A review of producing fields inferred to have upslope stratigraphically trapped turbidite reservoirs: trapping styles (pure and combined), pinchout formation and depositional setting

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ACKNOWLEDGEMENTS

The work has been helped and encouraged by many past discussions on stratigraphic traps with various colleagues including Jonathan Leather, Bill McCaffrey, Robert Dorrell, Ben Kneller, Peter Haughton, Ivan Lokmer, Aggeliki Georgiopoulou, Marco Patacci, Marco Fonnesu and Rémi Rateau. Jim Hendry and Emma Morris are specially thanked for providing helpful comments on earlier versions of the manuscript. The manuscript was further enhanced by the comments of the editor Dr Barry Katz and two anonymous reviewers. The Leeds Turbidite Research Group generously provided support to attend conferences and meetings to present results related to this study.

ABSTRACT

Siliciclastic turbidite systems that pinchout updip towards their proximal margin are prime targets for hydrocarbon exploration especially in deepwater basins. Such ‘upslope stratigraphic traps’ potentially offer large volume discoveries but have significant geological risks, notably due to ineffective closure or containment. In the published literature, at least 20 fields from 11 basins globally with 6-7 BBOE of cumulative discovered reserves have been inferred to be reliant on upslope pinchout traps. These fields are reviewed in terms of their interpreted trapping styles, pinchout formation process and depositional-tectonic setting. Reservoirs display a range of upslope trapping styles, including pure (depositional and erosional) stratigraphic pinchouts and combined stratigraphic-structural traps. In one third of cases, faulting appears intimately linked to updip trapping: either through offsetting slope feeder conduits or assisting pinchout development, and in some cases faulting may be the most important updip trapping element. Sediment bypass and erosion in proximal areas is the most common inferred pinchout formation mechanism. Some reservoirs also demonstrate the ability of erosional truncation by mud-prone channels and mass transport deposits to form viable stratigraphic traps and seals. Encouragingly for exploration, robust pinchout traps occur in various tectonic settings, on a variety of different slope types and positions along the slope profile. Most large-volume discoveries to date, however, are restricted to the toe-of-slope environment in graded passive margins or out-of-grade rift and transform margin settings. Insights into the nature and occurrence of upslope stratigraphic traps are important for future exploration, especially for evaluating new license areas and risking prospects.

INTRODUCTION

Stratigraphic traps formed by updip pinchout of reservoirs towards the proximal basin margin of deepwater depositional systems has become an increasingly important focus for hydrocarbon exploration, particularly in deep- and ultra-deepwater regions (**Figure 1**). This 'upslope' trapping configuration for turbidite channel- and fan-complexes is embedded within a variety of deepwater exploration models, including the 'stratigraphic trap' (MacGregor et al., 2003), 'basin-margin pinchout' (Stoker et al., 2006), 'detached basin-floor fan' (Fugelli and Olsen, 2005; Milton-Worssell et al., 2006), 'stratigraphic pinchout' (Flinch et al., 2009), and 'abrupt margin' (Biteau et al., 2014) plays. Such stratigraphic pinchouts potentially offer opportunities for large volume discoveries in frontier or mature acreage where structural traps are absent or have already been tested (Stoker et al., 2006; Biteau et al., 2014; Stirling et al., 2017). Giant commercial discoveries (> 500 MMBO recoverable reserves) previously discussed to have upslope stratigraphic trapping include the Jubilee Field (Tano Basin, offshore Ghana), the Buzzard Field (Outer Moray Firth, UK Central North Sea) and Marlim and Marlim Sul fields (Campos Basin, offshore Brazil). Recent drilling campaigns with a particular focus on upslope stratigraphic traps include those that have targeted Late Cretaceous deepwater sequences of the Atlantic along the West African Equatorial transform margin (Ghana, Cote d'Ivoire, Sierra Leone) and its conjugate South American margin (Guyana, Suriname, French Guyana) (Flinch et al., 2009; MacGregor et al., 2003; Dailly et al., 2012*;* Biteau et al., 2014).

Whilst there has been a more positive attitude towards and willingness to drill deepwater stratigraphic traps (Allan et al., 2006; Stoker et al., 2006; Dailly et al., 2012; Biteau et al., 2014; Stirling et al., 2017), the number of commercial discoveries specifically with upslope pinchout traps has remained limited. Hence, despite offering the potential for the 'big prize', the chance of commercial success based on past exploration experience may be judged to be relatively low. Closure and containment, as related to the presence of a robust trap and seals capable of preventing updip leakage of hydrocarbons, are often deemed the principal geological risks (Straccia and Prather, 1999; Prather, 2003; Loizou, 2014). This is a critical issue for all types of stratigraphic trap including deepwater turbidite systems whether located at proximal, lateral or distal margins (**Figure 2**). A particular risk for upslope pinchout traps is the potential for coarse-grained deposits of the feeder system to extend updip, attaching deepwater systems to those higher on the slope or shelf-fluvial systems. Such thief sands may be relatively thin making them difficult to resolve on seismic data. There is also a propensity for erosional systems on the proximal margin which may compromise top or base seals. The nature of the proximal margin, therefore, arguably makes pinchout traps considerably higher risk in this location compared to lateral or distal margins.

In this study, fields with turbidite reservoirs previously inferred in the literature to have upslope stratigraphic trapping are reviewed. A number of aspects critical for prediction and derisking this trap type in exploration studies are focussed upon here: i) the nature of the upslope trapping configuration – whether upslope trapping is by stratigraphic pinchout alone or combined with structural trapping mechanisms; ii) the processes responsible for pinchout development; and iii) the tectono-depositional setting in which proven pinchout traps occur. A better understanding of these aspects of upslope traps provide valuable insights into which basin margins and areas along the slope profile, and hence license areas, offer the best potential for upslope stratigraphic traps with large volume discoveries. In the following, the approach taken to identify fields with upslope stratigraphic traps is first outlined, before discussing each of the three themes mentioned above and summarising key lessons for exploration. This to our knowledge is the most comprehensive summary of fields with this trap type within the public domain.

IDENTIFICATION OF RESERVOIRS

The work here synthesises information from previous published studies on fields inferred to have upslope stratigraphically trapped reservoirs. Examples of producing turbidite reservoirs, where the total or a significant fraction of reserves are considered to be dependent on upslope stratigraphic pinchout, were compiled from the published literature. Initial identification of reservoirs was assisted using a consultancy database – C&C Reservoirs' Digital Analogs Knowledge System ('DAKS') – that holds published data on over 1400 reservoirs. This was followed by a broader review of the literature. Only well described reservoirs are considered here, including those from fields in development, currently producing and abandoned. Non-commercial and new discoveries have not been considered owing to the lack of detailed published information. The reservoirs include those with depositional systems orientated perpendicular or oblique to the structural dip direction, where upslope pinchouts of lobes or channel complexes are critical to hydrocarbon accumulation trapping (**Figure 3A**). Both depositional and erosional stratigraphic traps (*sensu* Allan et al., 2006) are considered; note the term 'pinchout' in this study is used broadly to indicate lateral stratigraphic terminations of reservoir against sealing facies regardless of whether a result of deposition, erosion or facies changes (**Figure 3B**).

In total 20 oil and gas fields with inferred upslope stratigraphically trapped turbidite reservoirs were identified from 11 basins globally (**Table 1 & Figure 4**). Recoverable reserves in these fields vary from a few million to over a billion barrels. Cumulative reserves for all fields are in the order of 6-7 BBOE. Fields were discovered between 1952 to 2010, with two prominent periods of discovery (between 1984-1992 and 2001-2010) corresponding to periods of high or rising oil prices. Further field information is detailed in **Table 1** and trap-related information in **Table 2**.

UPSLOPE TRAPPING CONFIGURATIONS

For each field, published maps and cross sections were used to verify and better understand reservoir trapping (**Figure 5 and 6**). A variety of trapping configurations, from pure pinchouts to those combined with faulting or dip closure, are considered as potential updip trapping mechanisms (**Table 2**). The various trapping interpretations applied to fields, and inferred in this review, is summarised schematically in **Figure 7**. For some fields multiple interpretation are proposed. Pure and combined trap configurations are discussed further below, with a focus on the potential importance of faulting cutting feeder channels for the latter, as exemplified in a number of well-known giant oil fields.

Pure upslope traps

For about half of the considered fields, a pure stratigraphic trapping mechanism is the principal inferred trapping mechanism (**Figure 7**). Reservoirs including Buzzard, Barracuda, English Colony, Jameson, Marlim Sul, Nautilus, Pabst, Bud, and Young North are inferred to rely solely on stratigraphic pinchout upslope as determined from seismic and well data (see **Table 1** for references). Authors describing these reservoirs do not indicate that structure plays a significant role. Dip closure also plays a partial role in conjunction with pinchout in the cases of Alba, Shwe and Lagoa Parda. The majority of these reservoirs (~80%) are inferred to display depositional pinchouts with fewer displaying evidence for erosional truncation pinchouts (**Figure 7**).

Traps associated with upslope faulting

A number of reservoirs including Jubilee, Foinaven and Marlim fields have updip field boundaries coincident with late stage (post-reservoir) faulting (**Figure 5**). Whilst stratigraphic pinchouts are identified in these fields, updip trapping may be reliant, wholly or partly, on post-reservoir faulting.

Jubilee Field

The Jubilee field is one of the most prominent discoveries of the 'abrupt margin' or 'stratigraphic pinchout' plays, often discussed in the context of an upslope stratigraphic trap (e.g., Jewell, 2011; Biteau et al., 2014; Flinch, 2014). Well-developed stratigraphic pinchouts of the Mahogany fan sequence are seen towards the northwest and east and locally updip towards the northeast and north (**Figure 8**). In addition to pinchouts, several large-scale normal basement-linked faults are present in the northeast defining the southern extent of the shelf-forming Tano Nose structure (**Figure 8C**). Dailly et al. (2012) noted that reservoirs appear to be trapped against a down-thrown fault towards the northeast. Kelly and Doust (2016) also suggested combined structural-stratigraphic trapping configurations involving faulting for the Turonian reservoir section. Based on seismic attribute maps, faulting may be inferred to cut across slope feeder systems (**Figure 8A**). Jubilee therefore may not be a simple pinchout trap but one with a fault component that offsets updip slope feeder systems. This interpretation is supported by the presence of coeval Turonian sands confirmed to occur updip of the Jubilee field on the crest of the Tano nose in the Teak discovery (Tullow Oil Ltd. media release, 2008).

Foinaven Field

Significant emphasis has also been placed on stratigraphic trapping in the Foinaven field, whist recognising this is a combined structural-stratigraphic trap (Straccia and Prather 1999; Carruth, 2003; Loizou et al., 2006). Straccia and Prather (1999) considered the Foinaven field primarily as a base-of-slope onlap trap, with T31-T34 sands pinching out upslope in the southeast corner of the field. However, they also discussed the potential importance of faulting elements in trapping as well as eastward dip closure. The importance of structural elements in trapping was also suggested by later analysis: Loizou et al. (2006) indicated trapping of the Palaeocene reservoir section upslope towards the SE, related to a combination of dip closure (due to the Westray inversion anticline) and faulting against Palaeocene mudstones (**Figure 9A**); Carruth (1993) also indicated that hydrocarbon-filled sands terminate against faults cutting across the inferred southern and southeastern sediment entry points (**Figure 9B & C**). Normal faulting is similarly inferred to be responsible for trapping in the neighbouring Schiehallion and Loyal fields comprising channelized turbidite reservoirs of a similar age (Leach et al., 1999).

Campos Basin Fields

Oligocene sandstones of the Marlim, Marlim Sul and Barracuda in the Campos Basin are inferred to comprise detached fan deposits with upslope pinchout on to the proximal slope towards the west (Peres, 1993; Bruhn et al., 2003). These fields display combined structural and stratigraphic trapping configurations (**Figure 10**). Field limits are defined mainly by reservoir pinch out towards the west and also north and south, with normal faulting towards the east, northeast and northwest (Candido and Cora, 1992). Faulting at the reservoir level is mainly in the form of growth faults, developed in response to renewed salt withdrawal after reservoir deposition during the late Miocene (Peres, 1993). Along the proximal western margin, faults locally dissect several of the inferred feeder systems

(**Figure 5 & 10C**). Thus, late stage faulting is seen to cross cut feeder systems, suggesting that it could play an important role in trapping.

From the above discussion, it is clear that a number of high profile reservoirs – commonly discussed as stratigraphic traps – have upslope field limits controlled by faulting. Considering all the fields in Table 1, almost one third of cases faulting may play an important role in upslope trapping (**Table 2**). Post-depositional faulting through feeder systems offsetting potential thief sands may be critical in forming or aiding traps in Foinaven, Jubilee and Marlim. Other reservoirs including Buzzard, Glenlivet, Oribi and Laggan are located on strongly faulted slopes. Whilst younger faulting cutting the reservoir interval is difficult to confirm in these cases, subseismic scale faulting within thinned parts of the reservoir intervals on the slope may assist in trapping in these systems. Their location on strongly faulted slopes may also have encouraged pinchout development (as discussed further below).

FORMATION OF UPSLOPE PINCHOUTS

A range of processes operating in deepwater turbidite systems at various temporal and spatial scales can give rise to pinchout development, as indicated previously in many process-based models (**Figure 11**). Subsurface studies on proven upslope stratigraphic traps infer three principal mechanisms responsible for pinchout development: those associated with i) sediment bypass by turbidity currents; ii) erosion by mud-filled channels and; iii) erosion by mass transport complexes (**Table 2**).

Bypass-related pinchout traps

In the majority of cases, upslope pinchouts of reservoirs are inferred to be 'depositional pinchouts' formed by sediment gravity flows that bypassed or eroded proximal parts of the slope system. Detached sands and gravels develop downslope of a sediment transfer zone with erosional-bypass conduits that are subsequently filled by sealing lithologies. This interpretation has been applied to Alba (Harding et al., 1990; Newton and Flanagan, 1993), Buzzard (Doré and Robbins, 2005), Glenlivet (Stephensen et al., 2013; Horseman et al., 2014) and Young North (Montgomery, 1997) fields. Seismic and well data for these examples do not support erosional truncation of the reservoir intervals by younger depositional elements or systems.

As discussed earlier, many of the reservoirs were deposited on faulted palaeo-slopes (e.g., Jubilee, Foinaven, Buzzard, Glenlivet, Lagan, Oribi, and Lagoa Parda). Faulting is a prime mechanism by which slopes can become oversteepened, encouraging erosion and bypass on the upper slope (Ross et al., 1994). Buzzard provides a well-studied example of a stratigraphic pinchout trap on to a fault controlled margin but where faulting at the reservoir level is not believed to ultimately control trapping (**Figure 12**).

As well as oversteepened slopes, faulting can form bathymetric irregularities on the palaeoslope encouraging local deposition on an otherwise bypass-dominated slope. The Glenlivet field of the Faroe-Shetland Basin provides a good example of this in context of syn-sedimentary faulting (**Figure 13**). The reservoir has an updip stratigraphic pinchout towards the southeast where it onlaps the base Cenozoic unconformity (Horseman et al., 2014). Seismic mapping of the late Palaeocene reservoir level suggests deposition on a relatively steep slope with a complex bathymetry controlled by syn-sedimentary growth faults (**Figure 13C & D**). Local deposition occurred on the upper slope in topographic lows formed on the downthrown side of a growth fault (Stephensen et al., 2013; Horseman et al., 2014). The nearby Laxford gas discovery is similarly interpreted as a growth fault controlled depocentre with upslope pinchout (**Figure 13C**).

Upslope and down-dip terminations observed in the Alba field are inferred to be bypass-related, formed as depositional flows traversed an irregular palaeoslope (Newton and Flanagan, 1993). In this case, palaeoslope is not thought to be directly fault-controlled but rather related to subsidence patterns and differential compaction over deeper structure (Harding et al., 1990). Deposition of channel sands is inferred to have occurred on the flatter portion of the relatively gently dipping terraced slope (Newton and Flanagan, 1993).

Erosional truncation by mud-filled channels

A number of producing reservoirs show evidence for pinchout related to erosional truncations by younger mud-filled channels, including Marlim, Marlim Sul, Barracuda (Campos Basin) and Shwe fields (Rakhine Basin) (**Figure 14**). In these systems, erosional channels imaged in high-quality seismic data are seen to dissect basin-floor fan deposits, apparently forming or assisting with upslope proximal and lateral stratigraphic trapping.

