Deepwater Depositional Systems: Advances and Applications

25-27 January 2017

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Wednesday 25 January

Session One: Channels and Canyons

Keynote Speaker: Scaling Relationships, Kinematics, and Stratigraphic Architecture of Submarine Channels: Application to Reservoir Prediction

Zane Jobe[1] and Nick Howes[2]
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Submarine channels are common persistent features in the modern seascape and stratigraphic record, representing a fundamental reservoir architecture in petroleum systems. However, the relationships between the morphological, kinematic, and architectural (stratigraphic) characteristics of submarine channels are still poorly understood. Simply stated, with what degree of confidence can one characteristic be used to predict another?. These types of relationships and predictions are particularly useful in cases of limited data (e.g., subsurface). This study quantifies morphological, kinematic, and architectural characteristics and explores the relationships between them based on an extensive seismic and core dataset of modern submarine channels on the western Niger Delta continental slope supplemented by data complied and derived from a global review of submarine systems.

We measure morphological, kinematic, and architectural statistics for more than 50 submarine channels. Geometric statistics resulting from these measurements are used to derive scaling relationships for submarine systems. Using these scaling relationships within and between systems, we identify channel kinematics rather than channel morphology as the first order control on stratigraphic architecture and show that seemingly similar channel forms have the potential to produce markedly different stratigraphy. For example, while fluvial and submarine channels have similar channel morphology, submarine channel-belt architecture is dominated by vertical accretion (aggradational channel fill deposits), in contrast to fluvial systems that are dominated by lateral accretion (point bar deposits). Differences in channel kinematics and thus stratigraphic architecture in submarine systems seem to be caused by higher quantities of suspended sediment in upper portions of the flow and the position of the velocity maximum close to the bed. These factors result in enhanced submarine levee development and channel-floor aggradation, leading to a channel belt dominated by aggradational channel fill deposits.

These channel fill deposits have predictable facies architectures, a topic extensively studied but rarely quantified. In general, thick, coarse-grained, amalgamated sands in the channel thalweg/axis transition to thin, fine-grained, bedded sands and muds in the channel margin. These trends can be quantified using high-resolution bathymetry, seismic reflection, and piston core data from the Y channel on the western Niger Delta slope. Core data shows that bed thickness, grain size, and deposition rate strongly decrease with increasing height above channel thalweg and/or distance from channel centerline. A 5x decrease in bed thickness and 1-2 ψ decrease in grain size are evident over a 20 m elevation change (approximately the elevation difference between axis and margin). Therefore, facies models for submarine channel deposits should take into account that rapid facies change requires change in elevation above the thalweg. A simplified in-channel sedimentation model that solves vertical concentration and velocity profiles of turbidity currents accurately reproduces the vertical trends in grain size and bed thickness shown in the core dataset. The close match between data and model suggests that the vertical distribution of grain size and bed thickness shown in this study is widely applicable and can be used to (1) predict grain size and facies architecture variation in data-poor areas (e.g., subsurface cores) and (2) populate reservoir models with realistic property distributions.

NOTES:

Entrenched slope channel complex systems: unified model for architectural element distribution

Bryan T Cronin

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Confined, entrenched, or simply slope channel complex systems, have been described from a range of outcrop, subsurface and sea floor settings for some time. Models have focused on the architecture of the main channel belt, and generally agree that the phases of channel complex system occupancy pass from a bypass phase, through a stacked channel element phase of various character, through an aggradational phase with smaller, usually meandering channel elements, to an end phase of progressive switch off of the system. A wide range of terms are now in common use that conflict in scale and usage, reflecting perhaps experience with specific case studies and belie the true range of slope channel complex system expression. A unified model that allows true variability to be captured is needed.

Channel complex systems range widely in net sand, net thin bed, or net mud slump or debris flow volume. The channel complex systems also vary widely in the proportion of channel element style. These styles range from (i) highly amalgamated sand bodies that extend across the channel complex system but are made entirely of individual meanderform, or braidform, channel elements, sometimes called ‘confined sheets’, to (ii) more clearly distinguished stacked channel elements that are underfit to the channel complex system, and have laterally equivalent inside levees and terraces, to (iii) even smaller scale skinny, later stage meanderform channel elements with higher proportions of related volumes of laterally equivalent, smaller scale internal levees, internal crevasse splays, internal frontal splays, or passive drape. The lateral channel complex system wall may have a range of morphologies that reflect the evolution of the system, from lateral rotational failure of the wall (often made of external master levee material), to erosional entrenchment and other types of terrace, to passive onlap of underfit late stage meanderform channel internal levee. Lateral rotational block failure and associated scalloped slump scar wall morphology, is often difficult to distinguish from internal levee and associated meander cut banks, though either can co-exist.

External to many of the slope channel complex systems are extensive master levee complexes, that are not always included in conventional models for slope channel complex system architecture. These external master levee complexes may themselves record multiphase occupancy of the main slope channel complex system, with each phase of levee build recording (i) a precursive phase of external crevasse splay build, followed by (ii) the principal phase of spill cap aggradation of the master levee, terminating in (iii) shutdown and hemipelagic drape of the external master levee complex. The timing of master levee build is also interpreted differently in current models, and needs further investigation here.

Beneath the slope channel complex systems, sedimentary architecture is highly variable, reflecting the position of the system on the slope or shelf. Some systems are highly entrenched and have excavated headwards on the upper slope, where they evolve to canyons, cutting into highstand shelfal systems such as deltas, beach-barrier systems or offshore bars. Further down system, in upper to mid-slope settings, slope channel complex systems are often preceded by mass-transport complexes, that may have initiated system entrenchment by providing diversion and fairway access to sand on the shelf. Channel complex systems may touch down onto, or erode through, such mass-transport complexes, leaving residual erosional remnants of the mass-transport complex lateral to the slope channel complex margin. Channel complex systems further downslope may also touch down into or erode through precursive frontal splay complexes, that were initially deposited outboard of the channel system. Distinguishing precursive frontal splays, from unrelated highstand deposits, and from crevasse splays, also requires further investigation here.

