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# A review of producing fields inferred to have upslope stratigraph trapping style (pure and combined), pinchout formation and depositio

Lawrence A. Amy

School of Earth Sciences, University College Dublin, Belfield,
lawrence.amy@ucd.ie

## Affiliations

Irish Centre for Research in Applied GeoSciences.

Co-investigator, Leeds Turbidite Research Group, School of Earth and Environment Leeds, Leeds, United Kingdom.

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# ABSTRACT

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

# INTRODUCTION

Stratigraphic traps formed by updip pinchout of reservoirs towards the proximal of basin deepwater depositional systems has become an increasingly important focus for hydrocarbon exploration, particularly deep- and ultra-deepwater regions (Figure 1). This upslope trapping configuration for turbidite fan and channel complexes embedded within many deepwater exploration models, including the stratigraphic trap (MacGregor et al., 2003), basin-margin pinchout (Stoker, 2006), detached basin-floor fan (Fugelli and Olsen, 2005; Worsell et al., 2016), stratigraphic pinchout (Finch et al., 2009) and updip margin (Biteau et al., 20 plays. Such stratigraphic pinchouts offer opportunity for large volume discove frontier or mature areas where structural traps are absent or have already been te (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 Jub Field (Tano Basin, offshore Ghana), Buzzard Field (Outer Moray Firth, UK Central North Sea) and Marlim and Marlim Sul Fields (Campos Basin, offshore Brazil). Recent campaigns with a particular focus on upslope stratigraphic traps have targeted the Cretaceous deepwater sequences of the Atlantic, along the West African Equatorial transf Cote d Ivoire, Sierra Leone) and South American margin (Guyana, Suriname, French Guyana) (Finch et al., 2009; MacGregor et al., 2003; Dailly et al., 2012; Biteau et al., 2014).

Whilst there has been a move towards actively drilling these deepwater stratigraphic traps (Stoker, 2006; Allan et al., 2006; Dailly et al., 2012; Stirling et al., 2017), the number of commercial discoveries specifically with upslope pinchout traps remains limited. Hence, despite offering the potential for the big prize of comme success based on past exploration experience, relatively low GCoS are judged to containment, related to the presence of robust traps and seals capable of preventing updip leakage of hydrocarbons, are the principal geological risks (Straccia and Prather, 1999; Prather, 2003; Zhou, 2014). This is a critical issue for all types of stra deepwater turbidite systems whether at the proximal, lateral or distal margin (Figure 2A) margi particular risk for upslope pinchout traps is the potential for the feeder system to extend updip, and deepwater systems to those higher on the slope or fluvial or systems. Such thief sands may be relatively thin making them difficult to resolve on seismic data. There is also a propensity for systems on the proximal margin whic or base seals. The nature of the proximal margin, arguably makes pinchout traps considerably higher risk compared to those on lateral margins.

In this study, fields with turbidite reservoirs previously referred to in the literature to have upslope stratigraphic trapping were reviewed. A number of aspects critical for predic this trap type in exploration are focussed upon: (i) the nature of upslope trapping configuration; (ii) whether upslope trapping is stratigraphic alone or combined with structural trapping; (iii) the processes responsible for the development of pinchout; and (iv) the tectono-depositional setting in which pinchout traps occur. A better understanding of aspects of upslope traps provides valuable insights on which basin margins and locations along the slope profile, and hence areas, offer the best potential for upslope s with large volume discoveries. In the following, the approach taken to identify upslope stratigra trap is first outlined, followed by discussing each of the three themes mentioned above and summarising key lessons for exploration. This is, to our knowledge, 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 required turbidite reservoirs, where the total or a significant fraction of reserves were considered to be dependent on upslope stratigraphic pinchout. We compiled these from published literature. Initial identification of reservoirs was assisted using consultancy databases, C&C Reservoirs Digital Analogs Knowledge System (DAKS) that holds published data on over 1400 reservoirs. This was followed by a broader review of Only well described reservoirs were considered, including those from fields in c currently producing and abandoned. Non-commercial and new discoveries have not been consid owing to the lack of detailed published information. These include those depositional systems orientated perpendicular to the structural dip, where upslope pinchout of lobes or channels are complicated by hydrocarbon accumulation (Figure 3A). Adopting depositional and erosional stratigraphic traps (Allan et al., 2006), the term pinchout in this study is used broadly to indicate a lateral stratigraphic termination of reservoir against sealing facies regardless of whether depositional, erosional or facies change (Figures 3A & 3B).