The depositional model for the Oligocene turbidite system of the Campos Basin envisages shelf-fed turbidite systems developed at the lower slope and basin plain, fed by outer shelf submarine canyons and lower slope canyon-channels (Peres, 1993) (**Figure 10D & 14A**). Feeder slope conduits appear to lack contiguity to upper slope canyons, with connections absent on the middle and upper slope regions (Peres, 1993). Lower slope erosional channel-canyons are mud-filled and heavily dissect the western parts of lower slope reservoirs of Marlim, Marlim Sul and Barracudas fields, and are responsible for forming isolated residual sand bodies (Peres, 1993; Bruhn 2001; Pinto, 2001; Defeo de Castro, 2014). Erosion is of the order of 70 m (230 ft) deep and 1-3 km (0.6 – 1.9 mi) wide (**Figure 14B & C**). In the Barracuda and Marlim fields, mud-filled channels in conjunction with depositional sand pinchouts and local faulting (as described above) appears to control reservoir distribution and field limits upslope towards the west.

The Shwe gas fields (Shwe, Shwe Phyla and Mya) of the Rakhine Basin similarly displays mud-filled channels that dissect basin-floor lobes forming isolated reservoir bodies with a strong stratigraphic trap component (Yang and Kim, 2014; Racey and Ridd, 2015) (**Figure 14E and E**). These reservoirs are stratigraphically trapped on the western limb of a NW-SE trending anticilinal nose plunging to the SE (Cliff and Carter, 2016). Sands in this system are inferred to have been sourced by both the Ganges-Brahmaputra and the nearer Rakhine shelf systems, from the NW and NE, respectively (Racey and Ridd, 2015). Whilst updip stratigraphic trapping is principally towards the crest of the anticline in a NE direction (involving the lateral lobe margins), there also appears to be stratigraphic trapping component towards the N and NW (up the plunge of the nose and up-depositional dip). Two types of channels are recognized in these fields: (i) sinuous feeder channel with sand-fill and (ii) larger low-sinuosity erosional channels with mud-fill. The latter channels prograded across and incised into pre-existing lobe deposits and are inferred to have been efficient sediment conduits before being abandoned and filled by mud (**Figure 14D**). These incisional channels, up to 100 m (328 ft) deep, greatly influence field size as well as compartmentalization of gas reservoirs (**Figure 14E**). In Shwe gas fields, erosional truncation by mud-filled channel in combination with depositional pinchouts (seen as downlap) are responsible for stratigraphic trapping. Similar stratigraphic traps, involving updip mud-filled channels cutting sandy depositional systems, are suggested to offer trapping potential in other deep water areas of the Rakhine Basin (Racey and Ridd, 2015).

Erosional truncation by Mass Transport Complexes (MTCs)

A number of middle Miocene reservoirs in the eastern Gulf of Mexico are reported to display upslope stratigraphic trapping related to erosional truncation and sealing against shale mass transport deposits (Godo, 2006). These include the Bud, Nautilus and Pabst gas fields; composed of channel-levee reservoir sands that occur as irregular isolated remnant patches (‘monadnocks’), having lost their original depositional geometry due to scouring (**Figure 15**). Gas-related seismic amplitude effects show no correlation to structure and are difficult to interpret without recognising the erosional origin of the sand bodies. Some of the mass flows responsible for scouring these sands were prodelta shales which failed from an oversteepened lateral shelf edge (**Figure 15A**). These particular gas reservoirs are relatively small in terms of reserves, due to the limited extents of eroded remnant sands. Such sands, however, are noted to become areally more extensive moving downslope, where there were fewer episodes of scour (Godo, 2006). Erosion by mass transport processes may also play a role in trapping in the larger Ram Powell field located to the south. These reservoirs may be inferred to be erosionally truncated and are overlain by an interval of chaotic seismic facies (e.g., see figure 2 in Clemenceau et al., 2000). In the L Ram Powell reservoir sand, stratigraphic trapping is principally towards the northeast and is considered as a lateral rather than an upslope stratigraphic pinchout of levee sands.

TECTONIC-DEPOSITIONAL SETTING OF UPSLOPE PINCHOUTS

Pinchout setting classification

Reservoirs were assessed in terms of their tectonic setting, slope type and position on the slope using published literature and evaluation of available regional seismic sections (**Figure 6**). Here the scheme proposed by Prather et al. (2016) is used for categorising: i) slope type; ii) position on the slope and iii) gross depositional environment (GDE) (**Figure 16**). The distributions of reservoirs using this scheme are shown in **Figure 17;** shown both for all the reservoirs considered and for those where structure has not been implicated in upslope trapping (see Table 2).

Tectonic setting

Reservoirs inferred to have upslope stratigraphic traps are found in a large variety of tectonic settings including extensional, convergent and strike slip basins (**Figure 17A; Table 3**). Extensional basins include the syn-rift setting of the outer Moray Firth (offshore UK Central North Sea), post-rift (or failed rift) settings of the Central North Sea and passive margin settings of the Campos and Espirito Santo basins (offshore Brazil) and the NE Gulf of Mexico (offshore USA). Strike slip basins settings include the San Joaquin Basin onshore (California). Reservoirs in convergent margins include those of the forearc Rakhine Basin (offshore Myanmar) and the foreland basin of the Permian Basin (onshore Texas and New Mexico). The majority of cases can be seen to come from extensional passive margin and rift basin settings, which also account for the majority of discovered reserves (**Figure 17A**).

Slope type

Regional dip profiles of selected systems are shown in **Figure 6**, showing that upslope stratigraphic traps are located in graded (Alba, eastern GOM reservoirs) and erosional out-of-grade or stepped systems (e.g., Buzzard) (**Figure 17B**). Whilst the Shwe reservoirs are in an overall prograding graded margin, they were deposited when the margin was out-of-grade, as indicated by seismic onlap on to an erosional margin. The Buzzard field occurs on an irregular bathymetric profile due to faulting and hence is considered as a stepped above-grade system. No examples of upslope trapping were identified from ponded systems. Reservoirs occurring in association with graded slopes are most common followed by stepped and out-of-grade margins.

Slope position and GDE

Proven upslope traps occur in a variety of locations along the slope profile, from the upper slope to basin floor (**Figure 17C**); toe-of-slope and lower slope locations are, however, most common. Reservoirs in this location are formed by toe-of-slope fans or aprons (e.g., Marlim Sul, Barracuda, Jameson, Young North and Shwe) and submarine valley deposits (Oribi, Alba). Reservoirs of the eastern GOM formed by erosional remnants also appear to be positioned on the lower slope. Reservoirs higher up on the slope include perched fans or aprons on stepped profiles (e.g., Buzzard) as well as submarine valley deposits (e.g. English Colony). In terms of GDE, most upslope pinchouts occur within toe-of-slope fans or aprons (**Figure 17D**).

Grain size

Evaluation of reservoir grain size indicates that most reservoirs examined in this study contain sands finer grained than medium-sand with few cases coarser sands or gravels (**Figure 18**). Compared to other turbidite reservoirs, those with upslope pinchout traps tend to be relatively fine grained.

DISCUSSION: SETTINGS PRONE TO UPSLOPE PINCHOUTS

Out-of-grade erosional margins have generally been considered to have better potential for detached turbidite system development, and by implication stratigraphic trapping, compared with graded margins (e.g., Ross et al., 1994; Fugelli and Olsen, 2005; Hadler-Jacobsen et al., 2005). Prather (2003) instead views toe-of-slope environments of graded slopes as key sites for upslope stratigraphic trapping. A key result of the present analysis is that pinchout development required for upslope trapping is not limited by tectonic setting, slope type nor slope position. A schematic summary of reservoir depositional location is shown in **Figure 19**. Documented examples of reservoirs demonstrating upslope pinchout traps are known from most tectonic and depositional settings including extensional, compressional and strike-slip basins. Furthermore, in extensional settings they occur in syn-rift as well as post rift sequences of failed rifts and along fully developed passive margins. As such, reservoir bodies are located on graded, out-of-grade and stepped slope types, different positions along the slope and affiliated with different gross depositional environments. Similarly, reservoirs include those with a range of gross depositional environments and reservoir architectures including submarine valley, perched and toe-of-slope fans or aprons. Hence, opportunities exist in a wide range of basins and deepwater depositional environments.

In terms of discovered volumes, however, and as surmised by Prather (2003), the majority of giant oil fields and reserves are found in a more limited number of settings, principally: i) the toe-of-slope of graded passive margins and ii) local breaks-in-slope on stepped out-of-grade rift and transform margins (**Figure 17**). Graded slopes of passive margins provide the single largest cumulative volumes (driven by the giant fields of the Campos Basin) with giant reservoirs located at the toe-of-slope. Jubilee, Foinaven and Buzzard provide examples of giant discoveries on stepped slopes. These occur relatively high up on the slope profile in association with local depocentres. Giant reservoirs in most cases are fans or aprons either perched on the slope or at the toe-of-slope (**Table 3; Figure 17**).

From a sequence stratigraphy perspective, deepwater stratigraphic traps are predicted in lowstand systems tracts with turbidite basin floor fans and slope channel systems, often shown as detached lowstand bodies above sequence boundaries (e.g., Posamentier and Vail, 1988; Dolson et al., 1999). The majority of reservoirs with upslope pinchouts examined here, however, are not reported to occur above key sequence or tectono-stratigraphic unconformities. Glenlivet displays pinchout of Paleocene reservoirs on to a top Cretaceous unconformity (Horseman et al., 2014). Reservoirs of the Oribi field are interpreted to be bound by third-order sequence boundaries within a progradational clinoform sequence (Brown et al., 1995). For other reservoirs, intraformational pinchouts are inferred as the common form of upslope termination (type 2 in **Figure 3B**). Sealing (base, lateral and top) in these cases is provided by intraformational deepwater shales or other pelagic sediments (Mattingly and Bretthaurer, 1992; Carruth, 2003; Ray et al., 2010; Horseman et al., 2014). The lack of association between upslope stratigraphically trapped fields and sequence boundaries may simply reflect an incomplete knowledge of the sequence stratigraphy for these systems. Alternatively, it may indicate that major sequence boundaries are not conducive to the development of robust stratigraphic traps, perhaps due to the lack of development of detached systems or poor quality seals.

Relatively fine-grained turbidite systems have been proposed to more readily form stratigraphic traps compared to coarse-grained systems (Reading & Richards, 1994; Fugelli and Olsen, 2005). This is due to their overall lower net-to-gross but also the greater ability of flows to bypass material downslope (high efficiency systems *sensu* Mutti & Normark, 1987). This view is supported in this analysis as most of the systems examined contain sands that are finer than medium-sand and are relatively fine-grained compared to other turbidite reservoirs (**Figure 18**). The combination of oversteepened slopes in conjunction with fine grained systems or parts of systems allowing efficient sediment bypass is likely critical to the development of many pinchout traps. Oversteepened slopes prone to bypass and erosion may develop in response to faulting, shelf-margin aggradation and carbonate margins with enhanced slopes (Ross et al., 1994). Examples of traps on faulted margins have been discussed (i.e., Buzzard, Glenlivet and Oribi). Reservoirs from the Permian Basin in the Jameson and Young North fields provide examples of upslope traps in association with carbonate margins that may have developed in response to bypass across oversteepened carbonate slopes forming detached turbidite systems. Scenarios discussed for oversteepened margins are in the context of overtly out-of-grade margins undergoing slope readjustment (Ross et al., 1994). However, overall stratigraphically graded margins (*sensu* Pyles et al., 2011) may also experience transient episodes of being out-of-grade, such that flows predominantly bypass sediment downslope. These may be challenging to identify at a seismic scale within an overall stratigraphically graded margin. Reservoirs of the Campos, Rakhine and eastern GOM basins with large scale progradational slope clinoform geometries may be considered within this category.

The notion of base-of-slope lobes detached from their feeding channel (or canyon) systems by a channel-lobe transition zone (CLTZ) is an important aspect of turbidite depositional models pertinent to stratigraphic trapping (Mutti & Normark, 1987; Wynn et al., 2002; Van der Merwe et al., 2014; Stevenson et al., 2015). Evidence for detached lobes comes from both modern and outcropping systems. Hydraulic jumps in sediment gravity flows, caused by a flow exiting the channel or running over a slope break, are commonly deemed to promote erosion and bypass in the CLTZ (Wynn et al., 2002; Brooks et al., 2018). Whilst this may be an important process, analysis of producing fields in this study does not confirm that the CLTZ is a prime location for stratigraphic trap development. Data on CLTZ indicate these zones may not always be environments of complete bypass or erosion, with seafloor examples containing coarse-grained lags (Wynn et al., 2002) and outcrop examples containing thin sand beds (Van der Merwe et al., 2014). This raises some doubt as to the effectiveness of CLTZ to provide robust pinchout traps, without relying on other factors such as erosional truncation and faulting.

KEY IMPLICATIONS FOR EXPLORATION

Existing reservoirs with upslope stratigraphic traps provide a number of key insights pertinent to future exploration, and specifically applicable to choosing new acreage and to prospect evaluation. Within this summary a number of key factors have been identified that likely aid trapping, whose identification in subsurface datasets may help derisk exploration opportunities.

- The range of tectonic and depositional settings that have upslope stratigraphic traps is encouraging for exploration, since many basins and deepwater license areas with active petroleum systems may offer robust stratigraphic pinchout traps. However, not all settings may guarantee large-volume discoveries given that most giant discoveries to date have been made in the toe-of-slope of graded passive margins and intraslope accommodation on stepped slopes on rift or transform margins (**Figure 19**).
- Upslope stratigraphic traps, including giant discoveries, occur on both ‘graded’ and out-of-grade margins (**Figure 19**). Slope type therefore does not uniquely discriminate opportunities, as suggested in some previous studies or as may be inferred from stratigraphic models (e.g., Ross et al., 1994; Hadler-Jacobsen et al. 2005; Fugelli and Olsen, 2005).
- The pinchout traps examined are rarely associated with major first- or second order sequence or tectono-stratigraphic boundaries. Rather they occur as intraformational depositional pinchouts or

truncations (**Figure 3**). This may indicate that such surfaces are prone to updip leakage or poor base seal.

- Targeting systems with limited maximum grain size and with relatively steep or oversteepened slopes is likely a critical success factor (**Figure 18**). Sediment grain size and slope angle are fundamental controls on downslope sediment transport processes including bypass potential of sediment gravity flows. Many systems with upslope stratigraphic trapping are noted to have relatively limited grain sizes and may be combined with oversteepened faulted slopes or progradation across carbonate margins. Where possible, predicted grain size range and palaeoslope should therefore be taken into consideration in acreage and prospect evaluations.
- Faulting through upslope feeder systems also appears to be a critical factor in many past discoveries (**Figure 7, 8 & 9**). Some reservoirs previously interpreted or discussed as upslope stratigraphic traps, are likely to be combination traps with faulting playing an important role (e.g., Jubilee, Foinaven, Lagan and Marlim fields). Faulting is likely to be key in coarse grained systems, where it is difficult for flows to achieve complete sediment bypass on slopes. Where depositional systems thin on to low net-to-gross basin margins, faults should have a high sealing potential and only limited offsets may be required to disconnect feeder systems. Faulting also has the advantage of providing a second potential trapping mechanism, if a robust pinchout trap is absent. Detailed fault mapping and analysis should therefore form a key component of the exploration workflow.
- Mud-prone channels and mass transport deposits can form trapping geometries and act as effective top and lateral seals (**Figures 14 & 15**). This appears to be a critical factor in a number of past discoveries. Identification and mapping these features can provide positive evidence for reservoir pinchout and help derisk closure, particularly where they are intimately associated with amplitude anomalies. However, predicting the seal potential of these erosive depositional elements may be challenging pre-drill, especially in frontier areas where geophysical-based

lithology predictions are uncalibrated and therefore containment may still carry high uncertainty. Understanding erosional truncations is also important for determining reservoir distribution, connectivity, and volumes which may be negatively affected in areas of intense erosion.

CONCLUSIONS

Deepwater upslope stratigraphic traps continue to be important targets for hydrocarbon exploration and seem likely to deliver future significant oil and gas discoveries in both mature and frontier basins. Achieving success remains challenging notably due to finding reliable closure and containment. Compilation and analysis of past commercial discoveries has provided insights into the trapping configurations, mechanism of pinchout formation and tectonic-depositional settings of upslope pinchout traps. Importantly, this demonstrates their occurrence in a range of tectonic and depositional settings including both graded and out-of-grade margins. The majority of large-volume discoveries to date have been made at the toe-of-slope of graded passive margins and at local breaks-in-slope on stepped out-of-grade rift and transform margins. Trapping geometries may result from the bypass of sediment by transporting flows but also erosional truncation by mud-filled channels and mass transport complexes. In many cases, faulting potentially plays a key role in trapping and as such many existing fields may better be considered as updip combination traps. The results suggest a number of success factors: i) faulting in upslope areas that disconnects thief sands or encourages pinchout geometries; ii) systems composed of fine-grained sediments transported in conjunction with steep slopes, allowing efficient sediment bypass; iii) erosional truncation and sealing by mud-filled channels and mass transport complexes. Identification of these factors may help derisk prospects and make better choices of acreage opportunities. Various research avenues remain to be explored to further understand upslope trapping potential in turbidite systems. Immediate priorities include constraining critical bypass slope angles for turbidity currents, understanding the development of erosive mud-filled channels and systematically assessing detachment in modern seafloor and ancient outcrop systems.

