport deposits (MTDs) is an overall term used to describe sediments that have undergone gravity-driven downslope movement and includes sliding, slumping, creep and flow processes (e.g. Posamentier and Martin, 2011). There is no restriction on the scale of sedimentary slides and MTDs, with downslope extents generally ranging from metres to 10 km (e.g. Woodcock, 1979) and exceptionally for 100 km (e.g. Fig. 2 in Alves et al., 2022, p. 365). Downslope movement of sediments may occur on slopes as little as 0.25° (Field et al., 1982) with Stow (1986, p. 402) noting “these processes are very widespread on slopes greater than about >0.5°”.

1.1.1. Distinctions between slump and slide sheets

The distinction between slumps and slides has been drawn by numerous authors, with a recent definition by Shanmugam (2020, p.64) being “A slide represents a coherent translational mass transport of a block or strata on a planar glide plane (shear surface) without internal deformation. A slump represents a coherent rotational mass transport of a block or strata on a concave-up glide plane (shear surface) with internal deformation.” (Fig. 1a and b). The distinction is therefore largely based on the amount of internal deformation with Tucker (2003, p.129) summarising this as “where there is little internal deformation of the sediment mass … then the transported mass is referred to as a slide” (Fig. 1a) whereas “where the sediment mass is internally deformed during downslope movement” then it is referred to as a slump (see also Stow, 1986, p.402) (Fig. 1b). In general, slumps are distinguished from sediment flows by the development of discrete sheets and folds within the slumped unit. Some MTDs contain elements of both slumps and translational slides (see Martin, 1994; Posamentier and Martin, 2011) in that bedding is largely intact but is strongly deformed, generally with contractional folds and thrusts (e.g. Sharman et al., 2017, p.7).

1.1.2. Orientation and geometry of slump and slide sheets

Slides are in general translated above a distinct basal shear surface (BSS) (e.g. Martin, 1994, p. 152) (Fig. 1a). The BSS in translational slides is inclined parallel to the surface slope and slabs of poorly lithified sediment move downslope above it (e.g. Coleman and Prior, 1988, p. 105; O’Leary and Laine, 1996). As the slope and bedding have similar orientations, then slide planes develop parallel to stratigraphy, making their identification potentially difficult (Fig. 1a).

Some authors make a distinction between geometries associated with different types of translational and rotational slides/slip sheets that form above listric faults (e.g. see Posamentier and Martin, 2011, p.5) (Fig. 1). Allen (1985, p.160) notes that translational slides are “very long compared to their thickness and surmount an essentially planar, slope-parallel glide surface”. Alternatively, rotational slides (or slumps) that are developed above concave up slide planes represent a smaller relative downslope movement (Allen, 1985, p.160) with submarine slumps showing thickness to downslope length ratios of 0.12–0.25 (i.e. a 10 m thick package of sediment above the listric slide surface (BSS) may be expected to extend for between 40 m and 83 m downslope). Translational slides are therefore a very efficient mechanism to transport sediment downslope into the deeper basin.

1.1.3. Basal shear surfaces and fluid pressure beneath slump and slide sheets

The BSS that are widely recognised beneath slump and slide sheets are generally parallel to bedding in the underlying undeformed sequence, forming the footwall to the sheet (e.g. Sobiesiak et al., 2018; Cardona et al., 2020). The overall geometry of the BSS may remain subsurface to create ‘frontally confined’ MTDs, or may ramp upwards to the surface to form ‘frontally emergent’ MTDs that are generally associated with greater downslope displacements (e.g. Frey-Martínez et al., 2006; Sobiesiak et al., 2018 for a review). The interaction of the BSS with the underlying stratigraphy has been further categorised into ‘free-slip’ flows where there is no, or only very limited, erosion or deformation of the substrate, and ‘no slip’ flows where more significant erosion and deformation occurs in the footwall of the slide (e.g. Sobiesiak et al., 2018, their Fig. 2).

The role of fluids, and in particular increases in pore fluid pressure that reduce the shear strength of sediments thereby allowing slope failures to develop, has been well documented from both outcrop and...
seismic sections (e.g. Maltman, 1994a, b and references therein: Chapron et al., 2004; Ogata et al., 2012; Wu et al., 2021; Crutchley et al., 2022; Olobayo and Huuse, 2024). Slides and slumps with long runout distances are generally considered to ‘ride’ or hydroplane on a seam of sediment with greater fluid pressure (e.g. see reviews in Ogata et al., 2014; Sobiesiak et al., 2018).

1.1.4. Types of internal deformation within slump and slide sheets

It is generally accepted that the upslope head of a slope failure is marked by extension, while the downslope toe is associated with contraction marked by folding and thrusting, (e.g. Lewis, 1971; Farrell, 1984; Alsop and Weinberger, 2020; see recent review by Scarselli et al., 2020). However, the exact nature of the deformation varies between slumps and slides.

Slump sheets are generally deemed to form coherent units with considerable internal deformation that includes discrete non-pervasive shear (e.g. Martinse, 1994, p.128) (Fig. 1b). Conversely, lithological units and beds within slide sheets remain intact and are “recognizably similar to the parent deposits in terms of stratigraphy and details of bedding” (Allen, 1985, p.159) (Fig. 1a). Structurally intact and tabular sheets of displaced sediment have also been termed ‘slide slabs’ by Booth et al. (2002, p.19). Within translational slides, the bedding may be tilted and rotated in hangingwall anticlines adjacent to fault planes, but is “not deformed as a direct response to simple shear or buckling” (Martinse, 1994, p.152). However, Martinse (1994, p.153) also recognises that layer-parallel slip may create folds within the translated mass, although they are still termed slumps as “the main part of the bedding is retained in its original configuration”. The downslope toe of some slides is marked by thrusts that accommodate shortening (e.g. Posamentier and Martinse, 2011, p.5), while the upslope head displays normal faults (Fig. 1a).

However, the retention of essentially continuous and undeformed bedding means that imaging of slides in seismic sections is frequently marked by high amplitude continuous reflectors (e.g. Moscardelli and Wood, 2008, p.76). The general lack of internal deformation within translational slides makes their recognition more difficult at outcrop and in seismics when compared to slump sheets.

In summary, identifying slides poses a greater challenge than recognising slumps due to the bed-parallel nature of slip surfaces, and the lack of internal deformation such as folds and thrusts. Slides are classified into two types: rotational, characterised by limited movement, and translational. The latter’s identification is crucial as translational slides can obscure large displacements with consequent effects on infrastructure and sediment redistribution in basins.

2. Models for stratigraphic repetition across slide sheets

Repetition of sequences during gravity-driven deformation of sediments is generally assumed to correspond to thrusting and contraction, most typically observed in the downslope or ‘toe’ area of MTDs (e.g. Martinse and Bakken, 1990; Scarselli et al., 2020; Alves et al., 2022).
However, gravity-driven collapse of sedimentary sequences in subaqueous or subaerial settings may create repetition of strata by one of three general mechanisms outlined below (Fig. 2). All of these models assume that displacement is directed downslope under the influence of gravity and that deformation occurs at, or close to, the sediment surface. The models also assume that, although stratigraphy is repeated, it remains essentially the correct way-up, meaning that scenarios involving recumbent isoclinal folds with inverted limbs can be discounted in this case.

2.1. Slab stacking model

Slab stacking develops where a gently dipping extensional detachment cuts through a more steeply inclined sedimentary sequence, resulting in older beds above the detachment being displaced downslope and repeated over younger beds beneath it (Fig. 2a–c). This model is long established with Harrison and Falcon (1934, p.533, 537, their Fig. 3g) describing “slip slabs” where competent beds are repeated as they slide downslope off anticlinal crests in the Zagros Mountains of Iran. More recently, Roberts and Evans (2013, their Fig. 12, p. 694) examined a sub-aerial landslide in the Zagros and show up to nine bed-parallel slide surfaces that locally ramp up through stratigraphy to create ‘stacked sliding plates’. Slide surfaces are recognised at different stratigraphic levels, with the BSS migrating downwards through the failed sequence in an upslope direction (Roberts and Evans, 2013, p. 695). No repetition of stratigraphy across slides was recognised by Roberts and Evans (2013), who suggested that slides were initially formed during flexural slip associated with compression and creation of the anticlines, with slide planes subsequently utilised and reactivated by gravity-driven landslides facilitated by earthquakes and high fluid pressures. The slab stacking model with extensional faults has also been considered in other orogenic belts, including the French Alps (Graham, 1981) and more recently in the Tunisian Atlas, where km-scale gravity-driven folds are thought to develop off regional anticlinal culminations (Amamria et al., 2023).