In total 20 oil and gas fields with upslope stratigraphically trapped 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 recoverable reserves for these fields are of the order of 6-7 BBOE. Fields were discovered between 1952 and 2010, with two prominent peri (between 1982-1994 and 2000-2010) corresponding to periods of high ri Further field information is detailed in Table 1 and trap-related information in Table 2.

## UPSLOPE TRAPPING CONFIGURATION

For each field, published maps and cross sections were used to better understand trapping (Figures 5 and 6). A variety of trapping configurations, from pure pinch-outs to combined with faulting or closures, are considered as potential updip trapping mechanisms (Table 2). The various trapping interpretations applied to fields in this review are summarised schematically in Figure 7. For some fields multiple interpretations are presented and combined trap configurations are discussed further below, with a focus on the potential importance of late cutting feeder channels, as exemplified in a number of known giant fields.

### Pure upslope traps

For about half of the considered fields, a pure stratigraphic trap is the principal inferred trapping (Figure 7). Reservoirs include Buzzard, Barracuda, English C Jameson, Marlim Sul, Nautilus, Pabst and Young North are inferred to rely solely on stratigraphic upslope pinch-out determined from seismic and well data (see Table 1 for references). Authors describing these reservoirs do not indicate that structural dip or closure also plays a partial role in conjunction with pinch-out in both cases of Shwe and Lagoa Parda. The majority of the reservoirs (~80%) are inferred to display depositional pinch-outs, with fewer displaying evidence of erosional truncation pinch-outs (Figure 7).

### Traps associated with upslope faulting

A number of reservoirs including Jubilee, Foinaven and Marlin have updip field boundaries coincidental with stage reservoir pinch-out (Figure 5). Whilst stratigraphic pinch identified in these fields, updip trapping may be reliant, wholly or partly, on reservoir faulting

## Jubilee Field

The Jubilee field is one of the most prominent discoveries to test abrupt or stratigraphic pinchouts, often discussed in the context of upslope stratigraphic (e.g. Crowell, 2011; 2014; Biteau et al., 2014; Flint, 2014). Well-developed stratigraphic pinchouts of the Mahogany sequence are seen towards the northwest and east and locally updip towards north (Figure 8). In addition to pinch-outs, several large normal basement-linked faults are present in the north defining the southern extent of the Tano North structure (Figure 8). Dailly et al. (2012) note reservoirs appear to be thrown up against a fault towards the northeast. Kelly and Doust (2016) also suggest combined structural-stratigraphic trapping configurations involving the Tano fault in the northern section. Based on seismic attribute maps, faulting can be inferred across the slope system (Figure 8A). Jubilee therefore may not be a simple updip pinchout trap without fault component to the updip feeder system. This interpretation is supported by the presence of Turonian sands co to occur updip of the Jubilee field on the crest of the Tano Horst (Tullow Oil Ltd. media release, 2008).

## Foinaven Field

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

## Campos Basin fields

Oligocene sandstones of the Marlim and Marlim Sul fields in the Campos Basin are inferred comprise detached fan deposits with upslope pinch out on the proximal slope towar (Peres, 1993; Bruhn et al., 2003). These fields display combined structural and stratigraphic configuration (Figure 10). Field limits are defined mainly by pinch out towards the west and north and south, with normal faults along the east, northeast and northwe and Cora, 1992). Faulting at the reservoir level is mainly in the form of growth faults, developed response to renewed salt withdrawal during the late Miocene (Peres, 1993). Along the proximal wall, faults locally segment the inferred feeder systems

(Figures 5 & 10). Thus late stage faulting occurs in these systems, suggesting that it could play an important role in trapping.

From the above discussion, it is clear that a number of high profile, commonly discussed as stratigraphic traps have upslope limits controlled by faulting. Considering all t fields in Table 1, in almost one third of cases faulting may play an important role in upslope trapping (Table 2). Post-depositional faulting through the feeder system offsetting potential thief san may be critical in forming traps in Foinaven, Jubilee. Other examples including Buzzard, Glenlivet, Oban and Laggan are located on strongly faulted slopes. Whilst t reservoir interval is difficult to confirm in these cases, faulting subsequent within the of the reservoir units may also persist in trapping in these systems. Strongly faulted slopes may also have encouraged pinchout development (as discussed furth below).