A unified model for entrenched slope channel complex systems is proposed that captures internal channel belt, external master levee complex, and precursive architectural element character, based on outcrop examples from the Cerro Torro Fm of southern Chile, various formations from southern and eastern Turkey, and the Eocene of the Spanish Pyrenees; seafloor examples from the Mediterranean and western California; and subsurface examples from offshore Myanmar, Equatorial Guinea, Angola, the North Sea, Colombia, and Ghana, to reflect commonality and contrast in slope channel complex architecture.

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Confined submarine slope channel complexes of the Cerro Toro: new insights on architectural elements and facies prediction.

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The Cretaceous Cerro Toro Formation, southern Chile, is characterised by thin-bedded turbidites that envelope a coarse-grained, confined slope complex system, interpreted as part of the Lago Sofia Member. This deep-water slope system overlies basin floor sheets of the Punta Barrosa Formation, and is overlain by the sand-filled slope channels of the Tres Pasos Formation.

The 3.5 km x 200 m channel complex sets are contained within topographically irregular bathymetric lows that formed sediment pathway corridors, interpreted to be either the result of tectonism, or contained by poorly preserved, tectonically disrupted or slumped external levee. Syn-sedimentary tectonism, or levee deposits instability led to the development of thick packages of MTDs that collapsed into the slope fairways from their margins, coexisting with other sediment gravity flow deposits.

This work proposes a refined architectural analysis based on the Exxonian model for submarine channels, subdividing the Cerro Toro deposits, at the Silla Syncline area, in at least 4 main channel complex sets, focusing on the recurrent pattern of debrites – conglomerate-filled channel complexes – ponded sheet sandstones. Thus, to avoid confusion in nomenclature with previous works, Pehoe A and B; and Paine A and B are combined forming the four channel complex sets Pehoe AB, Pehoe C, Paine AB, and Paine C.

This pattern recognised in the study area, which triggered the proposed subdivision, is characteristic of most of the submarine channel studies done both for academic and industrial purposes. Recognising these characteristics is critical for using the system as an analogue in hydrocarbon exploration, allowing the prediction of packages with economic interest such as reservoir and seal.

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Canyon sediment feeding systems in the Tyrrhenian Sea: a key to understanding deep-sea stratigraphy

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The early assumptions of the sequence stratigraphic models foresaw a simple dependence of deep-sea stratigraphy on sea level position. In particular, they envisaged a progressive shut down of deep-sea deposition during rising sea level and highstand, due to the progressive increase in the distance between coastal systems and canyon heads. We now recognize that some modern canyon heads are in shallow-water, coastal areas and were consequently close to the coast also during much of the last sea-level transit across the shelf. In addition, a source-to-sink approach is gaining importance in the interpretation of deep-sea stratigraphy. In this context, a better knowledge of the range of processes that can potentially feed sediment within canyons, and how they vary in time and in space assumes a relevant role when trying to interpret deep-sea depositional sequences. Submarine canyons are in fact the elements that transfer most of the sediment from the shallow-water areas to the deep sea. The processes that act at the canyon heads and that introduce sediment within the canyons are extremely variable both in time and in space. They span from sediment failure to hyperpycnal flows, to storms, long- and across-shore and tidal currents. They differ in the volume, grain size, and sorting of sediment that they are capable of introducing within the canyon head during a single event, and in their recurring time and efficiency, intended as the capability of transferring sediment down dip.

In this contribution we present data on modern canyons located along the Sardinian and Sicilian margin in the Tyrrhenian Sea. Here the shelf break is located at a depth of about 120 m, corresponding with the position of the sea level during the last lowstand. Many of the canyons of the studied margins have, however, their heads at depths shallower than 120 m, and therefore were directly connected with a coastal area for much of the last sea-level cycle when the coastline moved from the shelf-edge to the present-day coastline. Furthermore, in some cases the canyon heads reach the present day coastline. For the latter, multibeam and chirp subbottom data allow the direct observation of the processes that are feeding the canyon heads during the present-day highstand. Besides, since some portions of the study shelves are devoid of any Holocene deposits, the morphology of the coastal systems that developed and progressively migrated landward during the last transgression is still preserved and gives hints on how feeding processes to canyon heads varied in time.

The canyons that are at present located very close to the coastline are sometimes directly connected with a river mouth. The Sicilian margin in particular is a high-relief mountainous setting; both the Sicilian and Sardinian Islands rivers have torrential regimes with large flood events, which were recorded also recently; the canyon heads have gradients of up to 20°. Therefore, hyperpycnal flows are the most plausible processes that feed sediment within the canyon heads. In some cases, rivers build a delta with multiple distributary channels within the proximal canyon trunk, suggesting that the coarse-grained river-borne sediments are trapped in the canyon head and only the finer-grained sediment are delivered to the deep sea. In others, the absence of large depositional bodies suggest that all the river-borne sediment bypass the canyon heads and are presumably fed directly to the down-dip parts of the deep-water system. In one case, the coast-connected canyon head is far from any river mouth, but the distribution of Holocene sediment implies that sediment remobilization occurs in the surrounding shelf sector and along-shore currents can feed sediment within the canyon head.

Some of the canyons, whose heads at the present-day highstand are located at the shelf-edge or at shallower water depth, are however in both circumstances far from the present-day coastal systems. In some of these cases, sediment failure in the canyon heads and flanks are apparent and landslides are funnelled downdip within the system and become depositional in the basin plain. In other cases, the relatively high volume of river-borne sediment has allowed the distal part of highstand progradational deltas to reach the canyon heads, notwithstanding their distance from the coastline. Here the largest, presumably coarsest, sediment volume is accumulated in the proximal delta portions, but small channels developed in the distal delta enter the canyon head indicating that presumably fine-grained, small-volume flows can feed sediment within the canyon. In the Northern Sardinian margin, close to the Bonifacio Strait, the outer-shelf and shelf-edge areas are the sites of offshore tidal channels and ridges that sometimes terminate in the canyon heads. In this sector, it is likely that very well-sorted sediment, due to tidal current reworking, are introduced within the canyon heads even during the present-day highstand.