2.2. Thrust stacking model

Thrust stacking forms where a gently-dipping thrust fault carries a sedimentary sequence in its hangingwall up and over the same succession exposed in the footwall of the thrust, resulting in older beds above the thrust being translated and repeated over younger beds beneath it (Fig. 2d–f). Although thrust models are long established in orogenic belts (e.g. Willis, 1902; Peach et al., 1907; Elliot and Johnson, 1980; Boyer and Elliot, 1982), they have only been applied to the gravity-driven movement of sediment on passive margins in the past 40 years or so (e.g. see reviews in Morley et al., 2011; Scarselli et al., 2020). In such gravity-driven slope failures, thrusts are typically recorded in the downslope ‘toe’ of the failure where contraction is assumed to balance and broadly equate to the amount of extension preserved in the upslope ‘head’ region of the slide. However, detailed analysis of seismic sections frequently reveals that extension and contraction fail to match another, with this imbalance attributed to a range of factors including distributed ‘sub-seismic’ scale strain ultimately related to grain-scale deformation and de-watering (see discussion in Steventon et al., 2019).

2.3. Slide stacking model

Slide stacking is created where a bed-parallel slide cuts across an earlier downslope-dipping (synthetic) normal fault and translates the footwall of the normal fault over its own hangingwall. This results in older beds above the slide being displaced and repeated over younger beds beneath it (Fig. 2g–i). Although the concept of bed-parallel slide has long been associated with flexural slip folding (e.g. see review by Delogkos et al., 2022; Nabavi et al., 2020), it is also increasingly suggested to occur during gravity-driven deformation of sediments (e.g. Shillington et al., 2012; Alsop et al., 2020a, 2023). As the slide cuts across the earlier fault scarp created by the previous failure, there is little downslope support or ‘buttress’ and the slide propagates upslope away from this failure. Upslope propagation of the slide leads to extensional strain, with little contraction at the leading edge due to the lack of the supporting downslope wall. This failure model is therefore a variant of that suggested by Farrell (1984), where a significant domain of downslope contraction was developed at the downslope termination. We are unaware of the slide stacking process being described in the literature previously and therefore believe this to potentially be a new mechanism to explain stratigraphic repetition in basins.

2.4. Aims of research

Having outlined the different models of stratigraphic repetition, we now examine a case study of a sedimentary slide that formed in late Pleistocene sediments around the Dead Sea Basin. Our aim is to answer some fundamental research questions pertaining to gravity-driven slides in sub-aqueous settings.

a) What key characteristics distinguish the different structural stacking models?
b) Which stacking model best fits the observations from the Dead Sea case study?
c) What is the structural evolution during gravity-driven stacking?
d) How does the thickness and extent of slide sheets compare with other settings?
e) How are ‘contractional’ features and fault-bounded blocks created during extension?
f) Do slides continue to move after original slope failure?

3. Regional geology

3.1. Regional geology

The Dead Sea Fault (DSF) system bounds the Dead Sea Basin and comprises the left-lateral eastern border fault and the western border fault zone, which incorporates a series of oblique-normal stepped faults (Fig. 3a and b) (Marco et al., 1996, 2003; Ken-Tor et al., 2001; Migowski et al., 2004; Begin et al., 2005). These bounding faults have generated numerous earthquakes that trigger deformation of the basin-fill sediments and were active from the Early Miocene to Recent (Nuriel et al., 2017). Our study investigates slides developed in the Lisan Formation that was deposited in Lake Lisan at 70–14 ka, and formed a pre-cursor to the modern Dead Sea (e.g. Haase-Schramm et al., 2004) (Fig. 3a and b). The Lisan Formation comprises mm-scale aragonite laminae that precipitated from hypersaline waters during the summer, while detrital-rich layers, consisting of quartz and calcite grains with minor feldspar and clays (illite-smectite), were washed into the lake during sporadic winter floods (Begin et al., 1974; Ben-Dor et al., 2019; Haliva-Cohen et al., 2012). Thin detrital laminae are formed of fine-grained silt (with ~8–10 μm grain sizes), whereas thicker (~10 cm) detrital-rich beds deposited after major floods are composed of very fine (60–70 μm) sands (Haliva-Cohen et al., 2012).

The Lisan Formation contains a variety of deformed units associated with seismically-triggered sediment failure down very low-angle (~1°) slopes towards the depocentre of the basin. Gypsum horizons up to ~1 m thick are also precipitated within the Lisan Formation and are considered the result of mixing and overturn of the water column following major earthquakes (Ichinose and Begin, 2004; Begin et al., 2005). Seismically-triggered downslope movement creates MTDs that collectively define a radial pattern of regional slumping towards the depocentre of the basin (Alsop et al., 2020b) (Fig. 3b and c). Thus, westerly-directed slumping has been reported from the Lisan Formation on the eastern shores of the Dead Sea in Jordan (El-Isea and Mustafa, 1986), while east and ENE-directed movement is recorded from the
(caption on next page)
western margin of the Dead Sea (Fig. 3b and c). Directions of MTD movement are corroborated by magnetic fabrics in the Lisan Formation (Weinberger et al., 2017, 2022; Levi et al., 2018), which is thought to have been weak and fluid saturated at the time of failure and presently retains ~25% fluid content (Arkin and Michaeli, 1986; Frydman et al., 2008).

3.2. Rationale of the study area

Lacustrine settings containing laminated sequences represent the ideal situation to investigate slide systems because.

a) Lacustrine sequences may comprise a refined varved stratigraphy that permits the structural detail of slides to be recognised. Isotopic dating, combined with the counting of aragonite-detrital couplets, reveals average depositional rates of ~1 mm per year that records intricate deformation in the Lisan Formation (Prasad et al., 2009).

b) Slide planes are more likely to form in thinly-bedded heterogeneous sequences comprising both weaker and more competent units as developed in lacustrine sequences. Analysis of deformation within the Lisan Formation shows that detrital-rich beds tend to form more competent units, whereas aragonite-rich layers are relatively weak (e.g. Alsop et al., 2017, 2020c).

c) Pronounced bathymetric changes within lakes associated with deep basins generates greater potential for gravity-driven downslope sliding of the sedimentary pile.

The Dead Sea Basin therefore represents an ideal place to study slides and associated structures as numerous earthquakes along the DSF trigger sediment failure, while the regional slopes and bathymetry of the Dead Sea impose a clear kinematic framework to MTD movement (Fig. 3c). The bulk downslope transfer of sediment from the basin margins towards the centre results in the Lisan Formation being three times thicker in the depocentre, where drill cores penetrate numerous MTDs (Lu et al., 2017, 2021a, 2021b, 2021c; Kagan et al., 2018). The best sections for outcrop analysis of slides are preserved around the margins of the basin where the 31–15 ka finely-laminated upper ‘White Cliff’ portion of the Lisan Formation is well-exposed (Bartov et al., 2002; Torfstein et al., 2013).

3.3. Styles of deformation and the Miflat Slide

Various types of deformation occurred at a range of different depths below the depositional surface of the Lisan Formation and are listed below.

a) Deformation at the sediment surface results in MTDs that are directly overlain by sedimentary caps deposited out of suspension following the slope failure, i.e. there is a sedimentary ‘signature’ comprising an homogeneous and sometimes graded bed linked to the deformation (Alsop et al., 2018, 2020d).

b) Deformation in the shallow (<1 m) sub-surface results in Fold and Thrust Systems (FATS) that are bound by detachments that may still directly influence sedimentation at the surface (Alsop et al., 2021a, 2021b, 2022a).

c) Deformation at depths of up to 20 m below the surface (the thickness of the hosting White Cliff strata) creates intrastratal FATS and bed-parallel detachments or slides (Alsop et al., 2020a, 2022a). This depth of deformation means that it has little effect on sedimentary patterns.

d) The gravity-driven structures (noted above) are cut across by a suite of seisimically-triggered clastic dykes (e.g. Levi et al., 2006a, b). Sediment contained within the injected dykes gives ages of between 15 and 7 ka (Porat et al., 2007), confirming that they post-date deposition and deformation of the 31–15 ka upper White Cliff member of the Lisan Formation (Haase-Schramm et al., 2004; Torfstein et al., 2013).

e) Late-stage deformation linked to co-seismic shaking at depths of up to 20 m below the surface generates bed-parallel slip surfaces recognised by displaced clastic dykes and marked by 2–10 mm thick layers of gouge (Weinberger et al., 2016).