## FORMATION OF UPSLOPE PINCHOUTS

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

### Bypass-related pinchout traps

In the majority of upslope pinchouts, the reservoirs are inferred to be depositional pincho formed by sediment gravity flows so that they are deposited in proximal parts of the slope system. Detached sands and gravels develop downslope of sediment transfer zones or pathways conduits that are subsequently filled by sealing lithologies. This applies to Th Alba (Harding et al., 1990; Newton and Flanagan, 1993), Dorado (Robbins, 2005), Buzza (Stephens et al., 2013; Horseman et al., 2014) and Young (Montgomery, 1997) fields. Seismic and well data for these examples support truncation of the reservoir intervals younger depositional elements or systems.

As discussed earlier, many of the reservoirs were deposited on faulted slopes (e.g., Jubilee, Foinaven, Glenlivet, Buzzard, Laggan, and Lagoa Parda). Faulting is a prime mechani by which slopes become oversteepened, encouraging erosion and bypass on (Ross et al., 1994). Buzzard provides an example of a stratigraphic pincho fault controlled but where faulting at the reservoir level is not believed to ultimate trapping (Figure 12).

As well as oversteepened slopes, faulting can form the bat palaeoslope encouraging local deposition and promoted downslope bypass. The Glenlivet field of the Faroe-Shetland Basin provides an example of this in context of syn-sedimentary faulting (Figure 13). The reservoir has an updip stratigraphic pinchout where it onlaps the base Cenozoic unconformity (Horseman et al., 2014). Seismi Palaeocene reservoir development suggests a relatively steep slope with complex bathymetry controlled by syn-sedimentary growth faults (Figure 13C & D). Local deposition occurred in the upper slope in topographic lows formed on the downthrown side of a al., 2013; Horseman et al., 2014). The nearby Laxford gas discover fault controlled depocentre with upslope pinchout (Figure 3C).

Upslope and down-dip terminations observed in the Arbroath field are inferred to be related, formed as depositional flows traversed an irregular palaeo (Newton and Flanag 1993). In this case, palaeoslope is thought to be fault-controlled but not directly rel subsidence or to differential compaction over structures (Harding et al., 19 Deposition of channel sands is inferred to have occurred on the relatively flatter gently portio dipping terraced slope (Newton and Flanagan, 1993).

## Erosional truncation by mud-filled channels

A number of producing reservoirs show evidence for pinchout related to by younger mud-filled channels, including Marlim, Marlim Sul, Barracuda (Campos Basin) and Shwe fields (Rakhine Basin) (Figure 4). In these systems, channel margins imaged in high-quality seismic data are seen to dissect basin-floor fan deposits, apparently forming or assisting with proximal and lateral stratigraphic trapping.

The depositional model for the Oligocene of the Campos Basin composite system shelf-fed turbidite systems developed at the lower slope and basin plain, fed by submari canyons and lower-slope channels (Peres, 1993) (Figure 10A). Feeder conduits appear to lack continuity between upper slope canyons, with connections absent on the middle and lower slope regions (Peres, 1993). Erosional canyons are mud-filled and heavily di the western part of lower slope reservoirs of Marlim, Marlim Sul and Barracuda, and are responsible for forming residual sand bodies (Peres, 1993; Bruhn 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 depositiona sand pinchouts and local faulting (seen as scarp) control reservoir distribu field limits upslope towards the west.

The Shwe gas fields (Shwe, Shwe Phyu and Mya) of the Rakhine Basin display mud-filled channels that dissect basin-floor lobes forming isolated reservoir bo stratigraphic trap component (Yang and Kim, 2014; Racey and Ridd, 2015) (Figure 14E). These reservoirs are stratigraphically trapped on the western limb o NW-SE trending anticline plunging to the SE (Carter and Cliff, 2016). The sands in this system are inferred to have been sourced by both the Ganges-Brahmaputra and the nearby Rakhine shelf, from the NW and respectively (Racey and Ridd, 2015). Whilst updip stratigraphic trapping crest of the anticline in a NE direction (involving the lateral lo stratigraphic trapping component towards the N and NW (up-the pl depositional dip). Two types of channels are recognized in the (i) sinuous with sand-fill and (ii) larger low-sinuosity erosional channels with mud-fill. The channels prograded across and incised into existing lobe deposits and are inferred to sediment conduits being later abandoned and filled by mud (Figure 14D). The incisional channe up to 100 m (328 ft) deep, greatly influence field size as well as compartm reservoirs (Figure 14E). In Shwe gas fields, erosional truncation by mud-filled channels combi with depositional pinchouts (seen as downlap) are responsible Small stratigraphic, involving updip mud-filled channels cutting sandy depositional systems, are suggested to offer trapping potential in deeper water parts 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 Me are reported to display stratigraphic trapping related to erosional truncation and sea deposits (Godo, 2006). These include the Bud, Nautilus and Pabst gas fields; composed of channel-levee reservoirs that occur as irregular isolated remnant patches, having lost m their original depositional geometry (Figure 15). Gas-related seismic ampl effects show no correlation to structure and are difficult to interpret without recognising erosional origin of the sand bodies. Some of the mass flows responsible for sco prodelta shales which failed from a steep unstable shelf edge (Figure 5A).1 The particular gas reservoirs are relatively small due to the limited extents of remnanted sands. Such sands, however, became areally more extensive upslope, where there were fewer episodes of erosion (Godo, 2006). Erosional processes may also play a role in trapping at the Ram Powell field location. These reservoirs are inferred to be erosionally truncated and overlain by an interval of chaotic seismic facies (e.g., Figure 2 in Clemence et al., 2000). In the L Ram Powell reservoir sand, stratigraphic trapping is p towards the northeast and is considered as erosional rather than upslope stratigraphic pinchout of levee sands.