REFERENCES CITED

Allan, J. R., S. Q. Sun, and R. Trice, 2006, The deliberate search for stratigraphic and subtle combination traps: where are we now?, *in M. R. Allen, G. P. Goffey, R. K. Morgan, and I. M. Walker, eds., The Deliberate Search for the Stratigraphic Trap:* Geological Society, London, Special Publications, v. 254, p. 57–103.

Biteau, J. J., M. Blaizot, D. Janodet, and P. de Clarens, 2014, Recent emerging paradigms in hydrocarbon exploration: First Break, v. 32, no. 2, p. 49-58.

Bloomer, R. R., 1990, Jameson Field—U.S.A. Permian Basin, Texas, *in* N. H. Foster and E. A. Beaumont eds., Stratigraphic Traps I, AAPG Treatise of Petroleum Geology Atlas of Oil and Gas Fields, p. 137-157.

Bloomer, R. R., 1991, Sandstone systems and reservoirs on the eastern shelves and slopes of the Midland Basin, Texas, Southwest Section, American Association of Petroleum Geologists; Abilene Geological Society, p. 1-32.

Brooks, H., D. Hodgson, R. Brunt, J. Peakall, M. Hofstra, and S. Flint, S 2018, Deepwater channel-lobe transition zone dynamics: processes and depositional architecture, an example from the Karoo Basin, South Africa: Geological Society of America Bulletin. DOI: https://doi.org/10.1130/B31714.1

Bruhn, C. H. L. and R. G. Walker, 1997, Internal architecture and sedimentary evolution of coarse-grained, turbidite channel-levee complexes, Early, Eocene Regencia Canyon, Espirito Santo Basin, Brazil: Sedimentology, v. 44, p. 17-46.

Bruhn, C. H. L., 2001, Contrasting Types of Oligocene / Miocene, Giant Turbidite Reservoirs from Deep Water, Campos Basin, Brazil: 2001-2002 AAPG Distinguished Lecture Presentation.

Bruhn, C. H. L., J. Adilson, T. Gomes, C. Del Lucchese, and P. R. S. Johann, 2003, Campos Basin: Reservoir Characterization and Management – Historical Overview and Future Challenges, Offshore Technology Conference #15220.

Brown, Jr. L. F., J. M. Benson, G. J. Brink, S. Doherty, A. Jollands, E. H. A. Jungslager, J. H. G. Keenan, A. Muntingh, and N. J. S. van Wyk, 1995, Sequence Stratigraphy in Offshore South African Divergent Basins: An Atlas on Exploration for Cretaceous Lowstand Traps, AAPG Studies in Geology, v. 41, 184p.

Burden, P. L. A. and C. P. N. Davies, 1997a. South Africa Offshore E&P-l Exploration to first production on Block 9 off South Africa: Oil and Gas Journal, Sept. 8, p. 92-97.

Burden, P. L. A. and C. P. N. Davies, 1997b, South Africa Offshore E&P - 2: Oribi field is South Africa's first offshore crude oil production: Oil and Gas Journal, Sept. 15, p. 63-65.

Candido, A., and C. A. G. Cora, 1992, The Marlim and Albacora giant fields, Campos Basin, offshore Brazil, *in* M. T. Halbouty, ed., Giant Oil and Gas Fields of the Decade 1978-1988, p. 123–136.

Carruth, A. G., 2003, The Foinaven Field, Blocks 204/19 and 204/24a, UK North Sea, *in* J. G. Gluyas and H. M. Hichens, eds., United Kingdom Oil and Gas Fields, Commemorative Millennium Volume, Geological Society, London, Memoirs, v. 20, p. 121–130.

Clemenceau, G. R., J. Colbert, and D. Edens, 2000, Production Results from Levee-Overbank Turbidite Sands at Ram/Powell Field, Deepwater Gulf of Mexico, *in* GCSSEPM Foundation 20th Annual Research Conference, Deep-Water Reservoirs of the World, p. 241–251.

Cliff, D., and P. Carter, 2016, Exploration of the Rakhine Basin, Pushing Out the Barriers with New 3D, AAPG Search and Discovery Article #10848..

Cosmo, C.A., A. Palhares, H. D. Rangel, B. Wolff, and A. M. F. de Figueiredo, 1991, Lagoa Parda Field--Brazil Espirito Santo Basin, Southeaster Brazil. I*n*: Stratigraphic Traps II, AAPG Field Studies, p. 349-360.

Dailly, P., T. Henderson, E. Hudgens, K. Kanschat, and P. Lowry, 2012, Exploration for Cretaceous stratigraphic traps in the Gulf of Guinea, West Africa and the discovery of the Jubilee Field: a play opening discovery in the Tano Basin, Offshore Ghana: Geological Society, London, Special Publications, v. 369, p. 235-248.

Defeo de Castro, R., 2014, Stratigraphic Traps of Turbidite Fields in Campos Basin, Brazil, AAPG Search and Discovery Article #90204,AAPG Geoscience Technology Workshop, Stratigraphic Traps and Play Concepts in Deepwater Settings, May 14-15, 2014, Rio de Janeiro, Brazil.

Dolson J. C., M. S. Bahorich, R. C. Tobin, E. A. Beaumont, L. J. Terlikoski, M. L. Hendricks, 1999, Exploring for stratigraphic traps, *in* E. A. Beaumont and N. H. Foster, eds., Exploring for Oil and Gas Traps: Treatise of Petroleum Geology, Handbook of Petroleum Geology, American Association of Petroleum Geologists, v. 1, p 21.2–21.68.

Doré, A. G., and J. A. Robbins, 2005, The Buzzard Field, *in* A. G. Doré and B. A. Vining, eds., Petroleum Geology: North-West Europe and Global Perspectives, Proceedings of the 6th Petroleum Geology Conference, p. 241–252.

Flinch, J. F., J L. Huedo, H. Verzi, H. González, R. Gerster, A. K. Mansaray, L. P. Painuly, L. Rodriguez-Blanco, A. Herra, I. Brisson, and J. Gerard, 2009, The Sierra Leone-Liberia Emerging Deepwater Province: AAPG Search and Discovery Article #10224..

Flinch, J. F., 2014, Context, Challenges, and Future of Deep-Water Plays: An Overview, : AAPG Search and Discovery Article #41417.

Fugelli, E. M. G., and T. R. Olsen, 2005, Risk assessment and play fairway analysis in frontier basins: Part 2 - Examples from offshore mid-Norway: AAPG Bulletin, v. 89, no. 7, p. 883-896.

Godo, T. J., 2006, Identification of stratigraphic traps with subtle seismic amplitude effects in Miocene channel/levee sand systems, NE Gulf of Mexico, *in* M. R. Allen, G. P. Goffey, R. K. Morgan, and I. M. Walker, eds., The Deliberate Search for the Stratigraphic Trap: Geological Society, London, Special Publications, v. 254, p. 127–151.

Gordon, A., T. Younis, C. Bernard-Graille, R. Gray, J.-M. Urruty, L. Ben-Brahim, J.-C. Navarre, B. Paternoster and G. Evers, 2010, Laggan; a mature understanding of an undeveloped discovery, more than 20 years olds, *in* B.A. Vining & S.C. Pickering, eds., Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference, v. 7, p. 279-297.

Hadler-Jacobsen, F., Johannessen, E. P., Ashton, N., Henriksen, S., Johnson, S. D. & Kristensen, J. B., 2005. Submarine fan morphology and lithology distribution, *in* A. G. Doré and B. A., Vinning,eds., Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference, p. 1121–1145.

Harding, A.W., Humphrey, T. J., Lathan, A., Lunsford, M. K., Strider, M. H., 1990, Controls on Eocene submarine fan deposition in the Witch Ground Graben, *in* R. F. P Hardmanand J. Brooks, eds., Tectonic Events Responsible for Britain's Oil and Gas Reserves, Geological Society Special Publication, v. v. 55 p 353-367.

Hewlett, J. S., and Jordan, D. W., 1993, Stratigraphic and combination traps within a seismic sequence framework, Miocene Stevens turbidites, Bakersfield Arch, California, *in* P. Weimer and H. W. Posamentier, eds., Siliciclastic sequence stratigraphy—Recent developments and applications, AAPG Memoir, v. 58, p. 135-162.

Horseman, C., A. Ross, and S. Cannon, 2014, The discovery and appraisal of Glenlivet: a West of Shetlands success story: Geological Society, London, Special Publications, v. 397, p. 131–144.

Jewell, G., 2011, Exploration of the Transform Margin of West Africa: Discovery Thinking – Jubilee and Beyond & Exploration of the Tano Basin and Discovery of the Jubilee Field, Ghana: A New Deepwater Game-Changing Hydrocarbon Play in the Transform Margin of West Africa: AAPG Search and Discovery Article #110156.

Kelly, J., and H. Doust, 2016, Exploration for Late Cretaceous turbidites in the Equatorial African and northeast South American margins: Netherlands Journal of Geosciences, v. 95, no. 4, p. 393–403.

Lamers, E., and S. M. M., Carmichael, 1999, The Paleocene deepwater sandstone play West of Shetland, *in*: A. J. FLEET and S. A. R. BOLDY, eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, p. 645-659.

Leach, H. M. Herbert, N., Los, A., and Smith, R. L., 1999, The Schiehallion development, *in* A. J. Fleetand S. A. R. Boldy, eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, Geological Society, London, p. 683-692.

Loizou, N., I. J. Andrews, S. J. Stoker, and D. Cameron, 2006, West of Shetland revisited: the search for stratigraphic traps, *in M. R. Allen, G. P. Goffey, R. K. Morgan, and I. M. Walker, eds., The Deliberate Search for the Stratigraphic Trap:* Geological Society, London, Special Publications, v. 254, p. 225–245.

Loizou, N., 2014, Success in exploring for reliable, robust Paleocene traps west of Shetland: Geological Society, London, Special Publications, v. 397, no. 1, p. 59–79.

MacAulay, F., 2015, Sea Lion Field discovery and appraisal: a turning point for the North Falkland Basin: Petroleum Geoscience, v. 21, no. 2–3, p. 111–124.

MacGregor, D. S., J. Robinson, and G. Spear, 2003, Play fairways of the Gulf of Guinea transform margin, in T.J. Arthur, D.S. MacGregor, and N.R. Cameron, eds., Petroleum geology of Africa—New themes and developing technologies: Geological Society, London, Special Publication v. 207, p. 131-150.

Martin, J., G. Duval, and L., Lamourette, 2015, What Lies Beneath the Deepwater Tano Basin?: GEOExPro, v. 12, no. 5, p. 28-30.

Mattingly G. A. and H. H. Bretthauer, 1992. The Alba field – A Middle Eocene deep water channel system in the UK North Sea, *in* M. T. Halbouty, eds., Giant oil and gas fields of the decade 1978–1988, AAPG Special Publication, v. 54, p. 297–305.

Milton-Worssell, R. J., S. J. Stoker, and J. E. Cavill, 2006, Lower Cretaceous deep-water sandstone plays in the UK Central Graben, *in M. R. Allen, G. P. Goffey, R. K. Morgan, and I. M. Walker, eds., The Deliberate Search for the Stratigraphic Trap:* Geological Society, London, Special Publications, v. 254, p. 169–186.

Moore, I., 2014, Alba Field – how seismic technologies have influenced reservoir characterization and field development *in* T. McKie, P.T.S. Rose, A.J. Hartley, D.W. Jones, and T.L. Armstrong, eds., Tertiary Deep-Marine Reservoirs of the North Sea Region. Geological Society, London, Special Publications, v. 403, p. 355-379.

Moore, R. M., and R. D. Blight, 2006, The geological exploration techniques applied by BG in evaluation of the Buzzard Field prior to discovery , *in M. R. Allen, G. P. Goffey, R. K. Morgan, and I. M. Walker, eds., The Deliberate Search for the Stratigraphic Trap:* Geological Society, London, Special Publications, v. 254, p. 187–205.

Montgomery S. L., 1997, Permian Bone Spring Formation: Sandstone Play in the Delaware Basin Part I—Slope: AAPG Bulletin, v. 81, p. 1239–1258.

Mutti, E., 1992, Turbidite sandstones, AGIP, Instituto di Geologia, Università di Parma, 275p, San

Donato, Milanese.

Mutti, E., and W. R. Normark, 1987, Comparing examples of modern and ancient turbidite systems; problems and concepts: Marine clastic sedimentology; concepts and case studies, p. 1–38.

Newton, S. K., and K. P. Flanagan, 1993, The Alba Field: evolution of the depositional model: Petroleum Geology of Northwest Europe, *in* J. R. Parker, Proceedings of the 4th Conference on Petroleum Geology of NW Europe, , Geological Society of London, p. 161–171.

Offshore Technology website: <https://www.offshore-technology.com/> Accessed June, 2018.

Peres, W. E., 1993, Shelf-fed turbidite system model and its application to the Oligocene deposits of the Campos Basin, Brazil: AAPG Bulletin, v.77, no. 1, p. 81–101.

Petroleum Affairs Division, 2006. Petroleum Systems Analysis of the Rockall and Porcupine Basins, Offshore Ireland – Digital Atlas, PAD Special Publication 3/06, 2006, pp 148

Pinto, A. C. C., S. S., Guedes, C. H. L. Bruhn, J. A. T., Gomes, A. N. De Sa, and J. R., Fagundes Netto, 2001, Marlim complex development - a reservoir engineering overview: SPE Latin American & Carribbean Petroleum Engineering Conference, Buenos Aires, SPE 69438, 15 p.

Posamentier, H. W., and P. R. Vail, 1988, Eustatic controls on clastic deposition II—sequence and systems tract models, *in* C.K. Wilgus, B.S. Hastings, H.W. Posamentier, J. Van Wagoner, C.A. Ross, and G.C.St.C. Kendall, eds., Sea-Level Changes—An Integrated Approach: SEPM Special Publication, v. 42, p. 125–154.

Prather, B. E., 2003, Controls on reservoir distribution, architecture and stratigraphic trapping in slope settings: Marine and Petroleum Geology, v. 20, no. 6–8, p. 529–545..

Prather, B. E., C. O'Byrne, C. Pirmez, and Z. Sylvester, 2016, Sediment partitioning, continental slopes and base-of-slope systems: Basin Research, v. 29, no. 3, p. 394-416.

Pyles, D. R., J. P. M. Syvitski, and R. M. Slatt, 2011, Defining the concept of stratigraphic grade and applying it to stratal (reservoir) architecture and evolution of the slope-to-basin profile: An outcrop perspective: Marine and Petroleum Geology, v. 28, no. 3, p. 675–697.

Racey, A., M. F. Ridd, A. R.-, 2015, Chapter 9, Petroleum geology of the Rakhine region, Myanmar, *in A. Racey and M. F Ridd, eds., Petroleum Geology of Myanmar,* Geological Society, London, Memoirs, v. 45, p. 93–108.

Rangel, H. D., P. T. Guimarães, and A. R. Spadini, 2003, Barracuda and Roncador giant oil fields, deep-water Campos Basin, Brazil, in M. T. Halbouty, ed., Giant oil and gas fields of the decade 1990–1999, AAPG Memoir 78, p. 123– 137.

Ray, F. M., S. J. Pinnock, H. Katamish, and J. B. Turnbull, 2010, The Buzzard Field: anatomy of the reservoir from appraisal to production: Petroleum Geology, *in* B. A. Viningand A. & S. C Pickering, eds., Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference, v. 7, p. 369–386.

Reading, H. G., and M. Richards, 1994, Turbidite systems in deep-water basin margins classified by grain size and feeder system: American Association of Petroleum Geologists Bulletin, v. 78, no. 5, p. 792–822.

Ross, W. C., B. A. Halliwell, J. A. May, D. E. Watts, and J. P. M. Syvitski, 1994, Slope readjustment: a new model for the development of submarine fans and aprons: Geology, v. 22, no. 6, p. 511–514.

Sills, S., and D. Agyapong, 2012, Jubilee Field reservoir description and waterflood performance overview, Offshore Technology Conference #23451.

Stephensen, M. W., M. Larsen, G. Dam, and T. Hansen, 2013, The Glenlivet gas discovery - An integrated exploration history: First Break, v. 31, no. 7, p. 51–63.