For some canyons, surrounded by relict shelf sectors, the variations of sediment feeding systems during the last sea-level rise can be partially reconstructed. In many cases the canyon heads are at shallower water depth than the 120 m isobath. During the lowstand and the early sea-level rise, the present-day canyon heads were therefore the distal part of subaerial incised valleys, which deeply confined rivers. Consequently, the rivers were directly connected with the canyons and due to high, up to 20°gradient, hyperpycnal flows introduced all the range of river-borne sediment to the deep sea. With continuing sea-level rise, the river mouths became detached from the present-day canyon heads and deposition in a variety of coastal systems started to develop. In some cases a backstepping delta system is observed upslope from the canyon heads that therefore were first fed by channelized relatively coarse-grained flows of proximal delta environment and then by un-channelized finer-grained prodelta flows; finally, the coast migrated further landward and even the very distal delta deposits were stored in the shelf upslope from the canyon head. In other cases, backstepping strandplain deposits are observed upslope from the canyon heads suggesting that storm- wave- and current-reworked sediment were involved in progressively finer-grained and smaller-volume flows that entered the canyon heads. In one case, barrier and lagoon systems are observed upslope from the canyon head. Here, the first barrier formed just at the canyon head and storm- and wave-reworked sediment could enter the canyon head; successively, with continuing sea level rise, the barrier was submerged but prevented any connections between the further inland, newly developed coastal system and the canyon heads, which presumably did not receive any more sediment. Some of the canyons consist of a network of proximal tributaries that join downslope into a single trunk. Our data reveal that the heads of the single tributaries, both during the present-day highstand and the last sea level rise, can be close to different coastal systems suggesting that different processes can actively feed sediment within a single canyon at the same time. These settings must result in complex deep-sea stratigraphy, where deposits with highly varied character are to be found.

Our data highlight the large variability, both in time and in space, of the processes that trigger down-canyon sediment transfer. In the absence of any extensive data base directly linking each of these processes to its specific deposits in the modern deep-sea, our observations remain qualitative. However, reasonable estimates of the character of the sediment gravity flows and of their deposits, which different coastal systems can generate, are possible. Our results can therefore contribute to improving our knowledge of one of the fundamental aspects of the source-to-sink approach to the genetic interpretations of ancient outcropping and subsurface deep-sea successions. In addition, they can help in deciphering the significance of the vertical stacking of deep-water successions and in predicting proximal-to-distal facies tracts.

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Applying Models, Commonality and Analogues to Reservoir Prediction and Characterisation of Turbidite Slope Channels

Mike Mayall
Mike Mayall Geology Consulting and Imperial College, London

The discovery of large hydrocarbon volumes in slope channel reservoirs in the mid 1990's triggered an enormous number of studies on this depositional system. Over the last 15-20 years there has been an explosion of fabulous outcrop studies, exciting seismic analysis and tantalising depositional process advances. A large amount of industry effort, together with vibrant and successful academic studies, often funded by industry, have generated and documented vast volumes of data, ideas, models and training opportunities for potential application to subsurface problems. In many ways the sheer success of these programs has made it more difficult for working geoscientists (and engineers) to exploit this huge data resource and demonstrate its undoubted value. Well-constructed websites, data bases and workflows are all trying to make the material more accessible to the people who need to use it. The talk will focus on three areas where it is possible to convert the complexity of the available data, models, ideas etc. into formats for practical and pragmatic application.

Channel models. There are numerous published sketches of depositional models of turbidite channels which range from individual outcrop or subsurface examples to attempts at a broader synthesis. Often these models emphasise different aspects of the depositional system. In using them we need to be clear what practical purpose exhibiting a depositional model is trying to serve.

Commonality. From all of the documented examples we can recognise a number of characteristics which are common to most, if not all, turbidite channels (e.g. hierarchy of channels, facies). However there are a number of areas which are more poorly understood and deserve further attention (e.g. variability of basal lags, terraces/internal levees).

Analogues. We always consider analogues to be a very powerful tool. We generally know what they are not i.e. one-for-one look-a-likes, but how can we use the analogue concept with conviction? Giving us confidence in our interpretation and helping us predict beyond the limits of our data are two ways in which we can demonstrably gain value from analogues.

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Wednesday 25 January

Session Two: Mass Transport 1

Keynote Speaker: Mass Failure Processes and Deposits: A Spoonful of Sugar Approach

Lesli J. Wood
Colorado School of Mines, Golden, Colorado, U.S.A.

Exploration in the recent couple of decades in water depths off the continental margins of the world has led to an explosion in recognition of the important role that mass failures play in processes active in deep-water basins and their contribution to the fill architecture. However, such recognition has also led to the acknowledgment of how little we know and can predict regarding these enigmatic deposits and their impact on reservoir, seal, and fluid pressures and migration, and the hazards they present both beneath the waves and generate along coastlines. Much advance has been made in the use of 3D seismic to recognize the occurrence of these deposit types, but less knowledge exists from core and wells on their actual character at reservoir depth. Outcrops have allowed workers to document the details of rheology and lithologies, but translating these details into sealing capacity, reservoir potential and seismic-scale recognition criteria for these parameters still is woefully inadequate. Even more poorly understood are prediction of the impulses that drive margin failure, and the resultant tsunamigenic risks that are posed by failures. The sealing capacity of mass failures has everything to do with the lithology of the deposit and the stratigraphic relationship to the underlying or lateral reservoirs. Jubilee Field in the Gulf of Mexico shows a variety of attached and detached mass failures interacting with turbidite reservoirs. Microscopic analysis of lithology associated with sealing MTDs in core show increased grain shear in proximity to sealing intervals and may provide core-based recognition criteria for successful seals. The sealing capacity of MTDs can depend on their lithology, which is tied to their origin. In recent work in the deep-water fold and thrust belts of Borneo, as well as the deep-water regions of Barbados, faunal data have proven to be an effective identifier of shelf attached (i.e., sandy) versus shelf detached mass failures. In these basins, attached MTDs show an abundance of neritic foraminifera. As other researchers have shown, large rafted blocks, often common in mtds, tend to increase seal risk. Alternatively, rafted blocks, some documented up to several kilometers in space and 100's of meters in thickness, or amalgamated rock fall mass failures present often fractured, but otherwise undeformed reservoir opportunities in deep-water settings. Ongoing numerical modeling is being integrated with seismic analysis to develop and model turbidite deposition in and around the complex topographies formed by mass failures. These models offers new insights into healing phase top till reservoirs in fields such as Edop, Etim and Asasa in the Niger Delta. Due to the shear frequency of these margin failures, such healing phase top fills over mass failures offer great opportunity for exploration success along many of the world's deep-water margins. As we explore deeper beneath the world's Tertiary margin cover, encounters with the older rift phases of margin evolution necessitate the need to understand the nature of mass failures in rifts and deep lake settings. Some of the best exposed lake deposits in the world, the Green River Formation in Utah show a high abundance of mass failures occurring interbedded with lake turbidites. These failure deposits contain the highest total organic carbon of any of the deposits in these lake sequences, suggesting a connection between organic richness and failure propensity, as well as putting an emphasis on the importance of these deposits in the overall success of the lacustrine hydrocarbon system. Studies in these ancient lakes may also lead to improved understanding of the high risk areas in modern lakes, and the dangers lake failures present to lake margin communities, so often located where deltas create high organic lake margins prone to failure. This talk will touch on the importance of ongoing study of mass failures and processes in setting that range from ultradeep marine to lacustrine and discuss subaerial mass failure studies as important insights into the behavior of sediments under failure.