Our case study is located ~1–2 km east of the Dead Sea western border fault zone in the Miflat area [N31°:21.42′ E35°:22.49′] where the well-exposed Lisan Formation is overlain by a Holocene alluvial fan (Fig. 3a–f). In this area, wadis have locally incised into the Lisan Formation to reveal a newly-discovered spectacular example of a slide sheet, here named the Miflat Slide (Fig. 3g and h). At the time of deposition and creation of this slide, the area was marginal to Lake Lisan, with estimated water depths of <100 m, and up to 200 m between 26–24 ka (Bartov et al., 2002, 2003). Previous analysis of NWN-SEE trending fold hinges at Miflat, together with bed-parallel slip surfaces, indicate MTD transport towards the ENE (~075°) and the centre of the basin (Alsop et al., 2020a, 2022) (Fig. 3d and e). Modern drainage flows downslope broadly parallel to the earlier MTD and slides, thereby providing excellent transport-parallel sections through the slide sheet exposed along the vertical canyon walls (Fig. 3g and h). The use of a UAV (drone) allows detailed high-resolution photography orthogonal to inaccessible cliff sections, thereby allowing correlation of stratigraphic units across hundreds of metres. We now describe the geometry and key relationships of the Miflat Slide that enable us to test the various models for stratigraphic repetition across slide sheets.

4. Key characteristics of the Miflat Slide

We here present details of some of the main structural and stratigraphic observations from the Miflat Slide (Fig. 3). All outcrop photographs are oriented such that the downslope (eastern) direction is on the right-hand side of the image, with scale provided by a 1 m long pole, or 10 cm long chequered rule, while the location of photographs is shown on Fig. 3g and h and also noted in figure captions.

4.1. Basal shear surface and fluidised sediment along the slide plane

The Miflat Slide can be confidently traced for >500 m downslope (Fig. 3g and h). This represents a minimum extent for the BSS as erosion in modern wadis has not yet incised deep enough to reveal its upslope
4.2.4. Attenuation of stratigraphic sequences above the slide plane

The repetition of stratigraphy across the Miflat Slide noted above is marked by a relative thinning and attenuation of the upper sequence when compared to the equivalent stratigraphy below the slide plane (e.g. Fig. 5a, b, 6). As the intact footwall stratigraphy below the slide is little deformed, it is considered to be unmoved and preserves the original thickness, while the hangingwall sequence is therefore considered to have undergone attenuation. As individual beds are still clearly correlated across the slide plane (e.g. Fig. 6d–h), it is considered that attenuation was accomplished via bed-by-bed thinning, i.e. no actual units are cut out. Thinning may be achieved by independent particulate flow where grains move relative to one another during hydroplastic deformation, and which varies with composition and grain size (e.g. Alsop et al., 2020c, p. 82; Balaban-Fradkin et al., 2022). The reduction in hangingwall thickness varies from 13%–33%, depending on which sections of stratigraphy are used, but with an overall average attenuation of the hangingwall sequence of ~25% (Fig. 5a and b, 6d–h).

4.3. Luristic faults and ‘roll-overs’ detaching on the slide plane

4.3.1. Antithetic and synthetic luristic normal faults

Examples of luristic normal faults that detach downwards into the underlying BSS are widespread above the Miflat Slide. Luristic faults may be antithetic (i.e. they dip towards the upslice direction) (Fig. 7a–e) or synthetic where they dip towards the downslope movement direction (Fig. 7f, g, 8a–f). Antithetic luristic faults dip towards the west with the hangingwall, dropping down relative to the footwall that is moving downslope towards the east (i.e. an upslice-dipping normal fault does not indicate that the hangingwall is moving upslope – see discussion of faults in Alsop et al., 2017). Rotation of beds above the luristic fault may generate localised gravity-driven folding in the hangingwall to the fault (Fig. 7a–e). Tension in the extended hangingwall also results in fractures
Fig. 4. a) General view of repeated sequences and fluid escape structures along the Miflat Slide within the Lisan Formation. Location of Fig. 4a) shown on Fig. 3g [N31°21’27.6 E35°22:36.7]. b) The Miflat Slide sheet is overlain by an unconformity and undeformed beds with a competent gypsum horizon that caps the cliff. c) Photograph and d) associated line drawing showing details of the basal shear surface (BSS) to the Miflat Slide, together with the repeated detrital marker unit and fluid escape structures. e) Detailed close-up photograph of colour-coded repeated sequences and fluid escape structures along the Miflat Slide. Note the ‘double unconformity’ with the lower unconformity (1) being arched up by fluid escape, while the younger unconformity (2) cuts across the older unconformity (1) and structures. f) Photograph and g) associated line drawing showing mobilised and injected sediment along the basal shear surface (BSS) of the Miflat Slide. Location of Fig. 4f) shown on Fig. 3g [N31°21°27.6 E35°22:36.7]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 5. a) Photograph and b) associated line drawing showing colour-coded repeated sequences across the basal shear surface (BSS) of the Miflat Slide. Note that the upper sequence is thinned and attenuated and is overlain by an unconformity and a gypsum cap at the top of the section. Location of Fig. 5a shown on Fig. 3g [N31°21′31.5 E35°22:45.0]. c) Photograph and d) associated line drawing showing fluidised and injected sediment along contractional thrusts formed in the footwall to the Miflat Slide (location of photograph shown in b). Photographs e, f, g) show details of individual sediment injections sourced from detachments (locations shown in d). h) Photograph of fluidised and injected sediment along extensional normal faults formed in the footwall to the Miflat Slide. Location of Fig. 5h shown on Fig. 3g [N31°21′32.4 E35°22:42:5]. i) Photograph and j) close-up of injected sediment ‘ponding’ at the intersection of normal faults and detachments below the Miflat Slide. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 6. a) Photograph and b) associated line drawing showing colour-coded repeated sequences across the basal shear surface (BSS) of the Miflat Slide. Location of Fig. 6a) shown on Fig. 3g [N31°21’31.8” E35°22’41.9’]. c) Photograph showing repetition of colour-coded stratigraphy and MTD across the BSS. The overlying unconformities (1, 2) are highlighted in yellow and merge together across raised blocks and rafts of repeated competent strata. Photographs d-h) show details of colour-coded repeated stratigraphy and duplicated MTDs, together with attenuation and normal faulting of the sequence above the slide. Note the development of NE-verging slump folds above the unconformities. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 7. a) Photograph showing colour-coded repeated sequences and antithetic normal faults above the basal shear surface (BSS) of the Miflat Slide. Location of Fig. 7a shown on Fig. 3g [N31°21':31.3 E35°22:46.3]. b) Photograph and c) associated line drawing showing details of the antithetic listric fault detaching on the underlying basal shear surface (BSS) to the Miflat Slide, d) Detailed close-up photograph and e) line drawing of colour-coded repeated sequences and roll-over anticline above the listric fault. f) Photograph of synthetic normal fault above the basal shear surface (BSS) of the Miflat Slide (with inset line drawing). Location of Fig. 7f shown on Fig. 3g [N31°21':31.5 E35°22:45.5]. g) Photograph showing details of the colour-coded repeated stratigraphy and duplicated MTDs, together with the synthetic listric fault creating a roll-over hangingwall anticline above the BSS. The slide sheet is overlain by unconformities (in yellow) and later slumps. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
and injections of fluidised sediment, presumably sourced from the underlying BSS (Fig. 7a–e). The footwall to the listric faults is highly mobilised and filled with ‘mixed’ sediment that lacks the clear stratigraphy of the hangingwall (Fig. 7a–e). Synthetic listric faults dip towards the east with the hangingwall moving downslope. The listric fault shape results in hangingwall anticlines or ‘roll-overs’ that are locally cut across by low angle normal faults and detachments (Fig. 7f and g). Both the antithetic and synthetic listric faults detach on the BSS and cut the attenuated stratigraphy that has been repeated above the slide plane to create roll-over anticlines in the hangingwall to the normal faults. The well-defined stratigraphy maintains its thickness around the roll-over anticlines, indicating that the listric faults are not syn-depositional ‘growth geometries’, but rather post-depositional structures. The listric faults are cut across by the overlying unconformity, indicating that they formed during movement on the Miflat Slide.

3.4.2. Fault-related folding above the slide plane

As noted above, roll-over anticlines are commonly developed above both antithetic and synthetic listric normal faults. Above some synthetic listric faults, roll-over beds dip upslope with enhanced westerly-dips that may locally become overturned next to the BSS (Fig. 8a–e). Such localised areas of overturn are of significance as listric normal faults that may locally become overturned next to the BSS (Fig. 8a–e). The footwall to the listric faults is highly mobilised and filled with ‘mixed’ sediment that lacks the clear stratigraphy of the hangingwall (Fig. 8a–e). Synthetic listric faults dip towards the east with the hangingwall moving downslope. The listric fault shape results in hangingwall anticlines or ‘roll-overs’ that are locally cut across by low angle normal faults and detachments (Fig. 7f and g). Both the antithetic and synthetic listric faults detach on the BSS and cut the attenuated stratigraphy that has been repeated above the slide plane to create roll-over anticlines in the hangingwall to the normal faults. The well-defined stratigraphy maintains its thickness around the roll-over anticlines, indicating that the listric faults are not syn-depositional ‘growth geometries’, but rather post-depositional structures. The listric faults are cut across by the overlying unconformity, indicating that they formed during movement on the Miflat Slide.