Stevenson C. J., C., A.-L. Jackson, D. M., Hodgson, S. M., Hubbard, J. T., Eggenhuisen, 2015, Deepwater sediment bypass: Journal of Sedimentary Research, ,v. 85, no. 9, p. 1058–1081.

Stirling, E.L., E. M. G. Fugelli and M. Thompson, 2017, The edges of the wedges: a systematic approach to trap definition and risking for stratigraphic, combination and sub-unconformity traps, *in* M. Bowman and B. Levell, Petroleum Geology of NW Europe: 50 Years of Learning - Proceeding of the 8th Petroleum Geology Conference, Geological Society, London, Petroleum Geology Conference series, v. 8, p. 273-286.

Stoker, S. J., J. C. Gray, J. Haile, I. J. Andrews, and T. D. J. Cameron, 2006, The importance of stratigraphic plays in the undiscovered resources of the UK Continental Shelf, *in M. R. Allen, G. P. Goffey, R. K. Morgan, and I. M. Walker, eds., The Deliberate Search for the Stratigraphic Trap:* Geological Society, London, Special Publications, v. 254, p. 153–167.

Straccia, J. R., B. E. Prather, and S. I. Exploration, 1999, Stratigraphic Traps in Deep-Water Turbidite Reservoirs at the Base of Depositional Slope. SPE 56894.

Subseaiq website < http://www.subseaiq.com> Accessed June, 2018.

Tullow Oil Ltd., media release, 2008, <http://www.tullowoil.com/Media/docs/default-source/3_investors/2008-tullow-capital-markets-day-ghana.pdf> Accessed April 12, 2018.

Van Hoek, T., S. Gesbert and J. Pickens, 2010, Geometric attributes for seismic stratigraphic interpretation. Leading Edge, v. 29, no. 9, p. 1056-1065.

Van der Merwe, W. C., D. M. Hodgson, R. L. Brunt, and S. S. Flint, 2014, Depositional architecture of sand-attached and sand-detached channel-lobe transition zones on an exhumed stepped slope mapped over a 2500 km^2 area: Geosphere, v. 10, no. 6, p. 1076–1093.

Wynn, R. B., N. H. Kenyon, D. G. Masson, D. A. V. Stow, and P. P. E. Weaver, 2002, Channel-Lobe Transition Zones: AAPG Bulletin, v. 8, no. 8, p. 1441–1462.

Yang, S. Y., and J. W. Kim, 2014, Pliocene basin-floor fan sedimentation in the Bay of Bengal (offshore northwest Myanmar): Marine and Petroleum Geology, v. 49, no. 1, p. 45–58.

VITA

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CAPTIONS

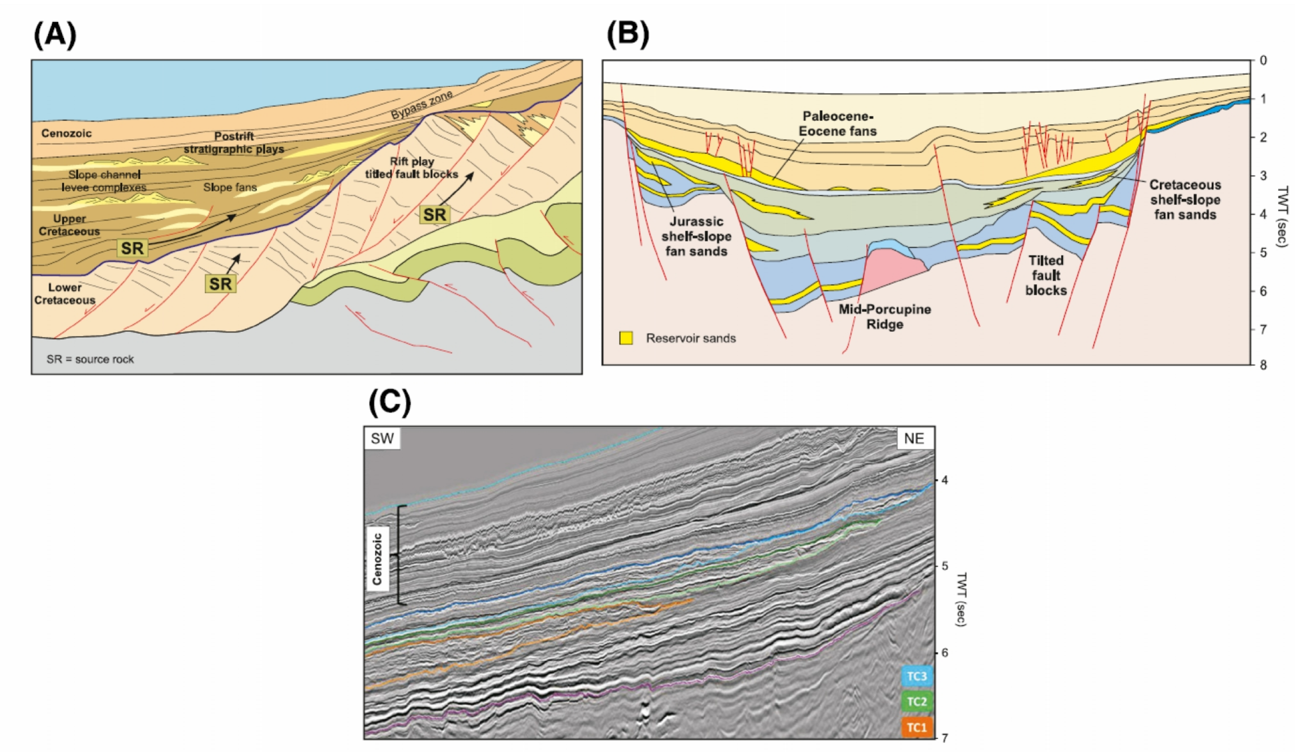

Figure 1. Examples of play models where upslope stratigraphic traps are recognised as important exploration targets: (A) West African Transform Margin model showing detached upper Cretaceous post-rift slope channel and fan systems (after Jewell, 2011); (B) Porcupine Basin (offshore Ireland) model showing detached Cretaceous and Paleocene-Eocene deepwater sands (after Petroleum Affairs Division, 2006). (C) Seismic section showing onlap of deepwater turbidite complexes (TC1-TC3) offering potential for pinchout traps – upper Cretaceous, offshore Ghana (from Martin et al., 2015; image courtesy of CGG Multi-Client & New Ventures).

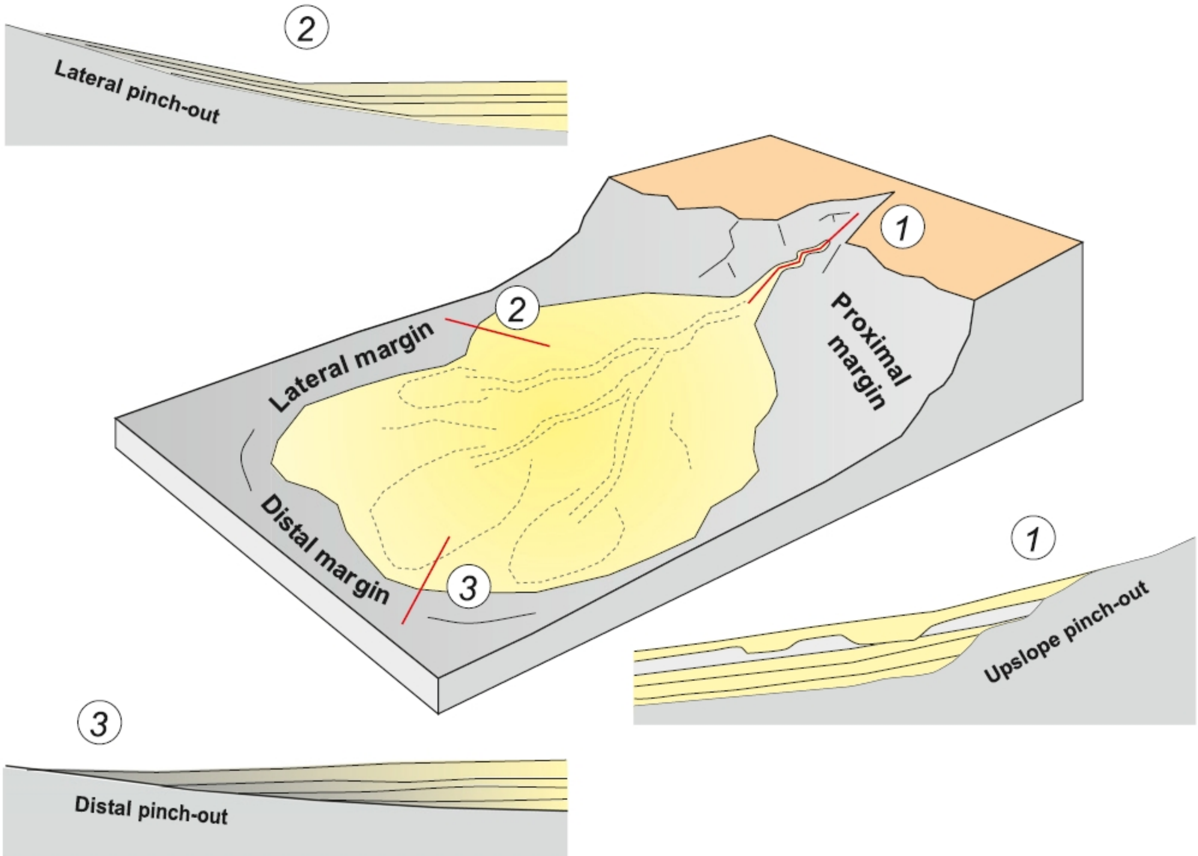

Figure 2. Schematic diagram illustrating the various depositional margin pinchouts that can offer large-scale stratigraphic traps in a deepwater turbidite system. The location along the depositional profile of the proximal pinchout on the inbound slope may vary or alternatively be absent where systems are attached to upslope shelf or fluvial sands.

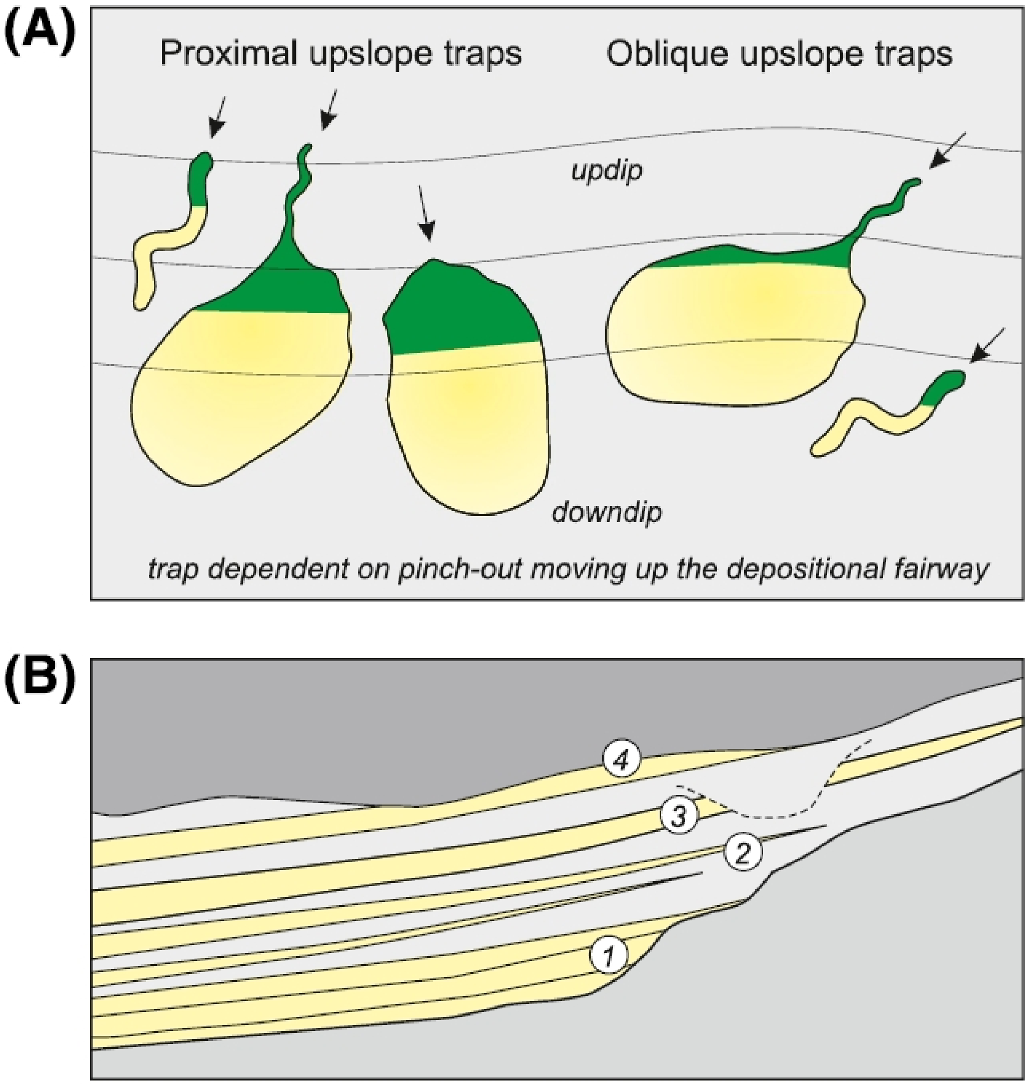

Figure 3. (A) Proximal and oblique upslope stratigraphic trap configurations for deepwater systems shown in map view (arrows indicate sediment transport direction). (B) Termination types associated with upslope stratigraphic pinchouts shown in cross section. 1) Depositional pinchout on to basin margin unconformity; 2) intraformational depositional pinchout; 3) intraformational erosional truncation; 4) erosional truncation by a major unconformity. These are broadly equivalent to onlap onto regional unconformity traps, lateral depositional pinchout traps, truncation-edge traps and regional subcrop traps, respectively *sensu* Allan et al. (2006).

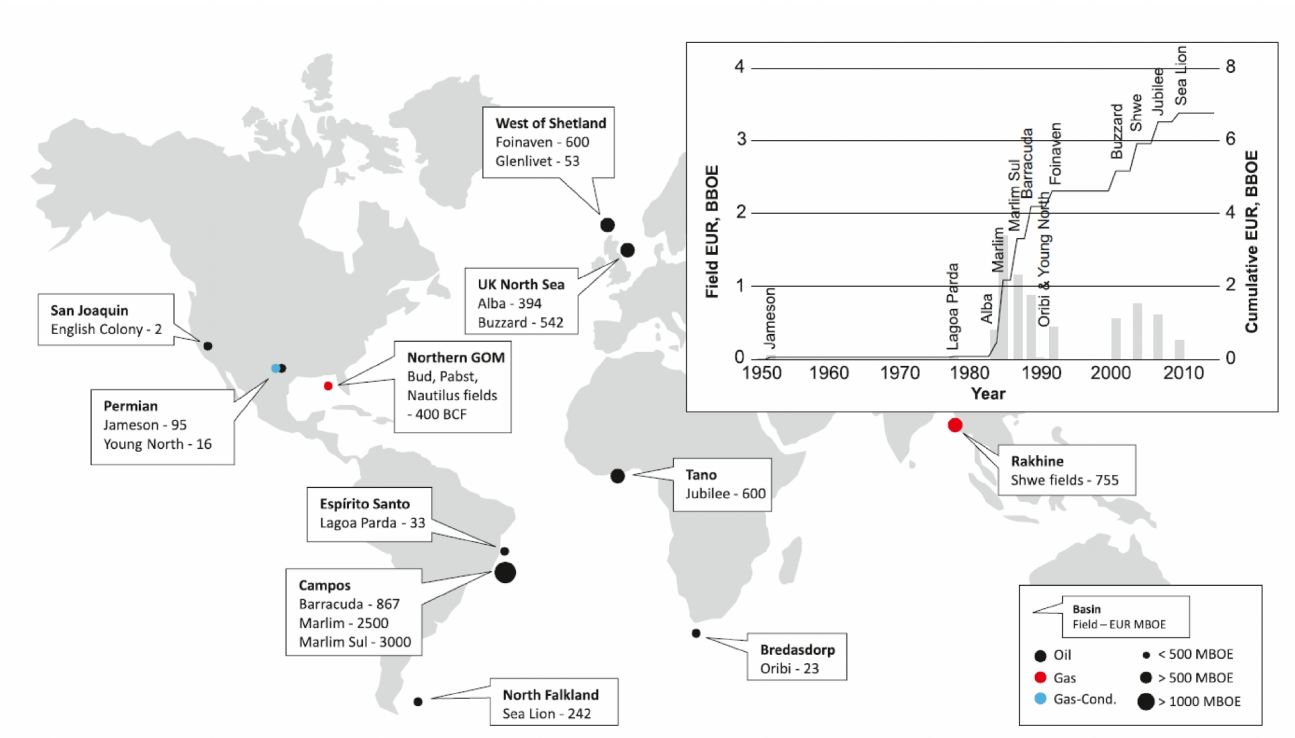

Figure 4. Global distribution of discovered commercial fields reported to have deepwater reservoirs with upslope stratigraphic reported (Table 1). Inset shows graph of the discovery record for these fields, along with Estimated Ultimate Recovery (EUR) for fields and the global cumulative EUR for this play type.