NOTES:

Structural heterogeneities in submarine slide blocks: Impact on seal-unit competence from macro- to mesostructural scales

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Three-dimensional (3D) seismic and outcrop data were recently used to review the significance of deformation structures in mass-transport deposits (MTDs) across a variety of geological settings. This talk will give emphasis to blocky MTDs generated during major instability events in SE Crete, and in a variety of geological settings, as they pose the largest risk in terms of seal competence in deep-water basins. By definition, blocks exceed 4.1 m in length but can be ~500 m high by >4.5 km long. They present complex deformation, including internal folding, thrusting and rolling over basal breccia-conglomerate carpets. Stratigraphic successions containing blocks are ubiquitous on tectonically active margins of Southern Europe, New Zealand and around Central Asia, to mention a few examples. They are also prolific on passive margins, particularly in regions with salt tectonics.

This talk will focus on soft-sediment deformation structures found at distinct portions of blocks. In particular, foliated strata, intrafolial folds, tiling, bookshelf sliding and dilational jogs reflect important shearing within blocks and their basal glide planes. These features are accompanied by sand injection features, load and flame structures and remobilised sand 'layers' at the base of the blocks. An important observation from outcrop locations in Europe is that blocks were translated above polymictic breccias, and other deformed strata. Rolled and translated limestone clasts occur within these polymictic breccias, which are often embedded in the interior of a clayey matrix. This complex structure puts in question the morphology of basal glide planes as interpreted on seismic data and highlights the presence of porous strata at the base of blocks and large MTDs. Blocks, polymictic breccias and (palaeo) seafloor strata are, at outcrop, deformed together. In addition, several other intervals with evidence for sand injection and sediment remobilization under high fluid pressures are observed inside the blocks themselves.

The talk will show that buried MTD blocks and associated coarse-grained debrites are capable of forming prolific intervals in which hydrocarbons and mineralized fluid will migrate into. The presentation will show that three-dimensional leakage factor models show the bulk of fluid flow to be focused in vertical and horizontal surfaces within, and immediately below displaced blocks. The generation of large slide blocks can also mark the sudden release of overburden pressure, and result in the loss of seal competence above existing hydrocarbon fields. Ultimately, the presentation will clarify the present-day understanding on the modes of formation of submarine slide blocks, confirming their economic importance in deep-water basins throughout the world.

Common characteristics in submarine slide blocks include the presence of key structural features at seismic scales i.e., chasms, faults and horizontal shear planes. These form the main features controlling fluid flow in between, hard cohesive (or cemented) strata in blocks. Specific remobilisation styles are observed at outcrop, such as the alternation in space of autochthonous blocks, in situ breccia-conglomerates with disrupted deep-water fan cones, and laterally spread blocks. These structures can form important compaction-related structural traps in overlying strata if buried at significant depths. However, their distribution may not follow the current MTD classifications used in industry and academia, in great part due to the effect of seafloor topography (and subsequent tectonic movements) on the MTDs' internal structure.

NOTES:

The role of tectonics and mass-transport complex (MTC) emplacement on upper slope stratigraphic evolution: A 3D seismic case study from offshore Angola

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Tectonics is a key control on intra-slope relief and accommodation, although much less is known regarding the role of depositional relief associated with mass-transport complexes (MTCs). Furthermore, the three-dimensional form and areal extent of MTC-related relief, and their impact on subsequent depositional patterns remain poorly constrained. These uncertainties partly reflect the limited extent and two-dimensional nature of the majority of outcrops, and the lack of subsurface datasets that have used high-quality, 3D seismic reflection data. Here we 3D seismic-reflection data imaging the mid-Pliocene-to-Holocene upper slope succession offshore Angola, to constrain the stratigraphic context, distribution, external morphology and internal strain within mass-transport complexes (MTCs). These data also allow us to assess the impact MTC-related erosion and relief have on upper slope deposition, and the role that MTCs play in achieving 'grade' on submarine slopes. The study area is dissected by a series of NW-SE-striking, salt-detached normal faults, bounding a slope-perpendicular, horst that divides the study area into two depocentres. Seismic-stratigraphic analysis reveals that, during the initial stages of deposition, a series of MTCs were emplaced, the thickness and distribution of which are controlled by the intra-slope horst. Substantial volumes of substrate were removed and entrained into the parent flow, and significant (150 m) and irregular relief was developed along MTCs upper surface. We infer that this MTC-rich package documents a time when the slope was above grade and degradational processes dominated. Furthermore, sediment was trapped on the upper slope due to tectonically generated accommodation. Subsequent deposition was from either turbidity currents and/or suspension fallout, at a time when the slope had begun to achieve 'grade' and depositional processes thus dominated. The associated depositional units display only minimal thickness variations with respect to the intra-slope horst, which had been 'healed' by this time; however, the lower of these units displays pronounced and abrupt changes in thickness due to them infilling relief generated at the top of the preceding MTCs. The uppermost strata imaged in the dataset document a time when the slope was at grade and constructional process (i.e. aggradation and progradation) dominated. Deposition at this time was characterised by progradation of a mudstone-dominated, gullied slope system. This study highlights the role that tectonically- and mass transport-driven changes in bathymetry can have on upper slope accommodation and sediment dispersal. From a hydrocarbon exploration perspective this is critical, because tectonic and depositional accommodation provide a mechanism for capturing and trapping clastic sediments in an upper slope setting, which may otherwise be associated with coarse-grained sediment bypass.