4.4.2. Disarticulated and folded blocks

It is frequently observed from seismic and outcrop analysis that MTDs may locally disintegrate into a series of jumbled blocks from the metre (e.g. Ogata et al., 2012; Sobiesiak et al., 2016b, 2020) to km scales, where they are termed ‘mega-clasts’ (e.g. Lia et al., 2023). Within the Miflat Slide, the repeated sequence from above the BSS is broken up into distinct ~ metre-scale blocks that are disarticulated and locally folded (Fig. 10). The stratigraphy within the blocks correlates with the sequence established from elsewhere within the slide sheet and demonstrates that some blocks and folds become locally overturned (Fig. 10a–e). In this area, the Miflat Slide sheet is > 5 m thick and rides on a locally exposed BSS (e.g. Fig. 10f–i) associated with NE-verging folds that detach on the slide plane (Fig. 10g and h). The upper contact of the slide is overlain by the same two unconformities recognised elsewhere (Fig. 10). The lower unconformity is erosive and locally drapes over blocks and also truncates folded beds in underlying clasts (e.g. Fig. 10a–e). A series of striped laminated beds (with thin detrital marker) forms above the unconformities and directly below the gypsum cap, and is similar to that observed elsewhere above the Miflat Slide. Disarticulated blocks are only developed in the sequence above the BSS, indicating that the creation of blocks occurred after the sequence had been repeated above the Miflat Slide and before the overlying erosive unconformity developed. The location of the jumbled blocks within the slide sheet itself (Fig. 3g) is consistent with sidewall collapse and potential lateral shears within the MTD representing differential downslope movement (e.g. Alsop et al., 2020d).

4.5. Toe of the Miflat Slide

The downslope limit of the repeated section above the Miflat Slide is marked by synthetic (E-dipping) normal faults that are truncated by the underlying BSS (Fig. 11a–c). The normal faults downthrow stratigraphy in their hangingwalls, including a thicker detrital bed that contains downslope-verging folds, and are cut across by the overlying unconformity (1) (Fig. 11a–c). The competent detrital unit that is recognised in the repeated sequence elsewhere above the BSS further to the west is no longer present downslope of the normal faults. This downslope area comprises a NE-verging fold and thrust culmination formed in argonite-rich sediments over a distance of 5–10 m (Fig. 11c–e). The fold and thrust stacking develops above the BSS and causes unconformities (1) and (2) to arch up and converge over the culmination, suggesting that thrusting had created topography on the lake floor. The overlying gypsum cap remains unaffected by the culmination suggesting deformation in this area had ceased by that stage.

5. Unconformities and structures formed above the Miflat Slide sheet

Slides and slumps are frequently overlain by an unconformable surface and undeformed beds, which are considered to mark the return to ‘normal’ sedimentation. However, detrital beds that are deposited in perched basins above MTDs have been termed ‘ponded turbidites’ elsewhere and, where deformed, they suggest that movement along the underlying MTD had continued (e.g. Sobiesiak et al., 2020). In the Lisan Formation, the upper surface of MTDs and slumps are frequently truncated by an erosive surface, which is itself overlain by a sedimentary ‘cap’ that is considered to be deposited out of suspension from the water column following slope failure (Alsop et al., 2020b, 2020d). Such
Fig. 9. a) Photograph and b) associated line drawing showing colour-coded repeated sequences across the basal shear surface (BSS) of the Miflat Slide. Note that the upper attenuated sequence is cut by conjugate normal faults that create sedimentary blocks that are overlain by unconformities. Location of Fig. 9a) shown on Fig. 3g [N31°21′31.8 E35°22′40.5]. c) Upslope-directed tilting of fault blocks creates local overturning of beds potentially related to shear on the underlying BSS. d, e) Unconformities (1, 2) merging over fault-bound sedimentary blocks, with e) showing minor normal fault cutting the unconformity surfaces. f) Comparison of stratigraphy below the BSS with the same repeated and attenuated sequence shown in e). g) Photograph and h) associated line drawing showing repeated sequences across the BSS with the upper attenuated sequence cut by conjugate normal faults that create sedimentary blocks. Location of Fig. 9g) shown on Fig. 3g [N31°21′30.5 E35°22′44.2]. i) Details of unconformities 1 and 2 draped over the sedimentary blocks created by normal faulting above the BSS. j, k, l) Photographs and m) line drawing of conjugate normal faults. In some cases (l, m), the normal faults also cut the overlying unconformity surfaces indicating continued movement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 10. a, b) General photographs of disarticulated sedimentary blocks formed above the BSS of the Miflat Slide. Location of Fig. 10a) shown on Fig. 3g [N31°21′34.1″ E35°22′41.5″]. c, d, e) Details of the blocks (some of which are folded) and overlain by unconformities (1, 2) that drape over blocks. NE-verging slumps develop above the unconformities. f, g) General photographs of disarticulated sedimentary blocks formed above the BSS of the Miflat Slide. The slide sheet is overlain by the double unconformity. Location of Fig. 10f) shown on Fig. 3g [N31°21′34.0″ E35°22′40.0″]. h) Photograph showing NE-verging fold rooting onto the underlying BSS. i) Details of disarticulated blocks and overlying unconformities. Position of h, i) shown on g).
Fig. 11. a) Photograph and b) associated line drawing showing colour-coded repeated sequences across the basal shear surface (BSS) of the Miflat Slide. Note that the upper attenuated sequence is truncated by normal faults that are themselves cut by the underlying BSS. Location of Fig. 11a shown on Fig. 3g [N31°21'32.4 E35°22'44.1]. c) Details of normal faults cut by the BSS and the fold and thrust culmination developed further downslope. Overlying unconformities and NE-verging slump system extend across the entire sequence. d) Photograph and e) close-up of fold and thrust culmination shown in c). Note that unconformities 1 and 2 converge and arch over the thrust stack. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 12. a) Photograph, and b) associated line drawing of a NE-verging fold and thrust system developed above the unconformity overlying the Miflat Slide sheet. The thrust system displays repetition of beds, folding and thickening of the sequence. Location of Fig. 12a) shown on Fig. 3g [N31°21′:31.1 E35°22′:31.8]. c, d, e, f) Photographs and associated line drawings showing details of repeated thrust sequences that overlie the Miflat Slide sheet and are capped by an unconformity. g) Photograph, h) associated line drawing and i) detailed photograph of sedimentary blocks cut by slides within the Miflat Slide sheet. The blocks are associated with a detrital bed marking the unconformity at the top of the slide sheet.
unconformities and caps are key in demonstrating that deformation occurred at or close to the sediment surface (Alsop et al., 2022a).

5.1. Unconformities above the Miflat Slide sheet

The Miflat Slide is overlain by an unconformity that in some places can be divided into two distinct or ‘double unconformity’ surfaces separated by an intervening package of aragonite- and detrital-rich sediment. The lower unconformity surface (1) truncates normal faults and tilted bedding formed during movement on the slide plane (Fig. 9a-f, 9g-m, 10). This unconformity and overlying sediment drapes and infills blocks and geometries created above the slide. The lower unconformity is most clearly distinguished in the troughs or ‘loows’ between the blocks, and tends to merge with the overlying unconformity (2) over structural ‘highs’ and culminations created by blocks (Fig. 9e-i).

Above roll-over anticlines, the two unconformities are separated by thickened panels of sediment that display minor slump folds verging towards the west down the locally west-dipping limb of the anticline (i.e. opposite to regional dip) (Fig. 8e). Localised East-directed slumping affecting the sediments between the lower and the upper unconformity surfaces also develops above antithetic roll-over folds (Fig. 7d and e).

The two unconformities are draped over and merge above the culmination created by thrusting at the downslope toe of the system (Fig. 11c and d).

The lower unconformity (1) cuts fluid escape structures and ‘diapirs’, indicating that fluid expulsion had largely ceased by the time of erosion and deposition of the overlying sequence. Where the lower unconformity is deflected upwards by fluid escape, it is then cut by the upper unconformity surface (2) (Fig. 4a–e).

5.2. Structures formed above the Miflat Slide sheet

A range of structures are developed in the sequence directly above the unconformities marking the top of the Miflat Slide sheet. These structures, including normal faults and thrusts, are significant as they suggest that some deformation may have continued after the initial slide failure.

5.2.1. Normal faults above the unconformities

While normal faults are ubiquitous in the slide sheet and repeated sequence above the BSS, the majority of these faults are truncated by the overlying unconformities marking the top of the Miflat Slide. However, in some cases unconformities above the slide sheet are cut and offset by normal faults that root downwards and detach on the underlying BSS (Fig. 9).