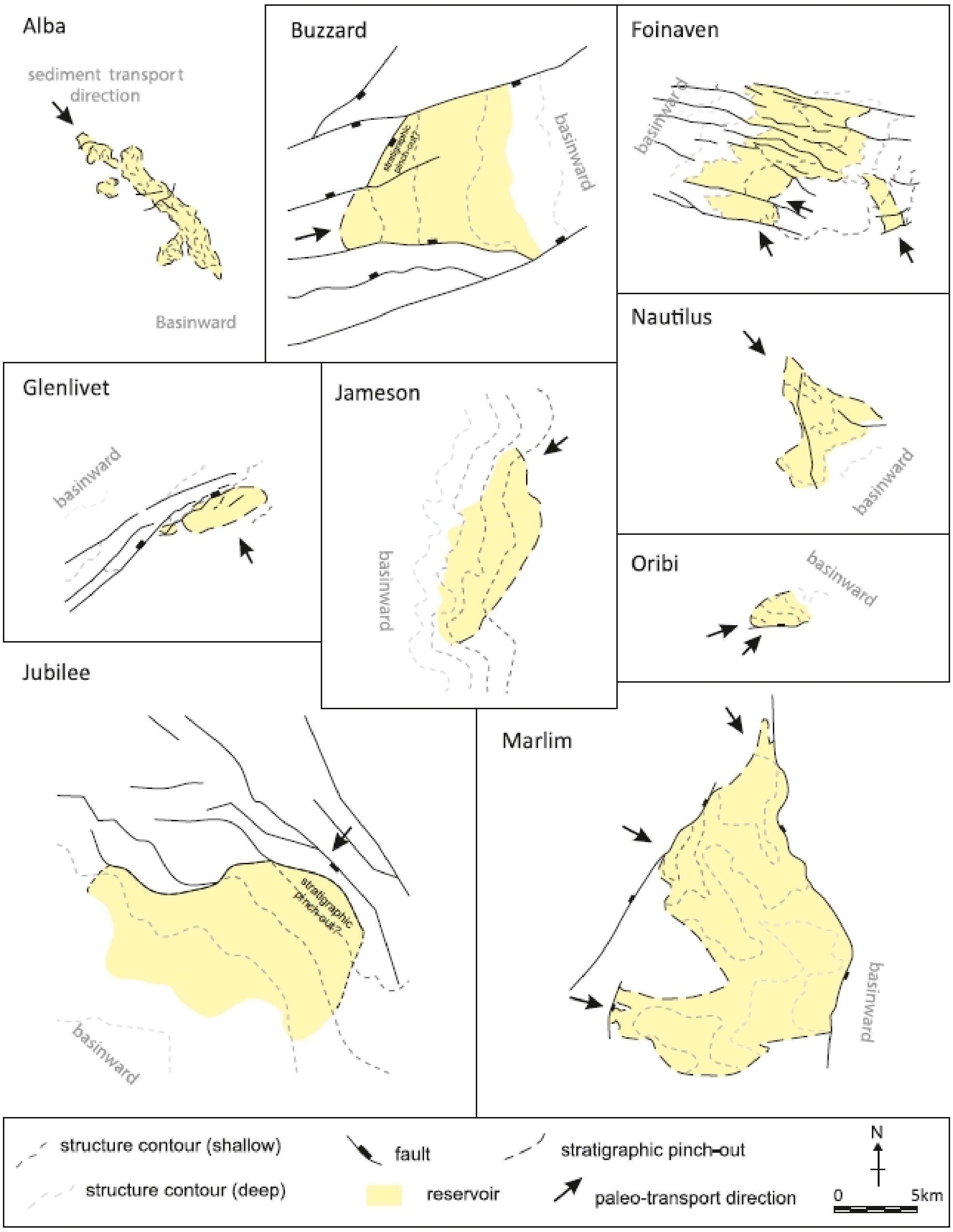

Figure 5. Simplified maps of oil and gas fields with upslope stratigraphic traps showing their field outlines, structure contours (top or near top reservoir), inferred trapping, sediment transport direction and location of depositional feeder system(s). Based on the following sources: Alba (Newton & Flanagan, 1993), Buzzard (Doré & Robins, 2005), Foinaven (Carruth, 2003), Glenlivet (Horseman et al., 2014), Jameson (Bloomer, 1990), Oribi (Burden & Davies, 1997b), Nautilus (Godo, 2006), Jubilee (Dailly et al., 2012), Marlim Sul (Candido & Cora, 1992).

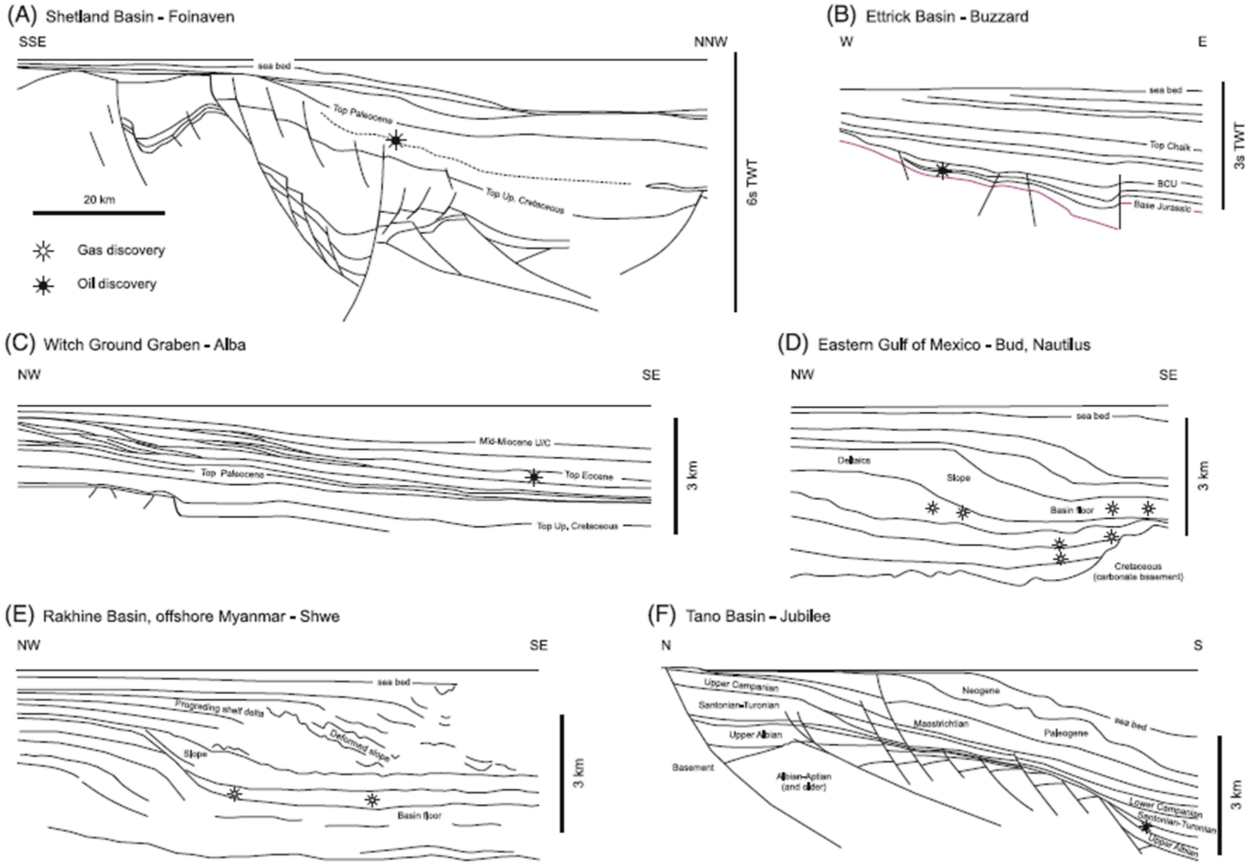

Figure 6. Geological cross sections based on seismic dip lines of basins with upslope stratigraphic trapped fields: A) Shetland Basin, Foinaven field; B) Ettrick Basin, Central North Sea, Buzzard field; C) Witch Ground Graben, Central North Sea, Alba field; D) Eastern Gulf of Mexico, Bud and Nautilus fields; E) Rakhine Basin, Shwe fields; F) Tano Basin, Jubilee field. Modified from Lamers & Carmichael (1999), Doré & Robbins (2005), Harding et al. (1990), Godo (2006), Yang & Kim (2014) and Tullow Oil Ltd. Media Release (2008), respectively. BCU = Base Cretaceous Unconformity.

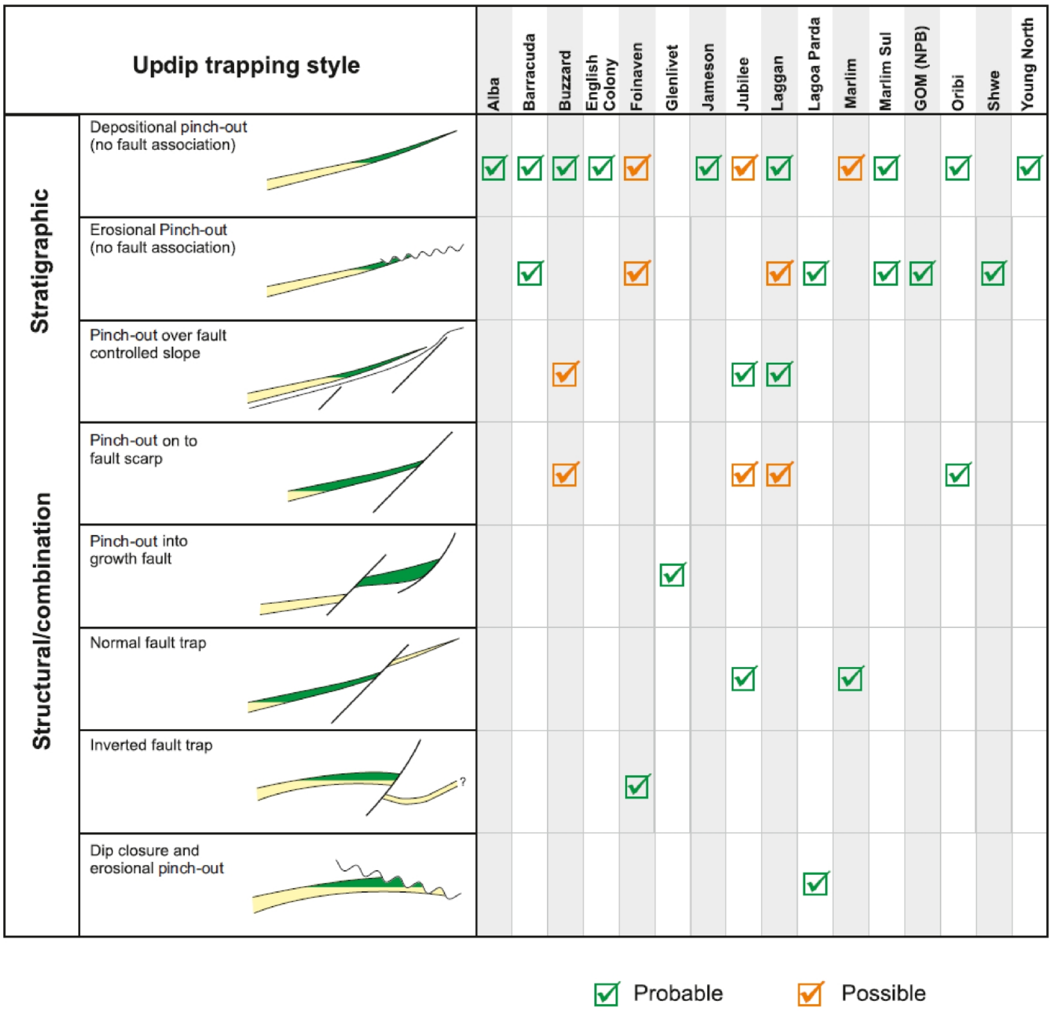

Figure 7. Summary of inferred updip trapping styles for reservoirs discussed in this study.

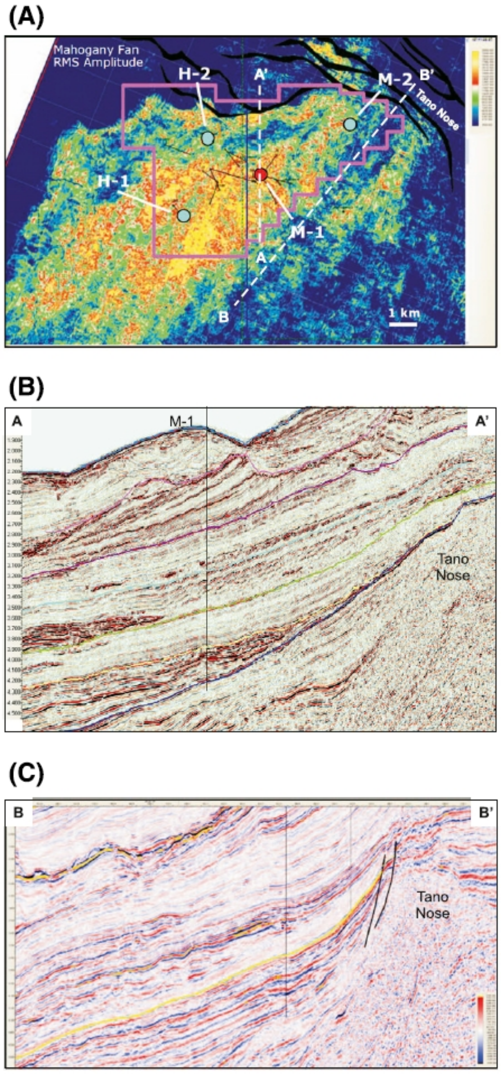

Figure 8. Jubilee Field. A) RMS amplitude extraction of the Mahogany fan reservoir interval (from Sills & Agyapong, 2012 and used with permission of Offshore Technology Conference). B) N-S seismic line showing onlap related pinchout at the inferred lateral margin (from Jewell, 2011 and used with permission of AAPG). C) SW-NE seismic lines showing upslope pinchout but also updip faulting at the reservoir level (from Dailly et al., 2012 and used with permission of the Geological Society of London). The Mahogany-1 (M-1) discovery well and the top of the Mahogany reservoir interval (yellow horizon) is shown in seismic sections.