## TECTONO-DEPOSITIONAL SETTING OF UPSLOPE PINCHOUTS

### Pinchout classification

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

## Tectonic setting

Reservoirs inferred to have upslope stratigraphic traps are found in a variety of tectonic se including extensional, convergent and strike-slip (Figure 17A; Table 2). Extensional basin include the syn-rift setting of the outer Moray Firth (offshore UK), post-rift (Central N failed rift) setting of the Central North Sea and passive margin settings of the Cam Santo basins (offshore Brazil) and the NE Gulf of Mexico. Strike-slip basins (offs include the San Joaquin Basin (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 are from extensional passive margin and rift basin settings, which account for the majority of disco (Figure 17A).

## Slope type

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

Slope position and GDE

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

Grain size

Evaluation of reservoir grain size indicates that most reservoir finer grained than medium sand with few coarse sands (Figure 18). Compared to other turbidite reservoirs, those with upslope pinchout traps te

## DISCUSSION: SETTINGS PRONE TO UPSLOPE PINCHOUTS

Out-of-grade erosional margins generally have 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 Hadler-Jacobsen, 2005; Hadler-Jacobsen et al., 2005). Pra instead views slope environments of graded slopes as key for upslope stratigraphic trapping. A key result of the present analysis is that pinchout development requir trapping is not limited by tectonic setting, slope type or position on slope. A schematic summar reservoir depositional location is shown in Figure 19. Documented examples of re demonstrating upslope pinchout traps are known from most tectonic and depositional including extensional, compressional and strike-slip basins. Furthermore, in extensional settings they occur in syn-rift as well as post-rift sequences of rifts and fully developed passive margins As such, reservoir bodies are located on graded, out-of-grade and stepped slope type positioned along the slope and affiliated with different gross. Similarly, positi reservoirs include those with a range of gross depositional env including submarine valley, toe-of-slope fans and aprons. Hence, opportunities ex wide range of basins and deepwater depositional environments.

In terms of discovered volumes, however, and as surmised by Pettingill (2003), the majority of giant oil field reserves are found in a limited number of settings, principally: i) the toe-of-slope of graded passive margins and ii) in-slope locations of out-of-grade rift and transform margins (Figure 17). Graded slopes of passive margins, with the single large cumulative volume (dominated by the giant fields of the Campos Basin) loc the toe-of-slope. Jubilee, Foinaven and Buzzard provide examples slopes. These occur relatively high up on the slope profile in as reservoirs [illegible] aprons [illegible] the toe-of-slope (Table 3; Figure 17).

From a sequence stratigraphy perspective, deepwater stra
lowstand systems tracts with turbidite basin floor fans [illegible]
detached lowstand bodies above sequence boundaries (Posamentier and Vail, 1988;
al., 1999). The majority of upslope pinchout reservoirs examined, however, are n
reported to occur above key [illegible] stratigraphic unconformities. Glenlivet displa
pinchout of Paleocene reservoirs on to a top Cretaceous unco
Reservoirs of the Oribi field are interpreted [illegible] the
a progradational clinoform sequence (Brown et al., 1995). [illegible]
pinchouts are inferred as the common form of upslope termination (Figure 3B; type 2
(base, lateral and top seals) provided by [illegible] deepwater shales o
pelagic sediments (Mattingly and Bretthauer, 1992; Carruth, 2003; Ray
2014). The lack of association between upslope stratigraphicall
boundaries may simply reflect an incomplete knowledge of the sequence s
systems. Alternatively, it may indicate major sequence boundaries are not conducive to th
development of robust stratigraphic traps, perhaps due to the lack of developm
systems or poor seals.