Synthetic normal faults with a larger (~1 m) displacement separate the repeated stratigraphy into blocks and can be traced across the overlying unconformities (e.g. Fig. 9a–e). The continuation of the fault above the unconformity displays markedly less displacement (<10 cm), suggesting that the fault may have been locally reactivated following deposition of the overlying sequence above the unconformity (Fig. 9e). In other cases, normal faults that root onto the BSS display >2 m displacement where they offset the (repeated) competent unit and also displace the overlying unconformity (1) by >1 m (Fig. 9g-m). The sedimentary package between the two unconformities (1 and 2) is thickened on the downthrown side of the fault as the overlying gypsum cap cuts across the fault and is deflected only slightly (e.g. Fig. 9j-m).

Normal faults rooting onto the underlying BSS are occasionally observed to cut the gypsum cap, suggesting that some localised reactivation of the faults and associated slide may have occurred at a late stage (Fig. 9a–d).

5.2.2. Fold and thrust systems above the unconformities

The beds deposited above the unconformities that overlie the Miflat Slide are deformed by downslope-verging fold and thrust systems (FATS – see Alsop et al., 2018) that affect large parts of the post-slide sequence (e.g. Fig. 6g, h, 7g, 10a-i, 11a-c). The FATS detach on a bed-parallel slide that overlies the unconformities. In some cases, a detrital marker bed above unconformities is transported off the crest of a culmination and is duplicated downslope by a detachment (Fig. 6c–h). This suggests continued downslope movement after the unconformities had formed above the Miflat Slide.

In a case study locality, NE-verging folds and thrusts are exceptionally well-developed above the Miflat Slide (Fig. 12a–i). The slide sheet is associated with disarticulated blocks, some of which created relief on the lake floor resulting in them projecting above the detrital and mixed units that mark the unconformity above the slide (Fig. 12g–i). The overlying fold and thrust system detaches on bed-parallel slides that generally form above the Miflat Slide sheet, and affects the younger sequence deposited after the initial movement of the slide (Fig. 12f–i).

Repetition of beds may occur over 10’s of metres and is marked by thrust imbrications and NE-verging folds that are truncated by a younger overlying unconformity, indicating that the FATS formed at the sediment surface (Fig. 12a–f). A thin undeformed sequence that overlies this younger unconformity is itself followed by the gypsum cap that may be traced along the length of the Miflat Slide, thereby demonstrating correlation of the overlying FATS with the sequence elsewhere.

6. Discussion

6.1. What key characteristics distinguish the different structural stacking models?

Within gravity-driven settings there are three main scenarios that may account for repetition of correct way-up sequences with older over younger stratigraphic relationships, namely the slab stacking, thrust stacking and slide stacking models (Fig. 2). In both the slab stacking and thrust stacking models, the fault plane cuts up across footwall stratigraphy in the downslope direction, whereas in slide stacking, the basal shear surface (BSS) maintains parallelism with the hangingwall sequence and only cuts across footwall stratigraphy where it has been previously offset by normal faults (Fig. 2). The thickness of footwall stratigraphy that the BSS cuts across is dependent on the amount of throw of the earlier normal fault.

Although the hangingwall block is considered to translate downslope in all three models, the direction of propagation of a failure surface is more variable. In the slab stacking and thrust stacking models, the direction of failure propagation is thought to be mostly downslope (Fig. 2a–f). Conversely, we suggest that during slide stacking, BSS failure may initiate in the footwall to the early normal fault close to where it forms an unsupported scarp on the sediment surface, and then propagates mostly upslope beneath a competent marker horizon that traps fluid (Fig. 2g–i). The normal fault scarp creates a buttress or ‘bulldozer’ that scarpes surficial sediments as it moves downslope on the BSS, but is otherwise largely unsupported (Fig. 2g–i).

During thrust stacking, contractional deformation results in repetition of beds associated with minor folds and thrusts, together with layer-parallel compaction and thickening of the hangingwall sequence when compared to the footwall (Fig. 2d–f, 12). Alternatively, extensional deformation associated with slab stacking and slide stacking models is considered to result in a thinning of the hangingwall sequence, which is marked by normal faults and bulk layer attenuation (Fig. 2a–c, g–i). A further difference is that thrust stacking is generally marked by ramps that create imbricates with repeated stratigraphy dipping upslope, whereas slide stacking is associated with repeated sequences that dip gently downslope parallel to the sediment surface (Fig. 2e, f, h, i).

In all three models under consideration, translation of the hangingwall blocks results in a downslope-directed mass transport of significant amounts of material. However, all models are considered to develop close to the ‘free’ sediment surface, meaning that there is no necessity to create large accommodation structures in adjacent sediment. In the slab stacking model, the detachment sheet simply translates down dip and is
accommodated by the overlying free surface further downslope (Fig. 2a–c). The thrust stacking model is marked by a thickening of the hangingwall sequence that raises the overlying ‘free’ sediment surface and thereby builds topography/bathymetry above the thrust stack (Fig. 2d–f). Such bulges and ridges are widely observed features on sea floor scars at the leading edges of MTDs (Martinsen and Bakken, 1990; Frey-Martinez et al., 2006; Bull et al., 2009). Conversely, during normal faulting the ‘free’ sediment surface is considered to be downfaulted and form depressions. In the slide stack model, sediment forming the translated sheet is accommodated by occupying this depressed ‘space’ evacuated by the earlier normal fault (Fig. 2g–i). There is therefore no necessity to thicken the entire sequence, especially as translated slide sheets have already been thinned and attenuated, and slide stacks would not necessarily build topography or bulges on the sediment surface.

The key characteristics noted above provide a list of criteria that may be used to distinguish the different stacking models during gravity-driven deformation in a range of settings. We now consider these models in relation to the Miflat case study.

6.2. Which stacking model best fits observations from the Dead Sea case study?

All of the slab stacking, thrust stacking and slide stacking models outlined above could potentially explain stratigraphic repetition observed across the Miflat Slide. Models must obey and fulfill some key observations and tenets that form the basic premise of applying these models to the case study area.

The assumptions for any model in the case study are.

a) sediment is moving downslope (rather than upslope) under the influence of gravity;

b) a thin upper block forming the hangingwall to the slide has been translated (rather than significant movement of the intact footwall);

c) the hangingwall of the slide cannot be geometrically restored back upslope beyond the steep rift margin fault marked by outcrops of Cretaceous carbonates. As the entrance of the wadi where the slide plane is exposed is 3 km east from the basin margin faults, this provides a maximum limit on slide translation (Fig. 3d and e); and

d) deformation largely occurred prior to the overlying unconformity that cross-cuts some slide-related structures.

We now evaluate the applicability of the three models to the case study.

6.2.1. Slab stacking model

Harrison and Falcon (1936, p.92), working in the Zagros Mountains, described stratigraphic repetition down the limbs of anticlines and originally noted that a slab stack “is a slab of rock which has become detached from its original place on a dip-slope and has slipped down, remaining more or less intact”. They go on to discuss repeated sequences and note that “a drilling would penetrate the formation twice, the beds being both times the right way up”. The slab stacking model assumes that the stratigraphic sequence dips toward the basin at a greater angle than a downslope-directed detachment that progressively cuts across the tilted beds, thereby duplicating stratigraphy (Fig. 2a–c).

There are two main issues in applying the slab stacking model to the Miflat Slide case study. The first problem is that beds in the Lisan Formation dip at < 1° and there is no regional compression or increased basin-ward tilting of the sequence. Indeed, increased basin-ward tilting of the Lisan Formation would itself undoubtedly lead to instability and minor slumping due to the largely unconsolidated nature of the sediments. While this lack of tilting is fundamentally at ‘odds’ with the slab stacking model, the slide plane itself needs to dip even more shallowly than the beds. If the slide plane is inclined at 0.5°, then this would require a distance of 400 m to cut out the 3.5 m of duplicated stratigraphy dipping at 1°. Although there is enough space (2.5 km) back to the basin margin faults that juxtapose the Lisan sediments with the Cretaceous carbonates, the lack of tilting negates this model. The second major problem in applying this model to the case study is that the observed slide plane maintains its stratigraphic position over 500 m across strike, and there is no evidence of progressive footwall cut out as demanded by the model. We therefore reject the slab stacking model as a viable explanation for the Miflat Slide.

6.2.2. Thrust stacking model

Models of thrust stacking and imbrication have long been proposed for orogenic belts (e.g. Peach et al., 1907; Elliot and Johnson, 1980; Boyer and Elliot, 1982), although only since the latter part of the 20th century have such interpretations been applied to fold and thrust systems formed during gravity-driven deformation in passive margin sequences (e.g. see recent reviews in Scarselli, 2020; Scarselli et al., 2022; Yang et al., 2020). It has also been recognised that limestone sheets may locally undergo repetition by thrust stacking in submarine settings (Callot et al., 2008, p.353).