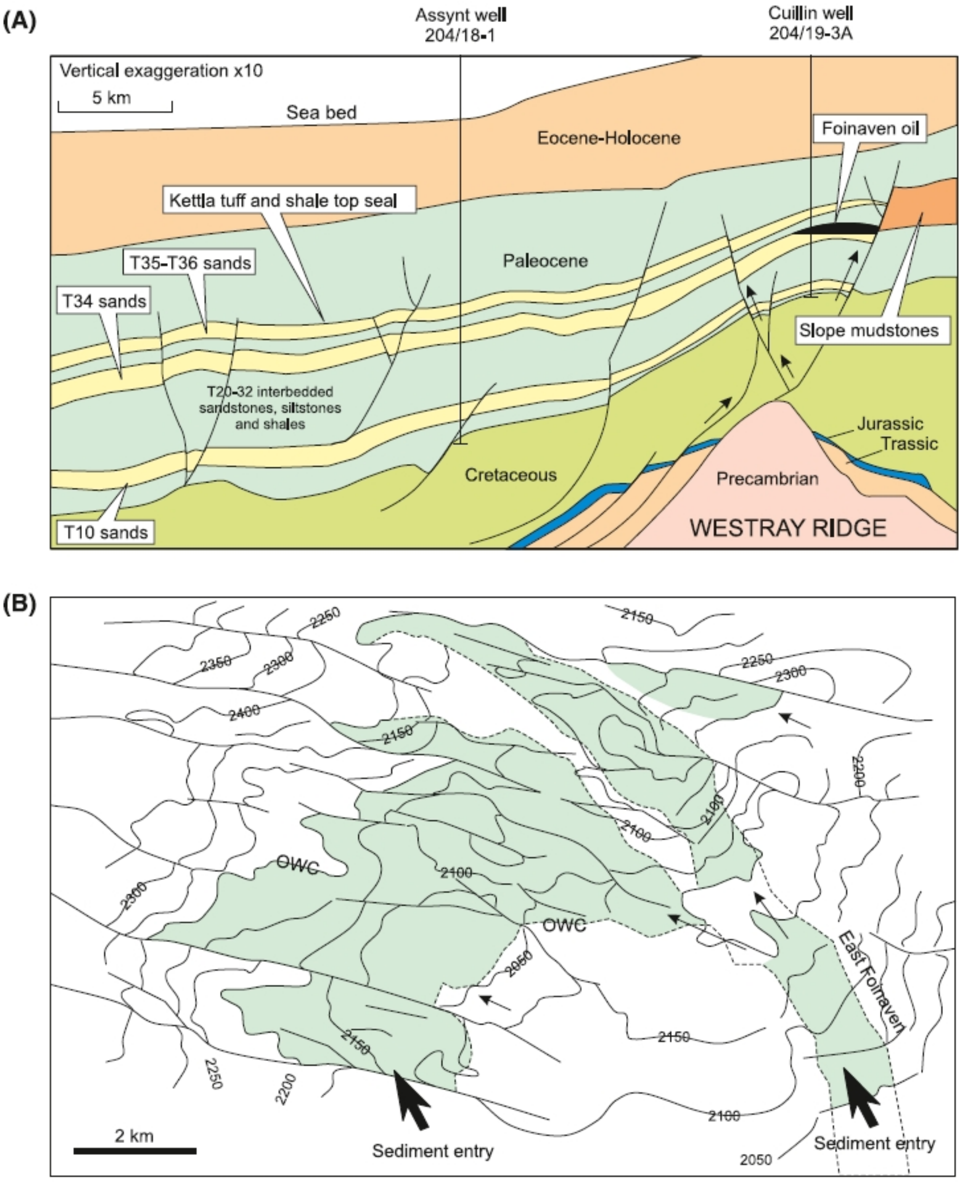

Figure 9. Foinaven Field. (A) Seismic based geological section of the Foinaven subbasin, West of Shetland (Loizou et al., 2006 and used with permission of the Geological Society of London). (B) Composite depth structure map showing hydrocarbon filled sands delineated into field segments by WNW–ESE faulting and stratigraphic (inter-channel) boundaries (based on Carruth, 2003 and used with permission of the Geological Society of London). Note faults that define the southern and southeastern upslope field boundaries cut across the inferred sediment entry points.

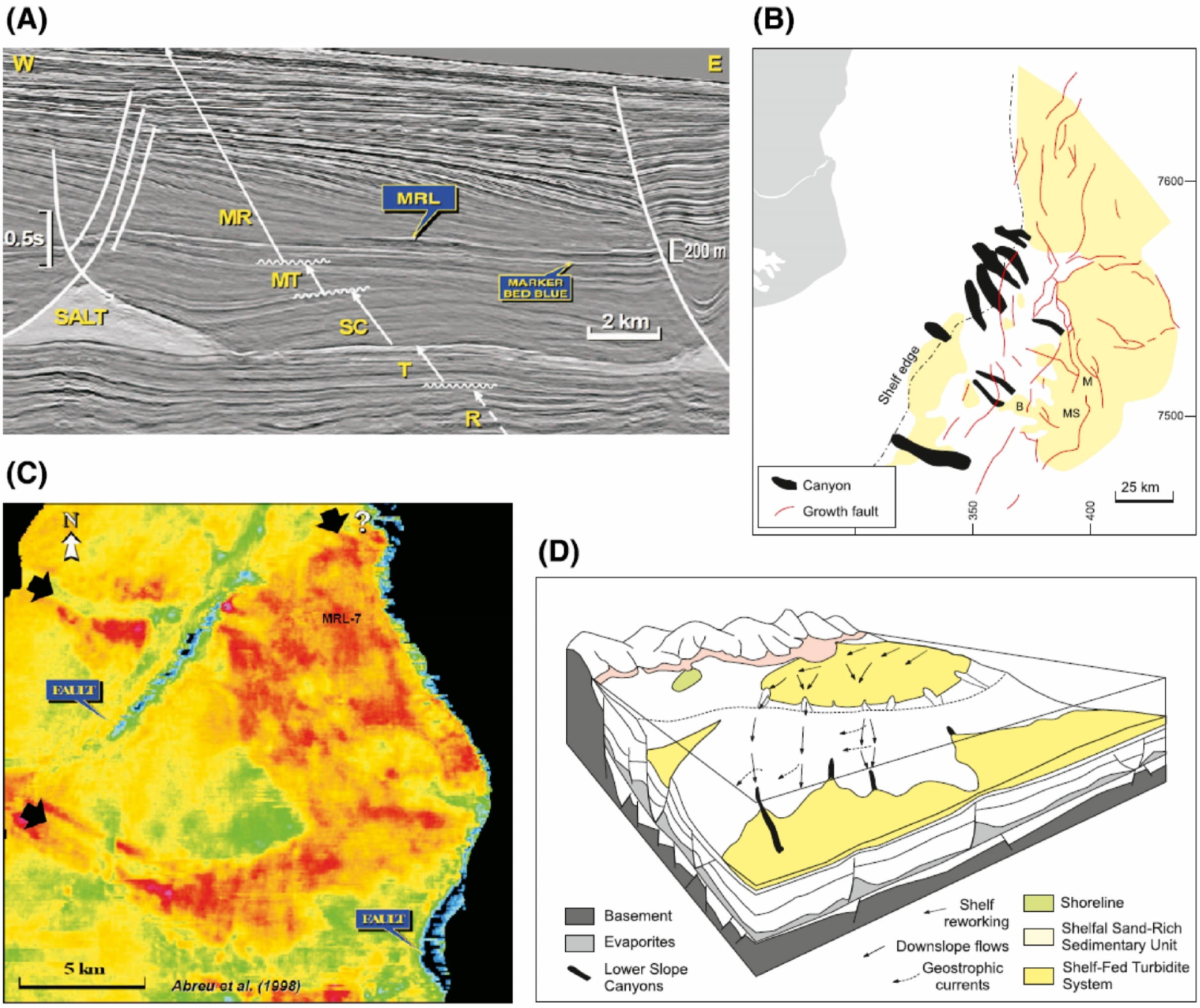

Figure 10. Marlim field. (A) Seismic profile for the eastern Brazilian margin (from Bruhn et al., 2003 and used with permission of Offshore Technology Conference). (B) Interpreted basin physiography, distribution and structure of the Oligocene turbidite system (from Peres, 1993 and used with permission of AAPG). Locations of the Marlim (M), Marlim Sul (MS) and Barracuda (B) fields are shown. (C) Seismic amplitude map showing unconfined sand-rich lobes and feeder channels with at least one offset by faulting (from Bruhn, 2001 and used with permission of AAPG). Arrows indicate sediment transport direction. Red and orange indicate thicker sandstone successions. (D) Inferred depositional model of a shelf-fed turbidite system during late stages of the Oligocene (from Peres, 1993 and used with permission of AAPG). Abbreviations: (R) Continental Rift Megasequence, (T) Transitional Evaporitic Megasequence, (SC) Shallow Carbonate Megasequence, (MT) Marine Transgressive Megasequence, (MR) Marine Regressive Megasequence and (MRL) top Marlim Field.

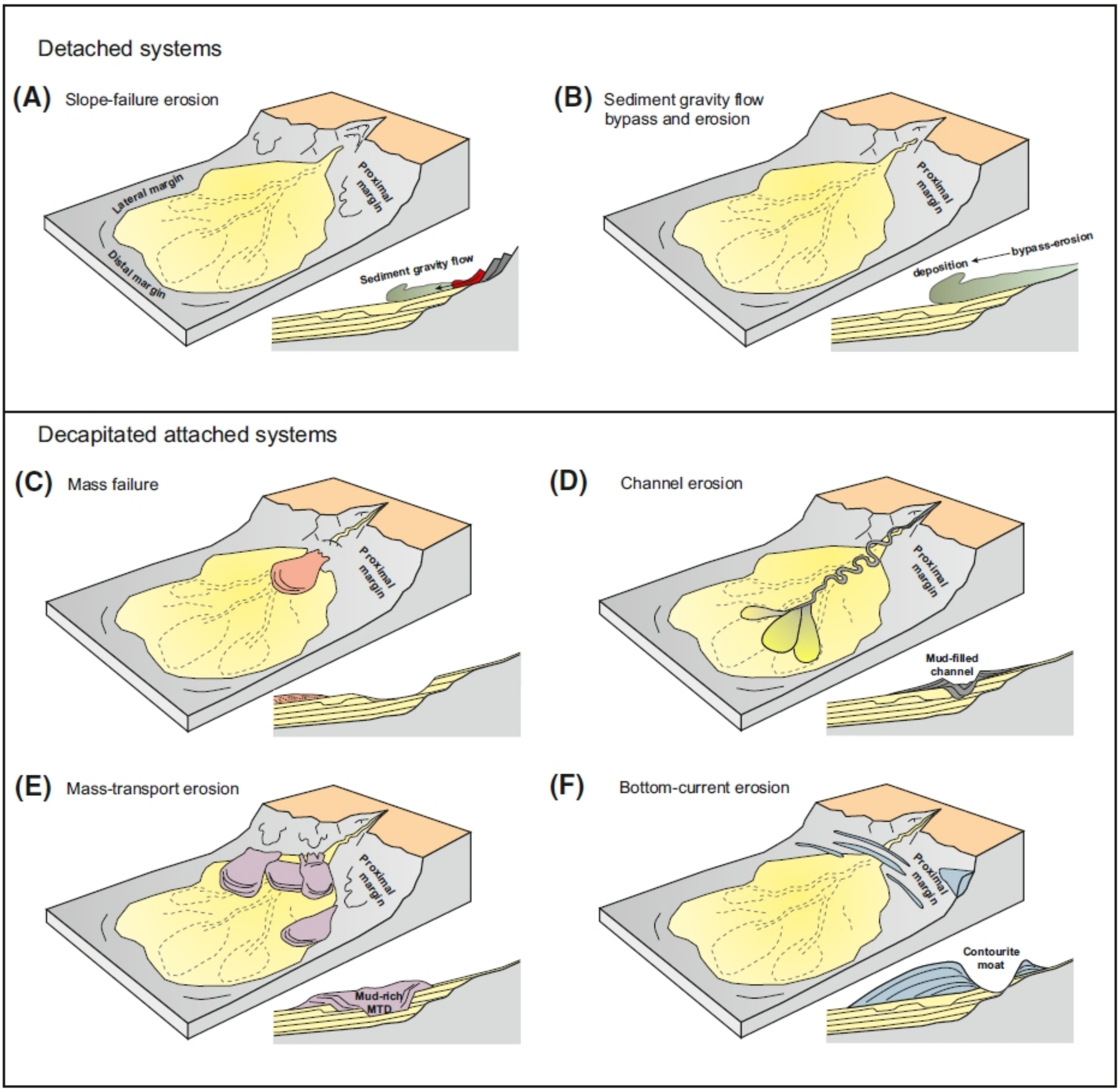

Figure 11. Summary of processes that may generate upslope stratigraphic pinchouts through erosion or non-deposition in relatively proximal upslope areas: (A) basin-margin slope failure; (B) sediment gravity flow erosion and bypass; (C) fan slope failure; (D) erosion by mud-filled turbidite channels; (E) erosion by mud-rich mass flows; (F) erosion by bottom currents. Cases A and B involve turbidite systems that are detached at the time of deposition, whereas, C-F involve initially attached systems that become detached through erosional decapitation.

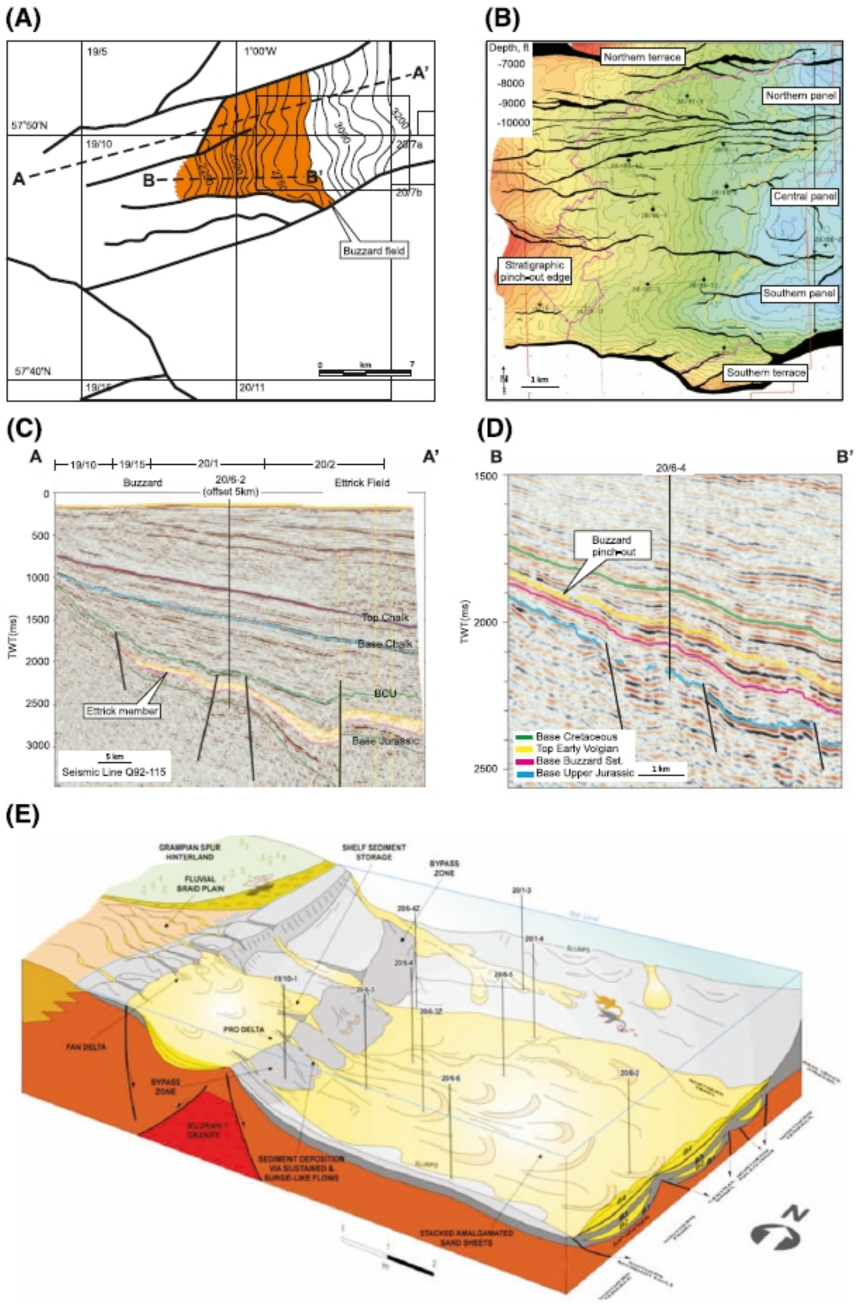

Figure 12. Buzzard field. (A) Pre-drill depth structure map of the Top Buzzard Member (Doré & Robbins, 2005 and used with permission of the Geological Society of London). (B) Depth structure map of top reservoir post-drill (Ray et al., 2010 and used with permission of the Geological Society of London); the main accumulation is offset by several west–east oriented normal faults that divide the field into three main regions referred to as the Southern, Central and Northern Panels, flanked by smaller structural terraces. (C & D) Seismic lines showing stratigraphic thinning of reservoir interval updip towards the west (Doré & Robbins, 2005 and used with permission of the Geological Society of London). (E) Depositional model for the Buzzard Sandstone Member (Doré & Robbins, 2005 and used with permission of the Geological Society of London).