NOTES:

Timing and deformation styles of confined mass-transport deposits: Examples from a salt minibasin in SE Brazil

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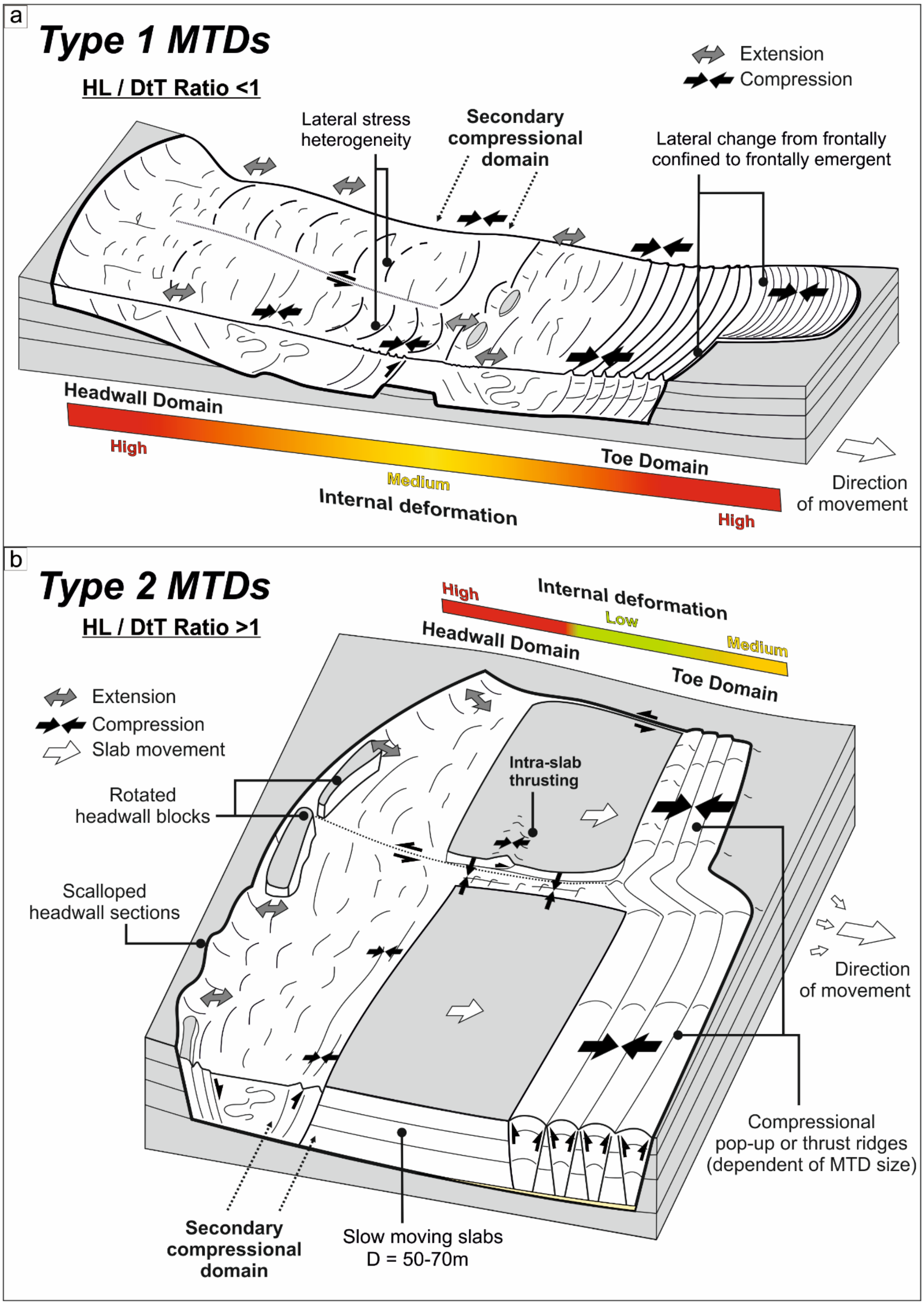
High-quality 3D seismic data reveal bi-modal deformation styles in mass-transport deposits filling a salt minibasin in SE Brazil (Espírito Santo Basin). We analyse three mass-transport deposits within the same Miocene stratigraphic interval, and four other in Holocene strata. Our interpretation reveals that deformation in the mass-transport deposits relates to their long-axis orientation, which is not always parallel to MTD length or distance-to-toe orientations. As a result, mass-transport deposits are divided in two types based on headwall length/distance-to-toe (HL/DtT) ratios: a) Type 1 have long axes parallel to the direction of movement (HL/DtT ratio <1) and show significant internal deformation; b) Type 2 have long axes perpendicular to the direction of movement (HL/DtT ratio >1), are highly heterogeneous and include large undeformed slabs. The long axes of Type 2 mass-transport deposits are parallel to the strike of bounding faults and structures.

The deformation styles of MTDs correlate to their types. Type 1 MTDs show intense, but less complex deformation with thinned evacuation domains followed by thickened toe domains with compressional ridges and variable frontal confinement. Type 2 MTDs show marked lateral changes of internal deformation styles, marked by slabs of coherent strata at transitional domains. Relative short remobilisation distances are inferred for both Types 1 and 2, but remobilisation velocity is likely much lower in Type 2.

In the study area, the timing of emplacement of mass-transport deposits was controlled by the growth of adjacent salt ridges. Earlier halokinesis in the northern axial areas of the minibasin shifted southwards in a second stage. Holocene mass-transport deposits suggest alternating growth of the eastern and western salt ridges.