The thrust stacking model assumes that the sequence above the thrust plane has moved up and over the same succession exposed in the footwall of the thrust, thereby duplicating the sequence (Fig. 2d–f).

There are two main issues in applying this thrust stack model to the case study. The first problem is that the hangingwall of the Miflat Slide is dominated by extension marked by normal faults, whereas the thrust stack model generates minor folds and thrusts (Fig. 2d–f). In all other examples of slumps within the Lisan Formation, minor folds and thrusts are ubiquitous, suggesting that it is not mechanically feasible to translate large thrust sheets without smaller imbricates developing (see Alsop et al., 2018). The spacing of thrust ramps compared to the thickness of thrust sheets in the Lisan Formation is generally at a ratio of 5:1 (Alsop et al., 2017, p.101) and it is therefore notable that no thrust ramps have been observed across hundreds of metres of section. The absence of folds and minor thrusts is therefore problematic and suggests that the thrust stack model is not viable in this case. The second major issue in applying this model is that thrust sheets generally undergo lateral compaction (e.g. Alsop et al., 2021b) and are thickened, whereas the observations from the Miflat Slide indicate a ~25% attenuation of the upper sequence. These observations are therefore incompatible with the thrust stack model, which can therefore be discounted for the case study.

6.2.3. Slide stacking model

The proposed slide stacking model assumes that the succession was initially cut by synthetic (downslope-dipping) normal faults that were then displaced by a bed-parallel slide that translates the footwall of the early normal fault over its own hangingwall, thereby duplicating the stratigraphy (Fig. 2g–i). This model is a development from >170 observations of smaller metre-scale repetitions of beds where bed-parallel slip cuts minor normal faults to create ‘sawtooth’ profiles in the Lisan Formation (e.g. Alsop et al., 2020a, 2023) (Fig. 13a–c).

The proposed slide stacking model fits many of the observations from the case study, including.

a) The slide is parallel to sub-horizontal beds and repeats stratigraphic sequences with older over younger relationships.

b) The basal shear surface (BSS) maintains parallelism with the hangingwall sequence and only cuts across footwall stratigraphy where it has been previously offset by normal faults (Fig. 2g–i).

c) The hangingwall of the slide is dominated by extensional faulting and thinning associated with ~25% bed-parallel attenuation. Extension is the same age as the BSS as normal faults root downwards into the slide and are generally cut by the overlying unconformity.

d) The early normal fault offset by the slide creates a scarp or bathymetric front that would affect sedimentation, as suggested by the thick detrital bed preserved in the hangingwall of the normal fault at the downslope end of the section (Fig. 11). This ponded sediment is
cut across by the overlying unconformity, indicating that it was deposited during downslope movement rather than as a later ‘infill’. e) Minor contractional deformation is only developed downslope of the early normal fault that created a buttress and bulldozed surficial sediments to create small-scale thrusts and folds as it moved downslope on the slide.

f) The unconformity surface broadly maintains the same stratigraphic position above the entire slide stack and does not cut down where thicker beds are repeated. This indicates that no significant topography was built and repeated beds were not raised above ‘regional’.

While the observations and relationships noted above support the slide stacking model, we do however note one issue with its application in that the normal fault predicted to occur beneath the slide surface is not exposed in the case study area. We suggest that this omission is because modern erosion and down-cutting into the sequence is not yet deep enough at the upper end of the wadis to expose the structure. Despite this exception relating to ‘absence of evidence’, our actual observations are entirely compatible with the slide stack model, which can therefore be applied to this case study.

6.3. What is the structural evolution during gravity-driven stacking?

We now provide insights into the contradiction of compressional geometries created during gravity-driven extension. During Stage 1 of the slide stacking model, a typical slope failure is formed with contractional folds and thrusts developed in the downslope ‘toe’, which are broadly balanced by extensional listric normal faulting leading to a tensional ‘depression’ at the head of the slump (e.g. Lewis, 1971; Scarselli et al., 2020; Alves et al., 2022 for recent reviews) (Fig. 14a). The translated beds directly above the slide plane are only “slightly deformed”, while beds upslope of the tensional head to the slump are “disturbed by intrastratal deformation beneath smooth seabed” (Lewis, 1971). Recent numerical modelling has suggested that slip surfaces extending over several km² may be created during even short periods of earthquake shaking (e.g. Zhang and Puzrin, 2022).

During Stage 2 of the model, a second slope failure creates a new slide that forms immediately upslope of the earlier listric normal fault (1) in the area previously noted to contain intrastratal deformation (Fig. 14b). The new basal shear surface (BSS2) develops directly beneath the upslope continuation of the same competent stratigraphic horizon that controlled slope failure in Stage 1, suggesting that some marker beds (and earlier MTDs) may be particularly susceptible to failure (e.g. Gatter et al., 2021). The competent marker bed in the footwall of normal fault (1) is carried over the same stratigraphy that originally formed the hangingwall to the fault, thereby repeating the sequence (Fig. 14b). BSS2 is considered to initiate just upslope of the earlier normal fault (1) due to a variety of potential reasons, including fluids being trapped beneath the competent unit (e.g. Ogata et al., 2014), heterogeneity and weakening in the vicinity of the normal fault itself, and the lack of...
support on the downslope head scarp, which forms a ‘free’ surface with the water column (Fig. 14b). The slide then translates downslope and propagates mostly upslope until it breaches the sediment surface along a new listric normal fault (2) (Fig. 14b). As BSS2 largely propagates upslope from its nucleation point, it is therefore expected that the amount of displacement will also reduce upslope, meaning that the overall slide sheet is in tension and will undergo extension and normal faulting. Upslope and downslope propagation of slip surfaces during landslides has been noted in the models of Zhang and Puzrin (2022).

During Stage 3 of the model, BSS2 continues to carry the competent...
beds in its hanging wall over the equivalent stratigraphy in its footwall to create greater overlap and duplication of the repeated sequence (Fig. 14c). Upslope-directed propagation of a failure surface while moving downslope results in normal faulting and attenuation of beds above the slide, i.e. this is in the extensional domain of flow cells (Farrell, 1984; Alsop et al., 2020a, 2020d; Assis et al., 2024). Conversely, propagation of the failure surface downslope from the point of initiation should result in compressional geometries (Farrell, 1984). However, if the original normal fault (1) breached the sediment surface to create a scarp at the head of the slump, then BSS2 becomes close to the sediment surface downslope of this normal fault (1) (Fig. 14c). BSS2 carries the normal fault and scarp downslope where it acts like a ‘bulldozer’ to scrape off surficial sediment, which is piled up in thrusts and folds. This zone of compression is relatively small as the slide is close to the surface with minor folds and thrusts only affecting a very thin sequence of near-surface sediments. As the amount of recorded downslope contraction is significantly less than the upslope extension, the slide stack does not therefore follow the classical model of Farrell (1984), where upslope extension and downslope contraction should balance. We prefer to follow the model of Lenz et al. (2023), who show that slides which rapidly translate downslope (60 m/s) create folding and thrusting in the sea floor sediments in front of the moving mass. If the observations of Lenz et al. (2023) are indeed analogous to the fold and thrust systems observed at the leading edge of the slide stack, then it may suggest that the Miflat Slide also represents extremely rapid slope failure.

Translation of new slide sheets into space evacuated at the head scarp of earlier slumps means that there is no necessity to raise the sea floor or build topographic ‘bulges’ (Fig. 14c). The whole system therefore creates regressive slope failure with new slides and normal faults forming progressively further upslope. Each slide sheet infills bathymetric depressions created by earlier slump movements further downslope, with slide stacking akin to ‘tarracotta tiles slipping over one another down a pitched roof’ (Fig. 14c).

6.4. How does the thickness and extent of slide sheets compare with other settings?

As noted above, slide stacking repeats sequences by translating older beds in the footwall of an earlier normal fault over younger beds in the downthrown hangingwall (Figs. 13 and 14). This geometry, where older beds are repeated above younger beds that is typically attributed to compression and thrusting, is thereby produced entirely through downslope-directed translation and gravity-driven extension. Callot et al. (2008, p. 341) describe gravity-slide deposits affecting a carbonate platform of Cretaceous age from Peru. They note that “limestone rafts can overlap each other and form stacks of two or more elements separated by breccias and red marly silstones”. These rafts, which are up to 40 m in length, are of more limited extent than at Miflat and clearly show that stacking and duplication of competent units may develop. However, the rafts differ from those above the Miflat Slide as they are associated with local folding and contraction rather than extension.