Relatively fine-grained turbidite systems have been proposed
stratigraphic traps compared to coarse-grained systems (Reading & Richards, 1994; Fugelli and Ols
2005). This is due to their [illegible] but also the greater [illegible] o
material downslope (high efficiency systems; Mutti & Normark, 1987). This view is suppor
in this analysis [illegible] systems examined [illegible] finer than medium

are relatively fine-grained compared to other turbidite systems (Figure 8). The combination of oversteepened slopes in conjunction with fine grained systems sediment bypass is likely critical to the development of many pinchout. Oversteepened slopes prone to bypass and erosion may develop in shelf-margins [illegible] carbonate margins with enhanced slopes (Ross et al., 1994). Examples of traps on margins have been discussed [illegible]. Reservoirs from the Permian [illegible] Jameson and Young [illegible] provide examples of upslope traps in assoc margins that may have developed bypass in response to oversteepened ca forming detached turbidite systems. Scenarios discussed for oversteepened margins in the context of overly out-of-grade margins undergoing adjustment (Ross et al., 1994), between overall stratigraphically graded margins (Pyles et al., 2011) may also experience transient episodes of being out-of-grade, such that flows predominantly bypass. These sedime may be challenging to identify at seismic scale within an overall stratigraphically graded m Reservoirs of the Campos, Rakhine and eastern GOM basins w clinoform geometries may be considered within this category

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

## KEY IMPLICATIONS FOR EXPLORATION

Existing reservoirs with upslope stratigraphic traps provide key insights important future exploration, and specifically applicable when approaching prospect evaluation. Within this summary a number of key factors have been identified that likely apply, whose identification in subsurface datasets may help de-risk exploration opportunities.

- The range of tectonic and depositional settings that have upslope stratigraphic tr encouraging for exploration, since many basins and deepw petroleum systems may offer robust stratigraphic pinchout traps. However, that setting may not guarantee large-volume discoveries given that most giant discoveries to date have been made the toe-of-slope of graded passive margins and intraslope accomm rift or transform margins (Figure 19).
- Upslope stratigraphic traps, including giant discoveries, occur on 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 second-order sequence tectono-stratigraphic boundaries. Rather they form at local depositional pi

truncation (Figure 3). This may indicate that such surfaces are prone to updip lea base seal.

- Targeting systems with limited maximum grain size or steepened slopes is likely a critical success factor (Figure 8). Sediment grain size and slop fundamental controls on downslope sediment transport processes including bypass potential of sediment gravity flows. Many systems with upslope stratigraphic trap relatively limited grain sizes and/or are combined with steepened or faulted slopes or progradation across carbonate margins. Where possible, predicting grain size and palaeoslope should therefore be taken into consideration in evalua
- Faulting through upslope feeder systems appears to be a critical factor in many past discoveries (Figures 7, 8 & 9). Some reservoirs previously interpreted or discussed as upslope stratigraphic traps are likely to be combination traps with a faulting component (e.g. Jubilee, Foinaven, Lagan and Marklin fields). Faulting is likely to be key in coarse grained systems, where it is difficult for flows to achieve complete sediment bypass. Where depositional systems thin on to low-gradient basin margins, faults should have a high sealing only limited offsets may be required to do so. Faulting has the advantage of providing a potential trapping mechanism, if a robust pinchout. Detailed fault mapping and analysis should therefore form a key component of the exp
- Mud-prone channels and mass transport deposits can form seals and act a effective top and lateral seals (Figures 5 & 14). This appears to be a critical factor in a number of past discoveries. Identification and mapping of these features can provide positive evid reservoir pinchout and lower risk, particularly when they are intimately associated amplitude anomalies. However, predicting the potential of these erosional or depositional elements may be challenging, especially in frontier areas where well-based g

lithology prediction and lateral containment may still carry high uncertai Understanding erosional truncation is also important for determining distributi connectivity and volumes, which may be negatively affected in areas of inte