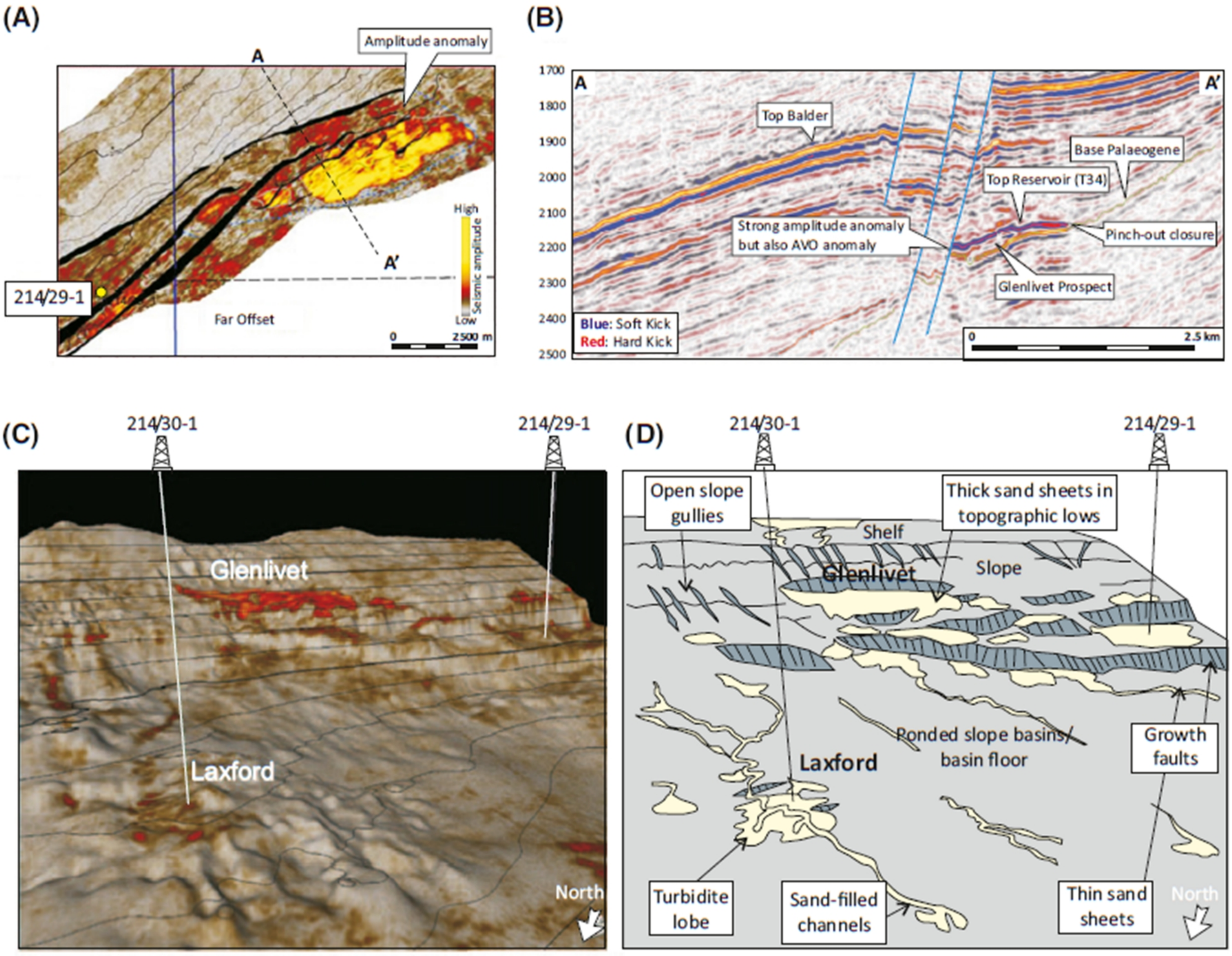

Figure 13. Glenlivet field. (A) Far offset amplitude response. (B) Full-stack seismic dip line through the Glenlivet Prospect showing a strong amplitude anomaly and amplitude versus offset (AVO) anomaly (from Horseman et al. 2014 and used with permission of the Geological Society of London). (C) Three-dimensional perspective view showing reservoir depth structure map showing far offset amplitude as surface attribute. (D) Depositional model based on seismic interpretation, well information and analogues for Glenlivet and neighbouring prospects: predicts thick stratigraphically trapped sandstones in topographic lows on a complex fault (figures 13B-D from Stephensen et al. 2013 and used with permission of EAGE).

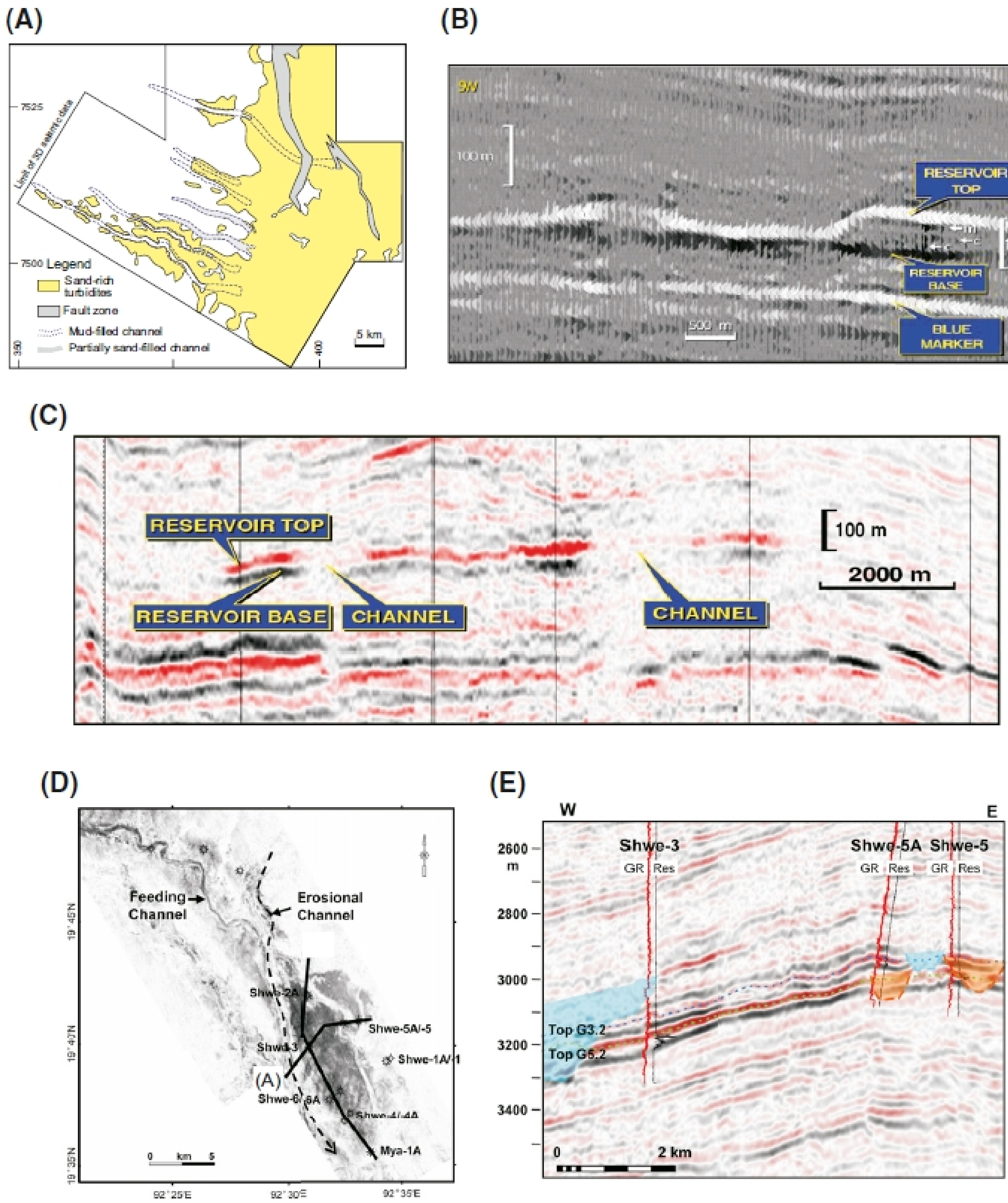

Figure 14. Examples of mud-filled channels that aid upslope stratigraphic trapping from the Campos and Rakhine basins. (A) Map of Marlim and Marlim Sul based on seismic amplitudes and showing interpreted mud-filled canyons and channels on the lower slope and basin floor (from Peres, 1993 and used with permission of AAPG). (B) SW-NE seismic section from Marlim Field showing a 70 m (230 ft) deep and 3 km (1.9 mi) wide mud-filled channel that erodes into the reservoir interval (from Bruhn, 2001 and used with permission of AAPG). (C) Sand rich lobes dissected by younger mud-filled channels in the Barracuda Field (from Bruhn, 2001 and used with permission of AAPG). (D). Maximum amplitude map of top G5.2 reservoir showing sand-filled sinuous feeder channel and larger lower-sinuosity, mud-filled, erosional channels dissecting the Shwe lobe reservoir (from Yang & Kim, 2014 and used with permission of Elsevier). (E) Strike line (line A in fig. 14D) through the Shwe field displaying large-scale erosional channel incising into the Shwe reservoir. Gamma ray (GR) and resistivity (Res) logs are shown for wells (from Yang & Kim, 2014 and used with permission of Elsevier).

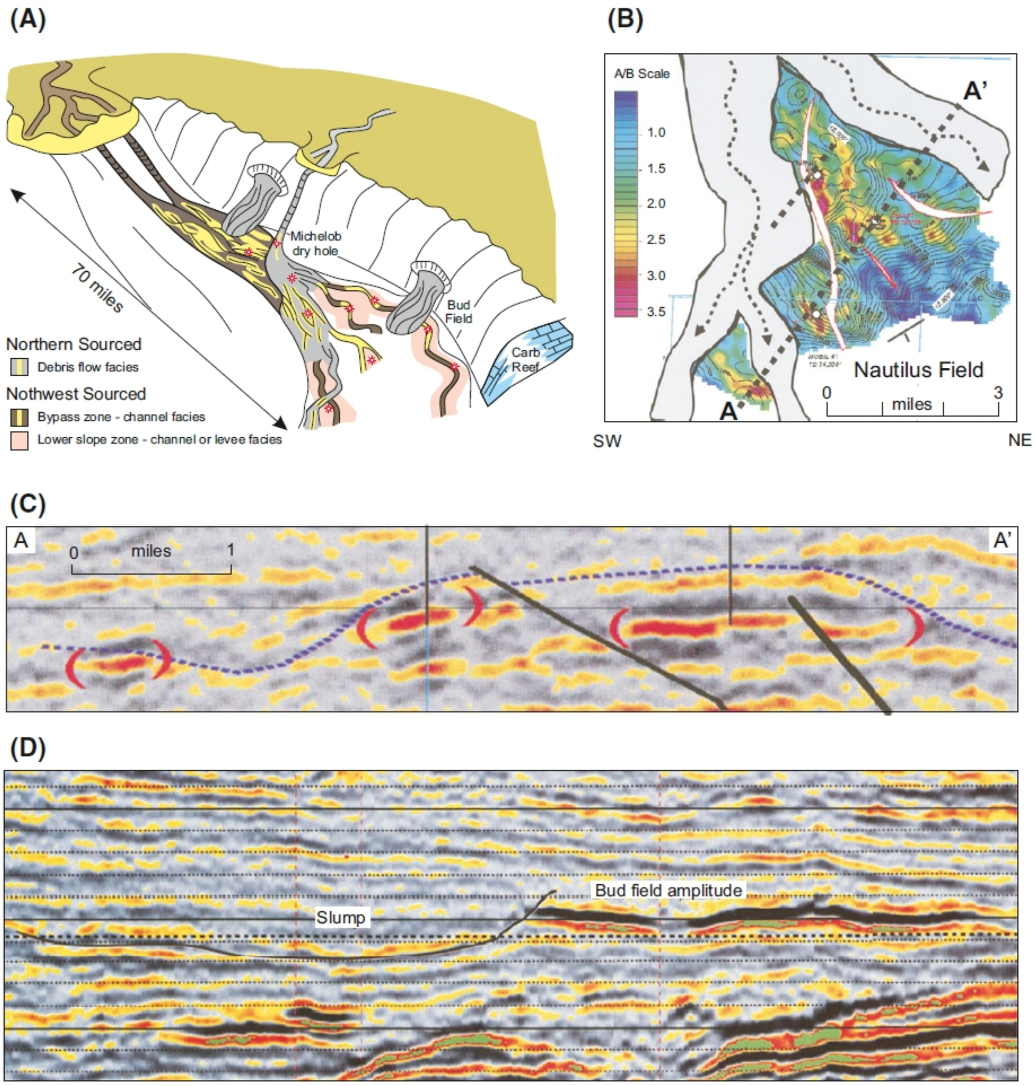

Figure 15. Reservoirs with upslope pinchouts related to mass transport erosion (from Godo, 2006 and used with permission of the Geological Society of London). (A) Depositional model for the Miocene of the eastern Gulf of Mexico with slumps and debris flows locally eroding sandy depositional systems. (B) Map of the Nautilus Field showing gas-related amplitudes constrained laterally and updip by slump-related shale-filled scours shown in grey. Dotted arrowed lines indicates direction of flow of mass transport. (C) Seismic section through the Nautilus Field showing gas sands separated by shale-filled scours at the base of the mass transport deposit (blue dashed line). Hydrocarbon-filled remnants sands are shown as red events. Shales and silts are grey to pale-yellow in the display. D) Seismic section showing the Bud field cut by a shale-filled scour at the base of a slumped interval.

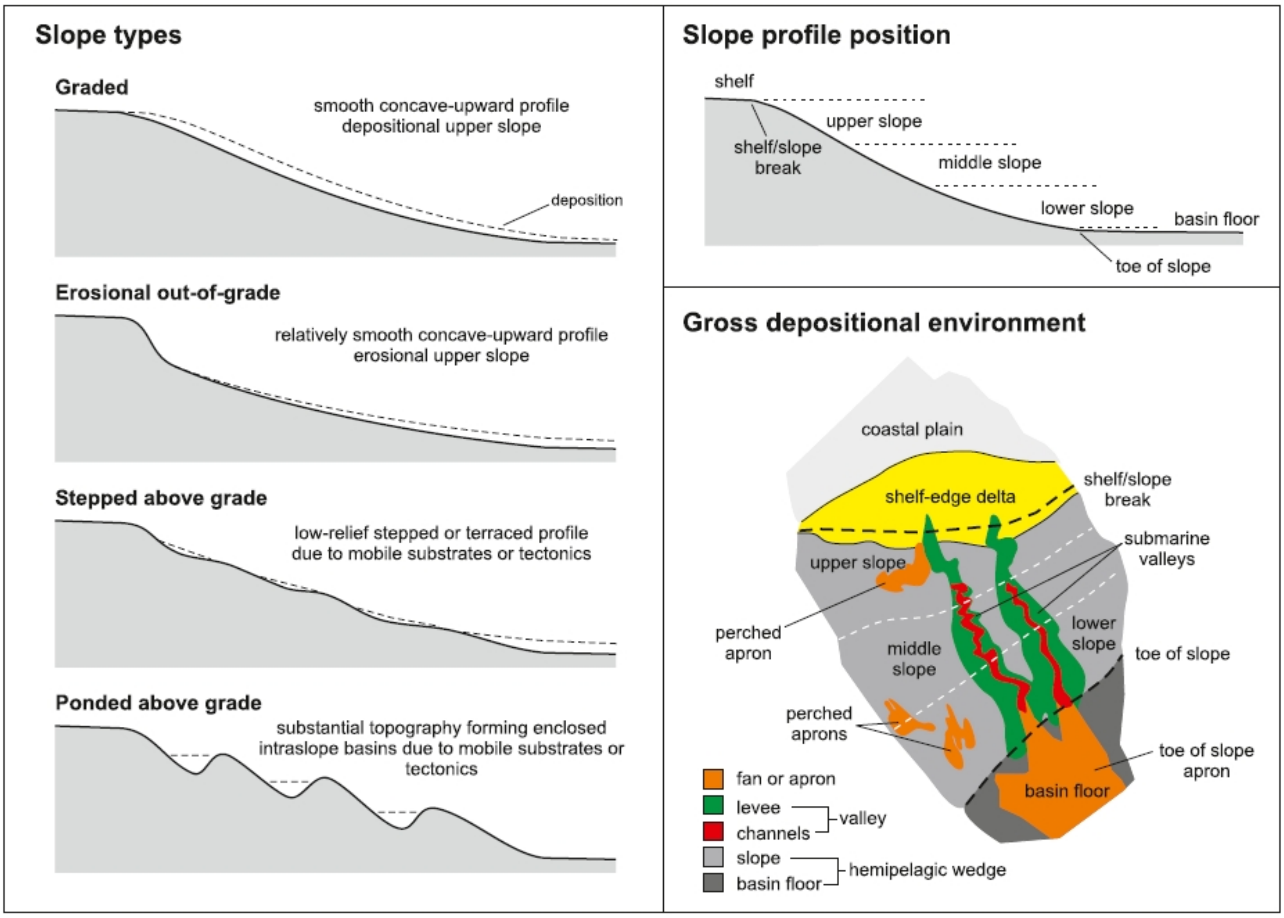

Figure 16. Summary of the classification scheme used to describe reservoir depositional setting (after Prather et al., 2016 and used with permission of John Wiley and Sons).