Our results show that detailed seismic-stratigraphic analyses are key to understand the timings and magnitude of deformation of mass-transport deposits in salt minibasins. The classification proposed can be applied to MTDs on continental margins and in lacustrine settings, and to predict the deformation character and remobilisation dynamics of these deposits.



a)Schematic diagram of the internal features interpreted in Type 1 MTDs. Internal deformation is significant in these deposits. **b**) Schematic diagram of the deformation styles observed in Type 2 MTDs. the diagram highlights the presence of slab with very moderate deformation. HL: Headwall Length, DtT: Distance-to-toe.

NOTES:

Wednesday 25 January

Session Three: Sedimentary Porcesses and Products 1

Keynote Speaker: Submision intended for oral presentation (invited keynote). Process based models of turbidite deposition: experiments, theory, & rocks.

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Process based models should, in the future, deliver on the promise to predict rock properties away from data control. This is one of the drivers towards process-based understanding of the link between turbidity current flow and deposit distribution, architecture, and internal characteristics. In this presentation we will set-out recent advances in experimentation and theory of turbidity current transport, and then demonstrate how utilizing state-of-the-art process understanding allows sedimentologists to approach turbidite outcrops with new ambitions for the quantitative interpretation of flow characteristics. Bringing quantitative sediment transport interpretation to outcrop and subsurface systems is becoming a viable objective of turbidity-current modelers.

The classic Froude scaling approach to turbidity current experiments (Peakall et al., 1996; Parsons et al., 1998) has proven to be valuable in understanding the flow dynamics of turbidity currents but it does not guarantee that flows are able to transport sediment in suspension. In order to predict whether currents are able to transport sediment in suspension it is important to consider the force ratios acting on the sediment grains. This leads to two additional constraints: the Shields parameter, being the ratio between the turbulent shear, as expressed by the shear velocity, and the gravity-induced settling; and the particle Reynolds number, which is the ratio of grain size to boundary layer thickness units (Figure 1; Shields, 1936).

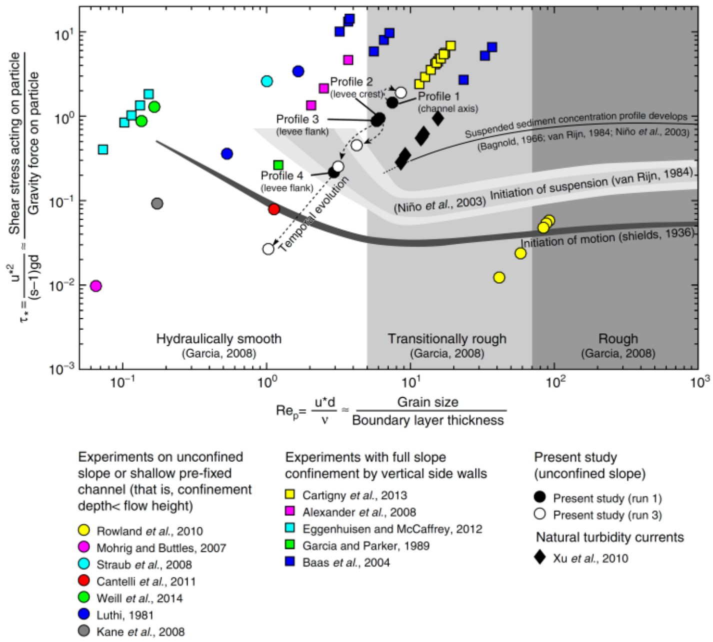

Figure 1. A consideration of sediment transport regimes shows that many previous experimental turbidity currents were performed outside the natural turbidity current regime. Shields scaling, rather than Froude scaling should be the emphasis of studies trying to incorporate flow-deposit interaction. From de Leeuw et al. (2016).

We demonstrate the added value of the new approach with examples of channel-levee development and on-lap sedimentation in a break-of-slope setting. The flow dynamics results of the experiments are consistent with the extensive body of previously published physical modelling results in both examples. The sediment distribution, however, shows a clear departure from the draping depositional behavior encountered predominantly in previous work. In contrast, the experimental deposits presented here display a subtle spatio-temporal interplay between erosion, transport, and deposition of sediment by turbidity currents, which results in a morphodynamic evolution that is a much better analogue for deep-water system development. These experiments are becoming a testing ground for geological conceptual models, and this role is illustrated with a number of examples highlighting channel formation and evolution, levee composition, and sediment on-lap in break-of-slope settings.

In addition to these experimental advances, theoretical understanding of the processes of sediment transport in turbulent flows is rapidly advancing. Key achievements have been made by relating turbulent flow hydraulics to transport of suspended sediment. Much is left to be done. However, this does not need to stop us from compiling our current understanding into first-order predictive models of turbidity current transport and deposition.

We will end the presentation with an overview of new first-order turbidity current flow reconstructions from outcrops in Chile and South Africa. In both cases, combined experimental and theoretical insights led to the formulation of simple models for turbidity currents, which can be easily parametrized with robust architectural observations from the outcrops. The model realizations lead to information on system-scale sediment budgets that can be incorporated into source-to-sink analyses of deep-water system context, and to predictions of lateral and proximal-distal facies differences within architectural contexts.

After remaining challenges have been met, the integrated process-product approach advocated here should lead to the establishment of predictive tools that can be applied in subsurface exploration and development workflows. Key to this endeavor is ongoing constructive collaboration between specialists in oceanography, modelling, outcrop, and subsurface studies.