## CONCLUSIONS

Deepwater upslope stratigraphic traps continue to be important targets and seem likely to deliver future significant oil and gas discoveries in both mature and frontie Achieving success remains challenging, notably due to reliable seal and containm Compilation and analysis of past commercial discoveries has provided insights into trapping configurations, mechanism of pinchout formation and depositional settings of upslope pinchout. Importantly, this demonstrates the occurrence of tectonic depositional settings including through graded- and out-of-grade margins. The majority of discoveries to date have been made at the toe-of-slope of graded passive margins an in-slope on steep-graded out-of-grade rift and transform margins. Trapping geometries may the bypass of sediment by transporting flows, erosional truncation, mud-filled channels and mass transport complexes. Faulting is potentially a key element in trapping and as such many existing fields may be considered combination traps. The results sugge a number of success factors: i) faulting in upslope areas that disconnects the sand cou pinchout geometries; ii) systems comprised of fine-grained sediment transported in conjunction with steep slopes, allowing efficient sediment bypass; iii) erosional truncation by mud- and se filled channels and mass transport complexes. Identification of these factors may help de prospects and make better choices. Various research avenues re explored further to understand upslope pinchout trapping in turbidite systems. Immedia include constraining critical slope angles for turbidity currents, and the development of levee-channel systems and associated collapsing detachment in seafloor and ancient outcrop systems

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VITA

Lawrence Amy is an Associate Professor in the School of Earth Sciences with a Ph.D. in deep water sedimentology from the University o interests range from stratigraphic traps, sediment transport to deltas and basins. Previously, he worked in reservoir characterisation for Saudi A Oil Ltd.

# CAPTIONS

Figure 1. Examples of play models where upslope stratigraphic trap exploration targets: (A) West African Transform Margin model showing det post-rift slope channel and fan systems (after Lewis, 2011); (B) Porcupine Basin (off model showing detached Cretaceous and Palaeocene-Eocene deepwater fans (after Petroleum Affairs Division, 2006); (C) Seismic section showing turbidite complexes (T TC3) offering potential for upper Cretaceous pinch-out traps, offshore Ghana (fro 2015; image courtesy of CGG Multi-Client & New Ventures).

Figure 2. Schematic diagram illustrating the various depositional large-scale stratigraphic traps in a deepwater turbidite system. T along the depositi profile of the proximal pinchout on the [illegible] slope [illegible] alternatively be ab systems are attached to upslope shelf or fluvial sands.

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

Figure 4: Global distribution of discovered commercial deepwater reservo with upslope stratigraphic (Table 1). Inset graph shows the discovery record fo fields, along with Estimated Ultimate Recovery (EUR) global cumulative field EUR play type.

Figure 5. Simplified maps of oil and gas fields with upslope stratigraphic traps show outlines, structure contours (top or near top reservoir), infe direction and location of depositional feeder system(s). Based on the following sour Alba (Newton & Flanagan, 1993), Buzzard (Doré & Robins, 2005), Foinaven (Horseman et al., 2014), Jameson (Bloomer, 1990), Nautilus (Gord 2006), Jubilee (Dailly et al., 2012), Marlim Sul (Candido & Cor

Figure 6. Geological cross sections based on seismic lines of basins with upslope stratigra

trapped fields: A) Shetland Basin, Foinaven field; B) Central North Sea, Buzza

Witch Ground Graben, Central North Sea, Alba field; D) Easte

fields; E) Rakhine Basin, Shwe fields; F) Taranaki Basin, Modified from Lamers & Carmic

(1999), Doré & Robbins (2005), Harding et al. (1990), Godo (2006), Y Oil

Ltd. Media Release (2008), respectively. BCU = Base Cretaceous Unconformity.

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

Figure 8. Jubilee Field. A) RMS amplitude extraction of the Mahogan & Agyapong, 2012 and used with permission of Offshore Technology Conference). B) Seismic line showing onlap related pinchout at the inferred lateral edge (from Jewell, 2011 and used with permission of AAPG). C) SWNE seismic lines showing upslope pinchout but reservoir level (from Dailly et al., 2012 and used with permission of the Geologica). The Mahogany-1 (M1) discovery well and the top of the Mahogany r horizon) is shown in seismic sections.

Figure 9. Foinaven Field. (A) Seismic-based geological cross-section of the Foinaven subbas Shetland (Loizou et al., 2006) used with permission of the Geological S (B) Composite depth structure map showing hydrocarbon field and sediments 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 s southeast upslope boundaries to the inferred sediment entry points.