6.4.1. Controls on the thickness and extent of slide stack sheets

The throw of the earlier normal fault that creates the scarp and offset of competent beds affected by slide stacking must be greater than the thickness of the competent unit that controls the position of the later slide plane (BSS) (Fig. 14a). The throw of the normal fault therefore controls the thickness of the subsequent slide sheet, while the extent of overlap and duplication of the sequence is governed by the amount of downslope translation. In some cases, the sequence in the hangingwall to the slide is cut by an erosive unconformity and so its thicknesses cannot be directly measured. However, the thickness of the sequence preserved in the footwall to the BSS, and which is then repeated above the slide, provides a ‘template’ and enables a minimum estimate to be made of the BSS depth below the sediment surface/sea floor.

When traced upslope, the Miflat Slide becomes buried beneath the floor and walls of wadis that have not yet eroded deep enough to expose the slide plane, while downslope exposure is lost along the leading edge of outcrops that form a scarp (Fig. 3g and h). Given these constraints, the Miflat Slide is traceable for a minimum of 500 m downslope and comprises up to 3.5 m of duplicated stratigraphy. The full thickness of the repeated stratigraphy is not preserved because of erosion along the later unconformities that cuts across the underlying slide stack, although it is estimated by using the undeformed footwall sequence as a template. Given these constraints, the Miflat Slide has a thickness to displacement (extent) ratio of 0.007, which is similar to the average of 0.005 for six slumps exposed elsewhere in the Lisan Formation (Alsop et al., 2020b).

In general, the extent of downslope movement may be controlled by fluid pressures along the BSS, with high fluid pressure enabling large translations on thrusts and detachments. This general mechanism of increased fluid pressure has been invoked by a range of authors since Hubbert and Rubey (1959), Mandl and Crans (1981) and summarised by Suppe (1985, p.300-307) and Fossen (2016, p.369-372), amongst others. In submarine settings, the ratio of translational slide thickness to downslope length is generally in the range of 0.1 to 0.02 (i.e. a 10 m thick package of sediment above the BSS may be expected to extend for between 100 m and 500 m downslope) (Allen, 1985, p.160). This ratio is therefore considerably greater for translational slides compared to slumps. Furthermore, the ratios from the Lisan Formation are smaller (0.005) than the overall values for submarine slides. This potentially reflects the nature of finely laminated water-saturated lacustrine sediments that may encourage thin sheets to move and extend for greater distances down the very low angle slopes (<1°) compared to the potentially more crudely bedded submarine sediments.

The thickness and extent of slide sheets may also reflect gravity-gilding, which is the downslope translation of deformed sediment parallel to the underlying detachment, or gravity-spread, which is marked by vertical thinning and lateral spread of sediment above a basal detachment (e.g. Peel, 2014; Fossen, 2016, p.371). In reality, a combination of both processes may occur (e.g. Rowan et al., 2004; Peel, 2014). If the weaker portions of slump sheets undergo a vertical thinning during extension, then this equates to the predominance of the gravity-spread mechanism (Peel, 2014). The observation in the Miflat Slide that the BSS maintains the same stratigraphic level, with deformation parallel to this boundary, indicates that gravity-gilding typically operates along the slide. However, attenuation and vertical thinning of the displaced sheet above the Miflat Slide suggests that gravity-spread or ‘extrusion’ may also occur as a sub-ordinate process.

6.5. How are ‘contractional’ features and fault-bounded blocks created during extension?

Despite the widespread evidence for extensional deformation during slide stacking, some features, such as folds, if examined in isolation may be misinterpreted as contractional in origin, while others, such as blocks, may be misconstrued as erosively sourced.

6.5.1. How are recumbent hangingwall anticlines created during sliding?

Recumbent hangingwall anticlines developed above thrust planes are widespread in both orogenic belts and in fold and thrust systems formed in unmetamorphosed sediments (Alsop et al., 2021a, 2021b). While they are classically considered to provide evidence of contractional deformation, we here discuss examples that display a range of unusual characteristics that are inconsistent with thrusting. The recumbent anticlines with overturned lower limbs in our case study are not considered to be related to thrusting and contraction because.

a) Stratigraphy does not clearly intersect the footwall of the listric fault to create a cut off, as observed in thrusts, but rather is separated from the hangingwall by extensional shears.
b) Marker beds are not raised above their regional elevation as would be expected with thrusting.

c) Unconformably overlying sequences are thickened above the anticlines rather than thinned, as would be expected above structural ‘hills’ created by thrusting. Thickening of sequences suggests that space was being created during subsidence associated with extension.

d) Hangingwall anticlines with overturned limbs are only observed above synthetic downslope dipping faults. If these were thrust related then they would represent backthrusts that generally have steeper dips (Alsop et al., 2017). However, our observations show that these faults are extremely gently dipping (not steeper), and there is an absence of overturning on the upslope-dipping faults.

e) Stratigraphy above the BSS is cut by numerous steep normal faults and is thinned and attenuated, rather than thickened as expected in thrust sheets.

Collectively these observations are incompatible with thrust-related collectively and we therefore propose an alternative model associated with extension. In our model, a synthetic listric normal fault creates a pronounced roll-over anticline in the competent marker bed above the BSS (Stages 1–3, Fig. 8f). Continued extension causes the marker bed to translate downslope and become entirely separated from the marker in the footwall of the listric fault (Stage 4, Fig. 8f). Normal faulting above the BSS allows fluidised sediments to inject in the ‘space’ created during extension, creating the mixed and chaotic footwall to the faults. The steep limb of the hangingwall anticline is further rotated and becomes locally overturned by enhanced shearing along the BSS. This process creates the upslope-verging recumbent anticline because strain gradients are focussed at the base of slide sheets (e.g. Sobiesiak et al., 2018) rather than being distributed throughout the entire unit as in slumps. We note that the geometry of the recumbent fold reflects this localised ‘flipping’ of the overturned limb, with most hangingwall anticlines created by fault-propagation folding in the Lisan Formation displaying a much longer overturned limb (Alsop et al., 2018). Although the geometry of the listric faults and recumbent folds could be locally enhanced by later compaction from overburden, there is only a thin (<20 m) overlying sediment pile and so any effects would be limited. We therefore suggest that the upslope-verging recumbent folds are modified roll-over anticlines created entirely during extension. The creation of such folds does not require thrust faulting, or contractional strain propagating back up-slope during ‘locking’ of the slide further downslope (e.g. Farrell, 1984), although folds could potentially be modified by such late-stage processes.

6.5.2. How are sedimentary blocks and rafts created during sliding?

Blocks are widespread within some MTDs and slides, and form conspicuous features from the metre to kilometre scale (see Ogata et al., 2012; Sobiesiak et al., 2016a, b; Rodrigues et al., 2020; Cox et al., 2020; McNall et al., 2023). It has also been noted that stratigraphy exposed along fault scarps may periodically collapse and then slide downslope to create giant sedimentary blocks (Callot et al., 2008, p.352). Blocks carried in MTDs must be derived from older stratigraphy and lithologies, and are generally considered to be either eroded and ‘plucked’ from the underlying substrate in the footwall to the BSS, or to be sourced from within the MTD itself as it moves downslope and fragments (e.g. Sobiesiak et al., 2016a, b, 2018, 2020). For blocks to be carried or ‘plucked’ from underlying substrate requires a high-energy system in which material generally sintegrates, creating a range of block sizes (e.g. Sobiesiak et al., 2016a, b).

We suggest that during or immediately after emplacement of the slide stack sheet, extensional strain resulted in normal faulting that broke up the competent beds into blocks and rafts. These rafts are locally separated from one another, but comprise a recognisable stratigraphy that always remains the correct way-up. There is no necessity for erosion of the substrate by high-energy flow or ‘plucking’ along the BSS, as the stratigraphy was emplaced as a slide sheet. The 1 m—10 m scale blocks remain angular as they have not been individually transported from the underlying stratigraphy, and there is therefore less chance for rounding. There is no necessity for large amounts of independent transport of individual blocks within a fluid-rich or fluidised matrix, as suggested during the creation of blocks from within MTDs, where individually transported boulders may be expected to undergo some rounding, together with rotation and potential inversion (Sobiesiak et al., 2018). The location of the jumbled blocks within the Miflat Slide sheet (Fig. 3g) is consistent with sidewall collapse and potential lateral shear within the MTD representing differential downslope movement (e.g. Alsop et al., 2020d).

The lack of erosion or deformation of the underlying sequence that forms the footwall to the Miflat Slide suggests that it forms a ‘free-slip’ flow (Sobiesiak et al., 2018, their Fig. 2). This is supported by the fluid escape and sediment injection structures that form directly along the slide plane (e.g. Fig. 4), indicating liquefaction, fluidisation and hydroplaning along a weak lubricating layer marking the BSS to the Miflat Slide. Hence, the slide stacking model allows stratigraphy preserved within individual blocks above the slide to be readily matched with the directly underlying sequence.

6.6. Do slides continue to move after original slope failure?

Although submarine landslides and associated MTDs may be geologically instantaneous, there is increasing evidence that they may continue to move after initial slope failure (e.g. Safadi et al., 2017; Alves et al., 2022; Jing et al., 2024 and references therein). The evidence for downslope movement of the Miflat Slide sheet continuing after the initial slope failure may be summarised as follows.