NOTES:

The stratigraphic record and processes of turbidity current transformation across deep-marine lobes

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Sedimentary facies in the distal parts of deep-marine lobes can diverge significantly from those predicted by classical turbidite models, and sedimentological processes in these environments are poorly understood. This gap may be bridged using outcrop studies and theoretical models. In the Skoorsteenberg Fm., a downstream transition from thickly-bedded turbidite sandstones to argillaceous, internally layered hybrid beds is observed. The hybrid beds have a characteristic stratigraphic and spatial distribution, being associated with bed successions which generally coarsen- and thicken-upwards reflecting deposition on the fringes of lobes in a dominantly progradational system. Using a detailed characterisation of bed types, including grain size, grain fabric and mineralogical analyses, a process-model for flow evolution is developed. This is explored using a numerical suspension capacity model for radially spreading and decelerating turbidity currents. The new model shows how decelerating sediment suspensions can reach a critical suspension capacity threshold beyond which grains are not supported by fluid turbulence. Sand and silt particles, settling together with flocculated clay, may form low yield-strength cohesive flows; development of these higher concentration lower boundary layer flows inhibits transfer of turbulent kinetic energy into the upper parts of the flow ultimately resulting in catastrophic loss of turbulence and collapse of the upper part of the flow. Advection distances of the now transitional to laminar flow are relatively long (several km) suggesting relatively slow dewatering (several hours) of the low yield strength flows. The catastrophic loss of turbulence accounts for the presence of such beds in other fine-grained systems without invoking external controls or large-scale flow partitioning, and also explains the abrupt pinch-out of all divisions of these sandstones. Estimation of the point of flow transformation is a useful tool in the prediction of heterogeneity distribution in subsurface systems.

NOTES:

Submarine channel sinuosity control on lower boundary stress distributions: implications for forward stratigraphic modelling and the concept of equilibrium

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Seafloor channels are the main conduits through which turbidity currents transport sediment to the deep ocean. These channels often form terminal fan-like systems which can cover thousands of square kilometres; both the channels themselves and the fan systems may form hydrocarbon reservoirs. These channels and fans share many morphological similarities with their subaerial river and delta counterparts but the dynamics that control their formation are rather different. A key source of this difference is the stratified nature of turbidity currents, which results in far more complex flow processes. This, along with the sparseness of field data due to the deep water location, means the hydrodynamic-morphodynamic relationship between currents and their containing channels is still poorly understood.

The process model proposed by Peakall et al. (2000) introduced the idea that, over certain timescales, a current and channel can be in equilibrium, whereby the channel's evolution is quasi-steady in nature. The concept of an equilibrium current has become widespread in the field but it remains unclear as to what exactly this entails. Studies of gravity and turbidity currents generally adopt an experimental or numerical modelling approach. This work combines both approaches to achieve a high resolution of basal dynamics and processes over the entire length and width of the channel. By analysing variations in calculated deposition rates and basal stresses as a function of channel sinuosity and flow magnitude, new insight can be gained into the meander evolution of channels. Predictions of future channel development, based on the deposition and erosion maps, allows not only forward stratigraphic modelling but also the identification of equilibrium current attributes that have previously been arbitrarily defined.

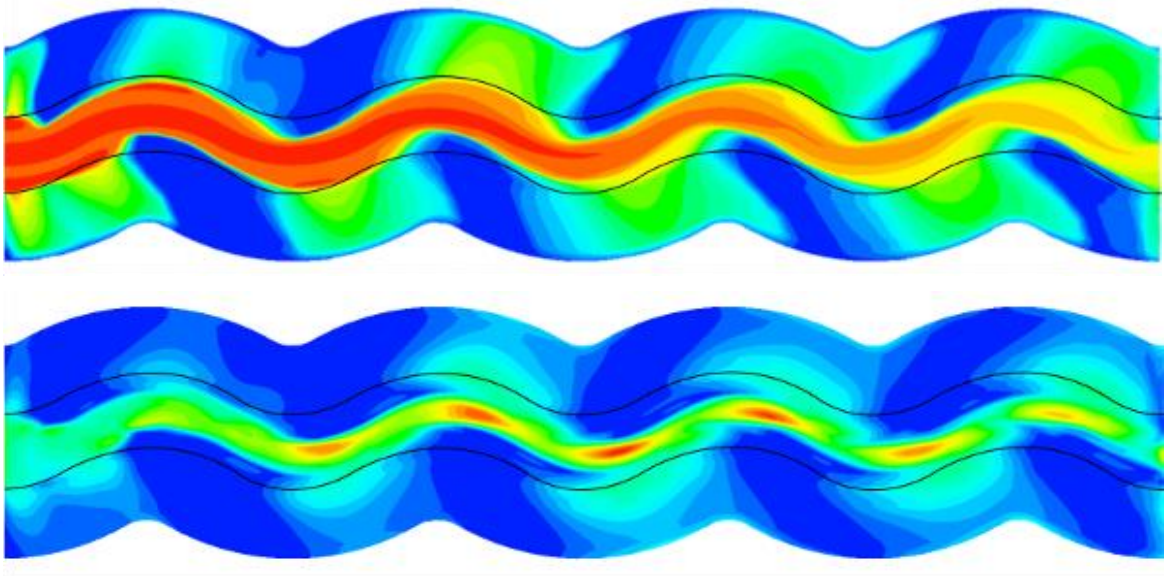

Figure 1: Deposition rate (top) and basal stress (bottom) contours, calculated from a computational fluid dynamics model of a turbidity current in a sinuous channel. Flow is from left to right. Black lines indicate the levee crests.

Peakall, J., McCaffrey, B. and Kneller, B., 2000. A process model for the evolution, morphology, and architecture of sinuous submarine channels. Journal of Sedimentary Research, 70(3), pp.434-448.

NOTES:

Deep-Water Sediment Bypass

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Submarine gravity flows are a key process for transporting large volumes of sediment from the continents to the deep sea. The location, volume and character of the sediment bypassed by these flows dictates the areal extent and thickness of the associated deposits. Despite its importance, sediment bypass is poorly understood in terms of flow processes and the associated stratigraphic expression. We first examine the relationships between the physical parameters that govern bypass in flows, before assessing the variable stratigraphic expression of bypass from modern seafloor, outcrop and subsurface data sets. Theoretical and numerical approaches distinguish grain size, slope, flow size and sediment concentration as parameters that exert major controls on flow bypass. From field data, a suite of criteria are established to recognize bypass in the geological record. We identify four bypass-dominated zones, each of which is associated with a set of diagnostic criteria: Slope-Channel Bypass, Slope-Bypass from Mass Wasting Events, Base-of-Slope Bypass, and Basin-Floor Bypass. As the expression of bypass varies spatially and is dependent on the scale of observation, a range of scale-dependant criteria are required for robust interpretation of these zones in the field or subsurface. The establishment of criteria to recognize sediment bypass, qualitatively linked with flow processes, is an important step towards improving our understanding of submarine flow dynamics and resultant stratigraphic architecture.