Figure 10. Marlim field. (A) Seismic profile for the eastern Brazilia 2003 and used with permission of Offshore Technology Conference). (B) Interpreted basin phy distribution and structure of the Oligocene turbidites (from Peres, 1993; used with permission of AAPG). Locations of the Marlim (M), Marlim Sul (MS) ar shown. (C) Seismic amplitude map showing unconfined sand-rich lobes and feeder chann least one offset by faulting (from Bruhn, 2001 and used with permission of AAPG). Arrows indicate sediment transport direction. Red and orange indicate thicker sandstones. (D) Inferred su depositional model of turbidite-fed shelf system during late stages of the 1993 and used with permission of AAPG). Abbreviations: (R) Continental Rift M Transitional Evaporitic Megasequence, (SC) Shallow Carbonate Megasequence, (MT Transgressive Megasequence, (MR) Marine Regressive Megase

Figure 1. Summary of processes that may generate upslope stratig or non-deposition in relatively proximal upslope areas: (A) slope failure; (B) gravity flow erosion and bypass; (C) fan slope failure; (D) channe erosion by mud-rich mass flows; (F) erosion by bottom currents. Cas systems that are detached at the time of deposition, whereas F involves initially attache that become detached through erosional decapitation.

Figure 12. Buzzard field. (A) Depth structure map of the Top Buzzard (Doré & Robbins, 2005, and used with permission of the Geological Society of London). (B) Depth structure map of top reservoir (Ray et al., 2010, and used with permission of the Geo London); the main accumulation is bisected by several East–West oriented normal faults tha field into three main regions referred to as the Southern, Cen smaller structural terraces. (C&D) Seismic lines showing stratigraphic thinn updip towards the west (Doré & Robbins, 2005, and used with permission of the Ge of London). (E) Depositional model for the Buzzard Sandstone Mem and used with permission of the Geological Society of London).

Figure 13. Glenlivet Field. (A) Far offset amplitude Full-stack seismic (B) line thro

the Glenlivet Prospect showing a strong amplitude anomaly a

anomaly (1). (from Horseman et al. 2014 and used with permission of th

(C) Three dimensional perspective view showing reservoir depth structure map show

amplitude as surface attribute. (D) Depositional model based on seismic, well

information and analogues for Glenlivet and neighbouring prospects. Stratigraphic

trapped sandstones in topographic lows in complex fault (figure 13D from Stephenson et

2018 and used with permission of EAGE)

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

Figure 15. Reservoirs with upslope pinchouts related to mass trans (from Gass, 2006; and used with permission of the Geological Society of London). (A) Depositional model Miocene of the eastern Gulf of Mexico with slumps and deb depositional systems. (B) Map of the Nautilus Field showing laterally and updip by shale-filled scours shown in grey. Dotted arrowed lines in direction of flow of mass transport. (C) Seismic section through the Nautilus F separated by shale-filled scours at the base of the mass transport depos Hydrocarbon-filled remnants sands are shown as red events. Shales yellow in the display. (D) Seismic section showing the Bullfrog Field slumped interval.

Figure S16. Summary of the classification scheme used to describe re

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 te slope type (B); position on the slope (C) and depositional environment (D). Dark grey bars fo all reservoirs considered in this study (Table 1). Light grey bars for those where upslope structur trapping components have not been inferred (i.e. higher confidence of pure stra Numbers indicate the commercially discovered reserves (median) P50 for all res Abbreviation: Toe of slope (ToS).

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

Figure 19. Schematic summary of depositional setting of upslope
commercial discoveries to date including those with gas-oil f -slope
environment. Fields that have previously been discussed as stratigraphic traps bu
structural component to their updip trapping mechanism (see Ta