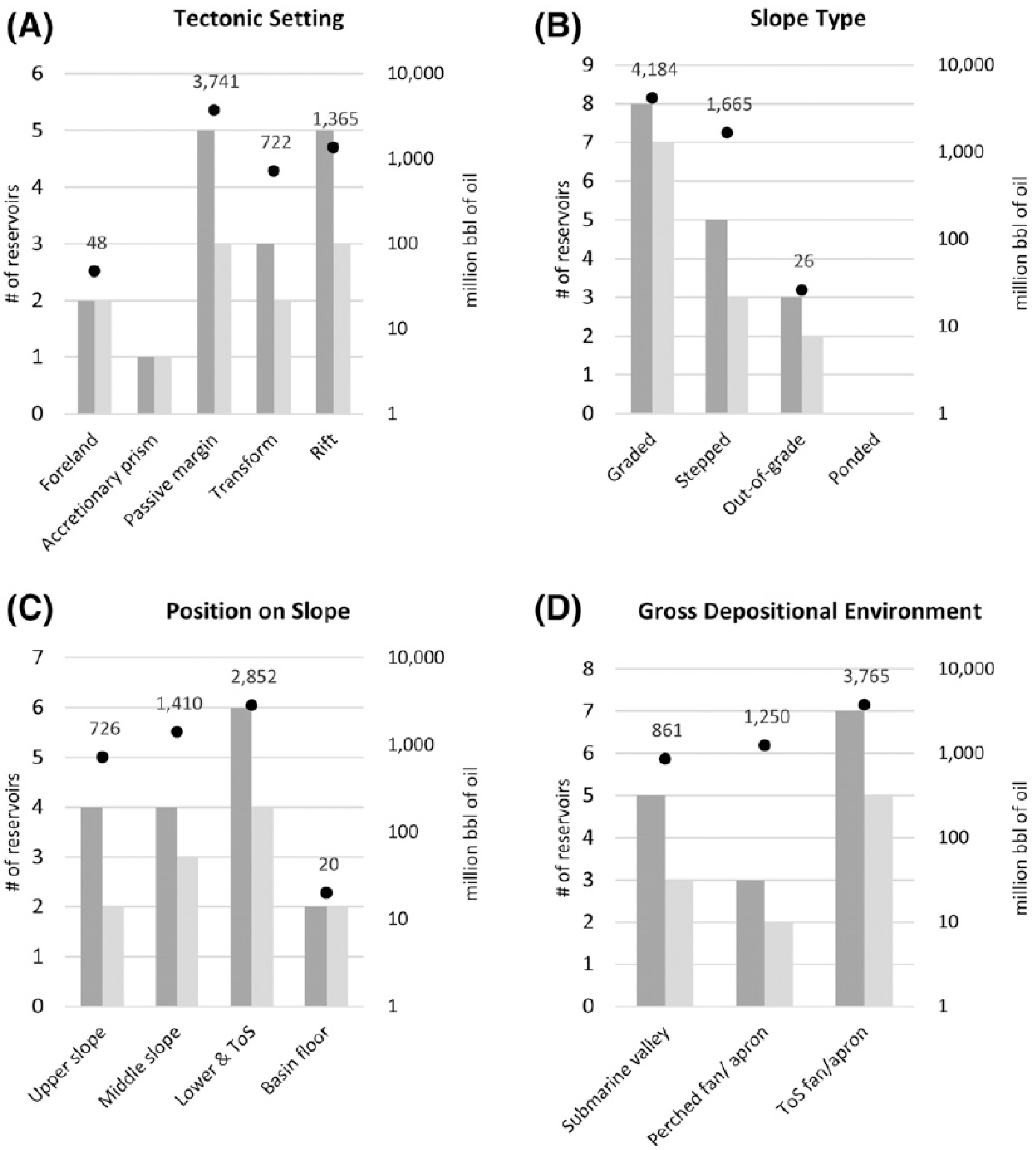

Figure 17. Number of reservoirs inferred to have upslope stratigraphic traps by tectonic setting (A); slope type (B); position on the slope (C) and gross depositional environment (D). Dark grey bars for all reservoirs considered in this study (Table 1). Light grey bars for those where updip structural trapping components have not been inferred (i.e. higher confidence of pure stratigraphic traps). Numbers indicate the commercially discovered P50 (median) oil reserves for all reservoirs. Abbreviation: Toe of slope (ToS).

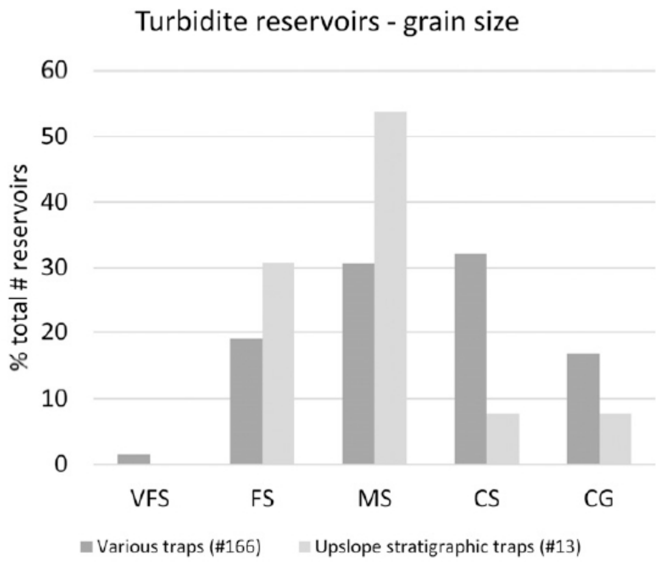

Figure 18. Frequency of turbidite reservoirs by maximum grain size for i) reservoirs with different trap types (dark grey bars) and ii) those with upslope stratigraphic traps (light grey bars). Abbreviations: very fine sand (VFS); fine sand (FS); medium sand (MS); coarse sand (CS); and conglomerate (Cg).

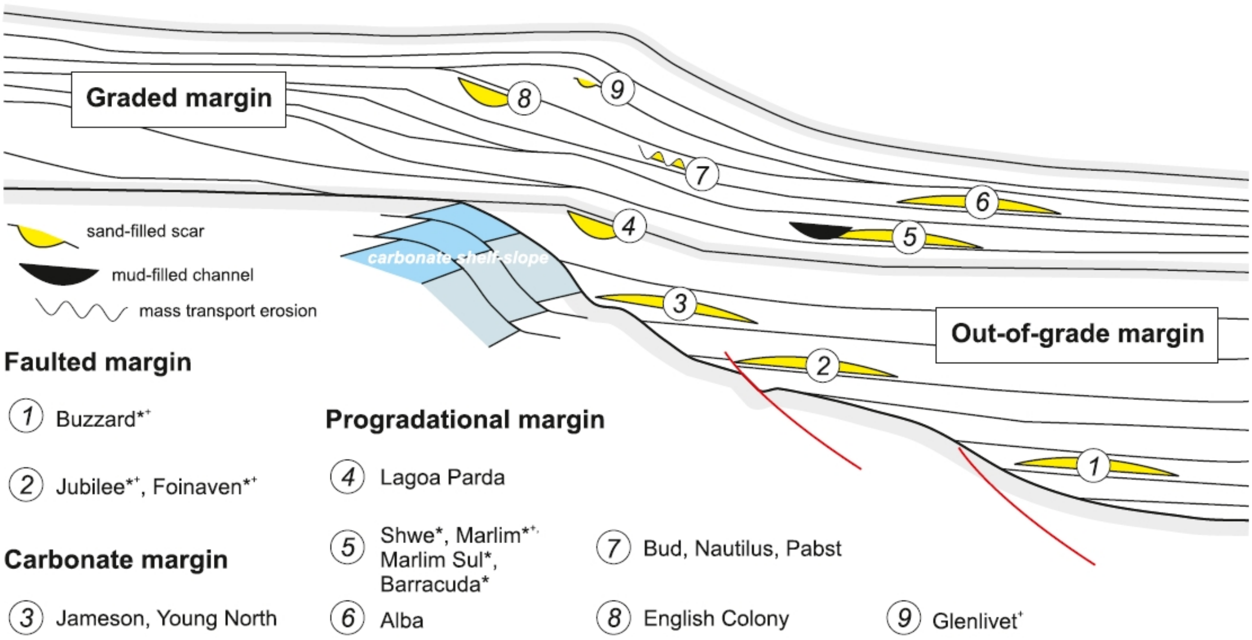

Figure 19. Schematic summary of depositional setting of upslope stratigraphic traps based on commercial discoveries to date including those with giant oil fields (*) encountered in toe-of-slope environments. [+]Fields that have previously been discussed as stratigraphic traps but may also have a structural component to their updip trapping mechanism (see Table 2 & Figure 7).

Table 1. Deepwater turbidite reservoirs with inferred upslope stratigraphic trapping.

Field - Reservoir Interval	Reservoir age	Basin	Water depth (m)	Discovery year	HC type[1]	Reserves[2]	Status	References[3]
Alba - Nauchlan	Middle Eocene	Central North Sea	140	1984	Oil	400[†]	Decline	Harding et al. (1990), Newton & Flanagan (1993), Moore (2014)
Barracuda - Carapebus	Eocene-Oligocene	Campos	600-1200	1989	Oil	867[†]	Producing	Bruhn et al. (2003), Rangel et al. (2003), Van Hoek et al. (2010), Defeo de Castro (2014)
[+] Buzzard - Buzzard Sandstone	Late Jurassic	Central North Sea	100	2001	Oil	550[†]	Producing	Doré, G. & Robbins (2005), Moore & Blight (2006), Ray et al. (2010)
English Colony - Stevens Sandstones	Miocene	San Joaquin	Onshore	-	Oil	1.6*	Abandoned	Hewlett & Jordan (1993), Gautier & Scheirer (2017)*
[+] Foinaven - Vaila Fm	Paleocene	Faroe-Shetland	400-600	1992	Oil	415[†]	Producing	Straccia & Prather (1999)
[+] Glenlivet - Vaila Fm	Paleocene	Faroe-Shetland	500	2009	Gas	-	Development	Stephensen et al. (2013), Horseman et al. (2014), Loizou (2014)
Jameson - Jameson-Cook Sandstone	Early Permian	Permian	Onshore	1952	Oil	45.3*	Mature	Bloomer (1990)*, Bloomer (1991)
[+] Jubilee - Mahogany	Turonian	Tano	1100	2007	Oil	>600*	Producing	Jewell (2011), Dailly et al. (2012), Biteau et al. (2014), Kelly & Doust (2016)*
[+] Laggan - Vaila Fm	Paleocene	Faroe-Shetland	600	1986	Gas-Cond.	-	Producing	Gordon et al. (2010), Loizou (2006)
[+] Lagoa Parda - Lagoa Parda	Early Eocene	Espirito Santo	0-200	1978	Oil	24	Decline	Bruhn (1993), Bruhn et al. (1997), Cosmo et al. (1991)*
[+] Marlim - Carapebus	Eocene-Oligocene	Campos	650-1050	1985	Oil	1700[†]	Decline	Candido & Cora (1992), Peres (1993), Bruhn et al. (2003), Defeo de Castro (2014)
Marlim Sul - Carapebus	Eocene-Oligocene	Campos	720-2600	1987	Oil	1150[‡]	Producing	Peres (1993), Bruhn et al. (2003)
Nautilus, Pabst, Bud fields - Miocene Sands	Miocene	Northern GOM	-	1985-2003	Gas	-	Producing	Godo (2006)
[+] Oribi - 14A Sequence	Early Cretaceous	Bredasdorp	120	1990	Oil	20*	Mature	Burden & Davies (1997a; 1997b*)
Sea Lion - SL10-SL20	Lower Cretaceous	North Falkland	450	2010	Oil	242[†]	Development	MacAulay (2015)
Shwe, Shwe Phyu, Mya fields - G Series	Late Pliocene	Rakhine	90-600	2004	Gas	755[†]	Producing	Yang & Kim (2014)
Young North - Bone Spring	Early Permian	Permian	Onshore	1991	Oil	1.5-3*	Mature	Montgomery (1997)*

[1]Principal hydrocarbon type. [2]Reported recoverable field reserves (MMBOE) from *reference listed, [†]Offshore Technology website field summary, [‡]Subseaiq website field summary. Websites accessed December 2016. [3]References for stratigraphic trap interpretation and *reserves. [+]Fields have previously been discussed as stratigraphic traps but may also have a fault-structural component to their updip trapping mechanism (see Table 2 & Figure 7).

Table 2. Trapping configuration of deepwater turbidite reservoirs with inferred upslope stratigraphic trapping.

Field - Reservoir Interval	Field trap type	Updip trapping	Updip stratigraphic pinchout style	Lateral trapping	Downdip limit
Alba - Nauchlan	Stratigraphic	SP (?with compactional dip closure)	DP	SP (?compactional dip closure)	OWC?
Barracuda - Carapebus	Combination	SP	ET (mud-filled channels)	SP	SP and faulting (dip closure?)
* Buzzard - Buzzard Sandstone	Stratigraphic/ combination	SP	DP	SP or faulting	OWC
English Colony - Stevens Sandstones	Stratigraphic	SP	DP	SP	OWC
* Foinaven - Vaila Fm	Combination	SP (dip closure and probably fault assisted)	DP and/or faulting	Faulting	OWC
* Glenlivet - Vaila Fm	Combination	SP (assisted by syn-depositional faulting)	DP associated with growth faulting	SP	Faulting
Jameson - Jameson-Cook Sandstone	Stratigraphic	SP	DP	SP	-
* Jubilee - Mahogany	Combination	SP (probably fault assisted)	DP and/or faulting	SP	OWC
* Laggan - Vaila Fm	Combination	SP (probably fault assisted)	DP and/or faulting	SP or faulting	GWC
* Lagoa Parda - Lagoa Parda	Combination	SP and dip closure (faulting?)	DP and/or faulting	SP and dip closure	OWC
* Marlim - Carapebus	Combination	SP and faulting	DP and faulting	SP and faulting	Faulting
Marlim Sul - Carapebus	Combination	SP	DP and ET (mud-filled channels)	SP	-
Nautilus, Pabst, Bud fields - Miocene Sands	Stratigraphic	SP	ET by MTD	SP	OWC or SP
* Oribi - 14A Sequence	Combination	SP (possibly fault assisted)	DP	SP and faulting	OWC
Sea Lion - SL10-SL20	Stratigraphic	SP	DP	SP	OWC
Shwe, Shwe Phyu, Mya fields - G Series	Stratigraphic	SP	ET (mud-filled channels)	SP	SP?
Young North - Bone Spring	Stratigraphic	SP	DP	SP	-

Abbreviations: Stratigraphic Pinchout, SP; Depositional pinchout, DP; Erosional truncation, ET.

Table 3. Setting of deepwater turbidite reservoirs with inferred upslope stratigraphic trapping.

Field - Reservoir Interval	Tectonic Setting	Slope Type	Slope Position	GDE
Alba - Nauchlan	Rift (post-rift)	Graded	Middle or lower slope	Submarine valley
Barracuda - Carapebus	Passive margin	Graded	Toe-of-slope	ToS apron
* Buzzard - Buzzard Sandstone	Rift (syn-rift)	Out-of-grade (stepped)	Middle slope (at local slope break)	Perched apron
English Colony - Stevens Sandstones	Transform	Graded	Upper slope	Submarine valley
* Foinaven - Vaila Fm	Rift (post-rift)	Out-of-grade (stepped)	Middle slope	Submarine valley
* Glenlivet - Vaila Fm	Rift (post-rift)	Out-of-grade (?stepped)	Upper slope	Perched apron
Jameson - Jameson-Cook Sandstone	Foreland	Graded	Middle slope or toe-of-slope	Submarine valley and ToS apron
* Jubilee - Mahogany	Transform	Out-of-grade (stepped)	Upper or middle slope	Perched apron
* Laggan - Vaila Fm	Rift (post-rift)	Out-of-grade (stepped)	Toe of slope	ToS apron
* Lagoa Parda - Lagoa Parda	Passive margin	Out-of-grade	Upper slope	Submarine valley
* Marlim - Carapebus	Passive margin	Graded	Toe-of-slope	ToS apron
Marlim Sul - Carapebus	Passive margin	Graded	Toe-of-slope	ToS apron
Nautilus, Pabst, Bud fields - Miocene Sands	Passive margin	Graded	Lower slope or toe-of-slope	Remnant slope sands
* Oribi - 14A Sequence	Transform	Graded	Toe of slope or basin floor	Submarine valley or ToS apron
Sea Lion - SL10-SL20	Rift (post-rift)	Out-of-grade (?stepped)	Toe-of-slope or basin floor (lacustrine)	ToS apron
Shwe, Shwe Phyu, Mya fields - G Series	Forearc	Out-of-grade	Toe-of-slope or basin floor	ToS apron
Young North - Bone Spring	Foreland	Out-of-grade	Lower slope or toe-of-slope	ToS apron