6.6.1. Multiple unconformities in the overlying sequence

The slide sheet is overlain by two unconformities (1 and 2) that are separated by a locally tilted and deformed package of sediments, indicating movement continued after the lower unconformity had formed. The merging of the two unconformities, which are draped over the culmination created by thrusting at the downslope toe of the system, demonstrates that thrusting was an integral part of the movement along the BSS rather than a later episode (Fig. 11c and d).

6.6.2. Slump folds formed above the lower unconformity

The preservation of slump folds in the sedimentary package between the upper and lower unconformities (e.g. Fig. 7d, e, g) indicates that instability and further deformation occurred after creation of the 1st unconformity and deposition of sediments. This suggests that there was continued movement along the BSS to create instability and local slumping.

6.6.3. Lower unconformity is deformed by slide structures

In some cases, the lower unconformity (1) is deflected upwards by fluid escape structures, but is then cut by the upper unconformity (2) (Fig. 4). Irregularity of the lower unconformity suggests that fluids continued to be expelled after its creation, although the upper unconformity (2) then truncates these structures and ultimately marks the cessation of deformation in the slide sheet at that locality (Fig. 4).

6.6.4. Fold and thrust systems and normal faults deform the overlying sequence

Stratigraphy that overlies the unconformity surfaces can be correlated along the length of the Miflat Slide. This sequence is, however, locally affected by detachments and associated downslope verging fold and thrust systems (FATS) (Fig. 12). The observation that these deformed units are capped by a younger unconformity (e.g. Fig. 12a–f) indicates that they formed at the sediment surface before deposition of the overlying sediments and gypsum cap.

Normal faults developed within the slide sheet and detaching onto
the underlying BSS are reactivated and cut across the unconformities above the slide sheet (and the sediments beneath the overlying gypsum horizon) (Fig. 9). The observation that unconformity (1) is locally cut by normal faults suggests that downslope creep continued after the lower unconformity formed. As some late normal faults that detach on the slide plane also cut the overlying sequence and the upper unconformity (2), then some slide movement must have locally continued after the 2nd unconformity.

In summary, the lower unconformity (1) forms after slide stacking with erosion removing up to ~2 m of stratigraphy from the slide sheet. Limited movement of the slide continued after unconformity (1), resulting in unconformity (2). The sediment package between the two unconformities is locally deformed by folds and faults, attesting to continued slide movement. The double unconformity is most clearly distinguished in trough/low areas between large sedimentary blocks, as the two unconformities join above topographic highs/crests. Although the upper unconformity (2) is in general draped over the underlying blocks without significant erosion, its downslope part is marked by a mixed ‘cap’, generally considered to be deposited out of suspension following slope failure (Fig. 10a–d) (Alsop et al., 2020b, 2020d). This suggests that a turbidity current may have developed with erosion in the upper part of the slide and deposition further downslope. Both unconformities (1 and 2) predate deposition of the uppermost sediments and creation of an overlying gypsum horizon that caps the sequence. Sediments above the unconformities but below the gypsum horizon are locally affected by NE-verging FATS, indicating that downslope-directed movement or creep deeply above the Miflat Slide had continued.

6.7. Consequences and further considerations of slide stacking

6.7.1. Balancing of contraction and extension in MTDs

Although repeated sequences are identified on seismic sections across MTDs, they are generally attributed to thrusting at the compressional toe to the system. When attempts are made to equate the amount of downslope contraction with the upslope extension, it is often found that the two components fail to balance (e.g. Butler and Paton, 2010; de Vera et al., 2010; Dalton et al., 2015, 2017; Morley et al., 2017; Morley and Naghadeh, 2018; Scarselli et al., 2022). If repetition partially represents a slide stacking process, then some of this mismatch may be alleviated.

6.7.2. Extensional duplexes in slide stacks

An extensional duplex, where normal faults are bound by underlying and overlying detachments, are described previously from a number of settings (Gabrielsen and Clausen, 2001; Zhao et al., 2020). However, normal faults associated with slide stacking are not considered to form an extensional duplex because the upper boundary is the ‘free surface’ on the lake floor and there is therefore no overlying detachment to bound the normal faults. The normal faults display displacement orders of magnitude less than the scale of repetition across the BSS (~500 m) and are not therefore interpreted to be ‘ramps’ that formed prior to ‘flats’ as in some (contractional) duplex models (e.g. Eisenstadt and de Paor, 1987; Ferrill et al., 2016).

6.7.3. Repetition of MTDs

We have shown that older MTDs that formed at the sediment surface and were subsequently incorporated into the stratigraphy may be duplicated across large areas during repetition of beds associated with slide stacking. If slide stacks remain unrecognised, then the use of MTDs to determine earthquake recurrence in palaeoseismic studies would lead to an overestimate of earthquake ‘events’.

6.7.4. Continued downslope movement of MTDs

It is becoming increasingly apparent that the inherent instability of MTDs that are deposited rapidly in slope settings may result in continued downslope-directed movement following the initial slope failure (e.g. McNall et al., 2023). This continued deformation is of concern for infrastructure such as pipelines and cables, which are vulnerable to further slope movement. In this study we have shown that slide stacking is marked by multiple overlying unconformities, normal faulting, thrusting and folding of the upper sequence above the slide sheet itself. This indicates sustained downslope movement to fill space evacuated by earlier slumping and highlights the protracted nature of continuing slope movements.

7. Conclusions

We introduce a process of slide stacking whereby earlier synthetic (downslope-dipping) normal faults are cut by translational slides that displace the footwall of the earlier fault downslope over its hangingwall. This results in repetition of sequences with older over younger stratigraphic relationships across the slide plane. However, this geometry is created entirely via extension associated with normal faults and bed-parallel slides, with no beds pushed up on top of one another (as in compressional thrust models). We summarise these relationships in Fig. 15 and highlight below some of the main observations and features.

Attenuation of the repeated sequence – The translated sequence above the detachment has suffered ~25% attenuation. Individual beds within the displaced sheet are correlated with the same stratigraphy in the footwall of the slide, indicating bed-by-bed thinning rather than stratigraphic ‘cut-out’ by detachments. Upslope propagation of a slide surface during downslope translation results in extension and attenuation of the slide sheet (Fig. 15).

Sedimentary blocks - The repeated sequence above the slide plane is broken up into large sub-angular blocks by normal faults (Fig. 15) that are consistently overlain by the same unconformity and overlying stratigraphy above the slide. Sedimentary blocks are not derived from plucking and erosion of substrate as: a) BSS is smooth and planar with no evidence of irregularity linked to plucking, b) blocks are too large and BSS would have to significantly cut down into 2 m of underlying stratigraphy, c) blocks are mostly the correct way-up and not rotated.

Upslope-verging folds – An increase in strain towards the BSS of the slide sheet means that upslope-dipping roll-over antclines above synthetic listric normal faults are sheared over from the vertical to become overturned (Fig. 15). This modification to ‘roll-over’ antclines results in them resembling classic hangingwall antclines of thrust sequences and potential confusion with contractional geometries in MTDs.

Lack of structural culmination - Each successive slide utilises and re-uses the same competent bed and underlying weak horizon preserved further upslope, resulting in retrogressive slope failure as the slide stack develops (Fig. 15). Although slide stacking involves stratigraphic repetition, it does not create a culmination or topographic bulge because i) stratigraphic repetition is partially accommodated by space created by the downthrow of the normal fault; and ii) overlying stratigraphy is extended with the attenuated stratigraphy being thinner.

Lack of thrusting in a downslope ‘toe’ - There is no necessity for a downslope contractional ‘toe’ that balances upslope extension as the bed-parallel slide is close to the sediment surface on the downslope side of the early normal fault, and compression is largely accommodated by displacing the water column. The narrow (~5 m wide) zone of thrusting at the downslope margin is a consequence of ‘bulldozing’ of surficial sediment by the early normal fault scarp (Fig. 15).

CRediT authorship contribution statement

G.I. Alsop: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. S. Marco: Writing – review & editing, Investigation, Funding acquisition. R. Weinberger: Writing – review & editing, Investigation, Funding acquisition. T. Levi: Writing – review & editing, Investigation, Funding acquisition.
Fig. 15. Summary cartoon of slide stacking model illustrating the main features of early normal faults (blue) being cut by a later slide (green) resulting in stratigraphic repetition within a gravity-driven extensional setting. Despite the repetition of sequences across the slide, there is only a localised area of compression at the downslope toe where the normal fault has ‘bulldozed’ surficial sediments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Declaration of competing interest

We can confirm that there is no conflict of interest with this work.

Data availability

No data was used for the research described in the article.

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References