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

| Field<br>- Reservoir Interval | Reservoir age | Basin | Water de (m) | Discovery year | HC type[1] | Reserves[2] | Status | References[3] |
|---|---|---|---|---|---|---|---|---|
| Alba<br>- Nauchlan | Middle Eocene | Central North Sea | 140 | 1984 | Oil | 400 | Decline | Harding et al. (1990), Nev (1993), Moore (2014) |
| Barracuda<br>- Carapebus | Eocene-Oligocene | Campos | 600-1200 | 1989 | Oil | 867 | Producing | Bruhn et al. (2003), Rang Hoek et al. (2010), Defeo |
| +Buzzard<br>- Buzzard Sandstone | Late Jurassic | Central North Sea | 100 | 2001 | Oil | 550 | Producing | Doré, G. & Robbins (2005) (2006), Ray et al. (2010) |
| English Colony<br>- Stevens Sands | Miocene | San Joaquin | Onshore | - | Oil | 1.6* | Abandoned | Hewlett & Jordan (1993), (2017)* |
| +Foinaven<br>- Vaila Fm | Paleocene | Faroe-Shetland | 400-600 | 1992 | Oil | 415 | Producing | Straccia & Prather (1999) |
| +Glenlivet<br>- Vaila Fm | Paleocene | Faroe-Shetland | 500 | 2009 | Gas | - | Development | Stephensen et al. (2013), (2014), Loizou (2014) |
| Jameson<br>- Jameson-Cook | Early Permian | Permian | Onshore | 1952 | Oil | 45.3* | Mature | Bloomer (1990)*, Bloomer |
| +Jubilee<br>- Mahogany | Turonian | Tano | 1100 | 2007 | Oil | >600* | Producing | Jewell (2011), Dailly et a al. (2014), Kelly & Doust |
| +Laggan<br>- Vaila Fm | Paleocene | Faroe-Shetland | 600 | 1986 | Gas-Cond. | - | Producing | Gordon et al. (2010), Loiz |
| +Lagoa Parda<br>- Lagoa Parda | Early Eocene | Espirito Santo | 0-200 | 1978 | Oil | 24 | Decline | Bruhn (1993), Bruhn et al. al. (1991)* |
| +Marlim<br>- Carapebus | Eocene-Oligocene | Campos | 650-1050 | 1985 | Oil | 1700 | Decline | Candido & Cora (1992), P et al. (2003), Defeo de Ca |
| Marlim Sul<br>- Carapebus | Eocene-Oligocene | Campos | 720-2600 | 1987 | Oil | 1150[†] | Producing | Peres (1993), Bruhn et al. |
| Nautilus, Pabst, B<br>- Miocene Sands | Miocene | Northern GOM | - | 1985-2003 | Gas | - | Producing | Godo (2006) |
| +Oribi<br>- 14A Sequence | Early Cretaceous | Bredasdorp | 120 | 1990 | Oil | 20* | Mature | Burden & Davies (1997a; |
| Sea Lion<br>- SL10-SL20 | Lower Cretaceous | North Falkland | 450 | 2010 | Oil | 242 | Development | MacAulay (2015) |
| Shwe, Shwe Phyu,<br>- G Series | Late Pliocene | Rakhine | 90-600 | 2004 | Gas | 755 | Producing | Yang & Kim (2014) |
| Young North<br>- 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 Offshore Technology website, [†] Subfield summary, field summary. Websites accessed December 2016. [3] References for stratigraphic trap interpretation and reserves. [+] Fields that have previously been discussed as st but may also have a structural/fault component to their updip trapping mechanism (see Table 2 & Figure 7).

Table 2. Trapping configuration of deepwater turbidite reservoirs

| Field<br>- Reservoir Interval | Field trap type | Updip trapping | Updip stratigra pinchout style | Lateral trapping | Downdip limit |
|---|---|---|---|---|---|
| Alba<br>- Nauchlan | Stratigraphic | SP (?with comp closure) | DP | SP (?compactio dip closure) | OWC? |
| Barracuda<br>- Carapebus | Combination | SP | ET (mud-filled channels) | SP | SP and faulting closure?) |
| Buzzard<br>- Buzzard Sandstone | Stratigraphic/combination | SP | DP | SP or faulting | OWC |
| English Colony<br>- Stevens Sands | Stratigraphic | SP | DP | SP | OWC |
| Foinaven<br>- Vaila Fm | Combination | SP (dip closure probably fault a | DP and/or faulting | Faulting | OWC |
| Glenlivet<br>- Vaila Fm | Combination | SP (assisted by depositional fa | DP associated faulting | SP | Faulting |
| Jameson<br>- Jameson-Cook | Stratigraphic | SP | DP | SP | - |
| Jubilee<br>- Mahogany | Combination | SP (probably fau assisted) | DP and/or faulting | SP | OWC |
| Laggan<br>- Vaila Fm | Combination | SP (probably fau assisted) | DP and/or faulting | SP or faulting | GWC |
| Lagoa Parda<br>- Lagoa Parda | Combination | SP and dip clos (faulting?) | DP and/or faulting | SP and dip closure | OWC |
| Marlim<br>- Carapebus | Combination | SP and faulting | DP and faulting | SP and faulting | Faulting |
| Marlim Sul<br>- Carapebus | Combination | SP | DP and ET (mud-filled char | SP | - |
| Nautilus, Pabst, B<br>- Miocene Sands | Stratigraphic | SP | ET by MTD | SP | OWC or SP |
| Oribi<br>- 14A Sequence | Combination | SP (possibly fault | DP | SP and faulting | OWC |
| Sea Lion<br>- SL10-SL20 | Stratigraphic | SP | DP | SP | OWC |
| Shwe, Shwe Phyu,<br>- G Series | Stratigraphic | SP | ET (mud-filled channels) | SP | SP? |
| Young North<br>- 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 trappi

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

863