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Wednesday 25 January

Session Four: Turbidites and Tectonics 1

Keynote Speaker: Salt tectonics and turbidite fairways distribution illustrated with 3D seismic imagery in the deep offshore Angola.

Philippe Crumeyrolle
CST JF Total, Avenue larribau France

The distribution of hydrocarbon bearing reservoirs in the Tertiary Angolan margin is clearly linked to the evolution of the salt gravity deformation trough time with sandy turbidites preferentially developed in the more subsiding local depocenters but marked by two main periods of structural evolution.

During the Lower to Upper Oligocene time, the large scale depocenter is located southward along the margin with symmetrical or asymmetrical troughs bordered by peripheral salt ridges and early compressive structures with a topography inherited from the Pinda time period while to the North the area is less subsiding and less affected by salt gravity deformation.

These local troughs started to be inverted by the early Miocene time. Laterally southward and northward the Oligocene series become thinner with more widespread and unconfined turbiditic channel complexes. Superposed on that tectonically controlled evolution an overall prograding evolution occurs punctuated by sea level variations from Lower to Upper Oligocene. This vertical evolution culminate with the deposition of the large constructive leveed channels in the Upper Oligocene correlative with a major sea level drop on the shelf (Chattian event) and finally draped by a major hemipelagite horizon marking a major regional flooding. The upper Oligocene depositional style contrast with the less constructive single phase channels that are developed in the Lower Oligocene.

During Lower Miocene to Pleistocene, following the Upper Oligocene flooding event, the inversion stage started in the Early Miocene, the turbiditic fairways start to be funnelled by roll-over synclines as well by the termination of turtle backs and listric faults at the location and updip of the Oligocene depocenter. Laterally large poorly confined sand rich turbidite systems spread out in areas less affected by salt gravity deformation. This explains the progressive increase of sand occurrence northward. Above the Oligocene depocenter, individual former troughs were progressively converted into topographic highs forming turtle-back anticlines that are progressively disrupted by transverse grabens that capture turbiditic fairways in a dip or strike directions perpendicular or parallel to the slope progradation.

In the frontal compressive areas, the turbiditic fairways are captured by elongated basins developed between salt cored anticlines. Saddles between these salt cored anticlines form pathways for turbidites fairways to pass from one mini basin to mini basin and finally spread out into the abyssal plain. In the Miocene, as the rate of extension increase up dip, mini basins are progressively thrusted and overthrusted with numerous isolated or imbricated salt overhangs.

NOTES:

Structural controls on turbidite sand fairway evolution in thrust belts: the Numidian (Miocene), Central Mediterranean.

Patricia Pinter[1], Rob Butler[1], Adrian Hartley[1], Rosanna Maniscalco[2]
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[2]*University of Catania, Italy.*

Several of the World's major deep-water sedimentary systems accumulate at active plate boundaries so that their older deposits have been progressively deformed and dismembered. Understanding the evolution of these systems, especially how facies relate to tectonic structure, not only requires the appropriate adoption of structural methods, including tectonic restorations, but also confronting the stratigraphic record of deformed sedimentary successions. Here we develop a better understanding of these deep-water systems – focusing on an example from the active orogenic system of the Central Mediterranean. Numerous turbidite systems in the region (e.g. Marnoso Arenacea, Macigno, Cilento, Gorgoglione, Numidian, Annot) have yielded important studies of turbidites that are widely used as outcrop analogues for subsurface examples in modern deep-water settings (e.g. along the South American-Caribbean margin). Much of this research has focused on the little-deformed sections that sample discrete parts of the original turbidite pathways. Yet the bulk of these systems are represented by deformed successions and these have attracted little modern sedimentological and stratigraphic investigation. One such, and arguably the sandiest system, is the Numidian (Miocene) of Sicily and the southern Apennines. Turbidites in this system include thick, ultra-mature quartz sandstones sourced from North Africa and deposited in now-deformed and dismembered basins caught up in the Apennine-Magrebian orogen of the Central Mediterranean (Fig. 1). The original composite sand fairway can be traced for at least 300 km offshore into what is now the southern Apennines.

We present new data based on field mapping, sedimentological/structural fieldwork, and biostratigraphy (foraminifera, nannofossils) that focus on central and eastern Sicily. These include the greatest extent of Numidian strata in the Mediterranean. Sandstones form aggradational bed-sets that presumably accumulated in elongate lobes along with local gravels. In general the sandstones show abrupt grain size breaks, bed tops, parallel lamination. This sedimentology is consistent with large-scale sediment bypass. The structureless nature of the Numidian sandstones, generally interpreted as result of rapid sand deposition, has been greatly over-reported.

There is no architectural evidence for major incisional channel systems in the outcrops. Erosional products of pre-Numidian strata are derived through local substrate incorporation. Muddy basin-floor substrate is locally incorporated through erosion of fold crests. Rock-falls from the limbs of growing folds characterize mass wasting products from carbonate substrates. Neither example produce significant contamination of the quartz sandstones which otherwise swamp any entrained materials. While there may have been significant bulk creep of substrate operating in tandem with thrust tectonics, there is only minor evidence for large-scale slumping or debris flows within the Numidian system - which presumably implies rapid deposition compared with tectonic tilt-rates.

Fairway margins with 200-300 m thick amalgamated sandstones passing over 1-2 km laterally into fine-grained slope deposits are abrupt, controlled by active thrusts and inherited structures (Fig. 2). Although parts of the system become occluded – for example by the influx of orogen-sourced immature turbidites – active structures largely serve to separate the distinct fairways. These in turn provide key markers in the restoration of the subsequent tectonics thus yielding better palaeogeographic models. Although classically interpreted as being unconfined, our work demonstrates the system accumulated across active contractional (and inherited largely extensional) structures. These provided tortuous, evolving corridors through which turbidity currents were routed, transporting coarse sand many hundreds of km.

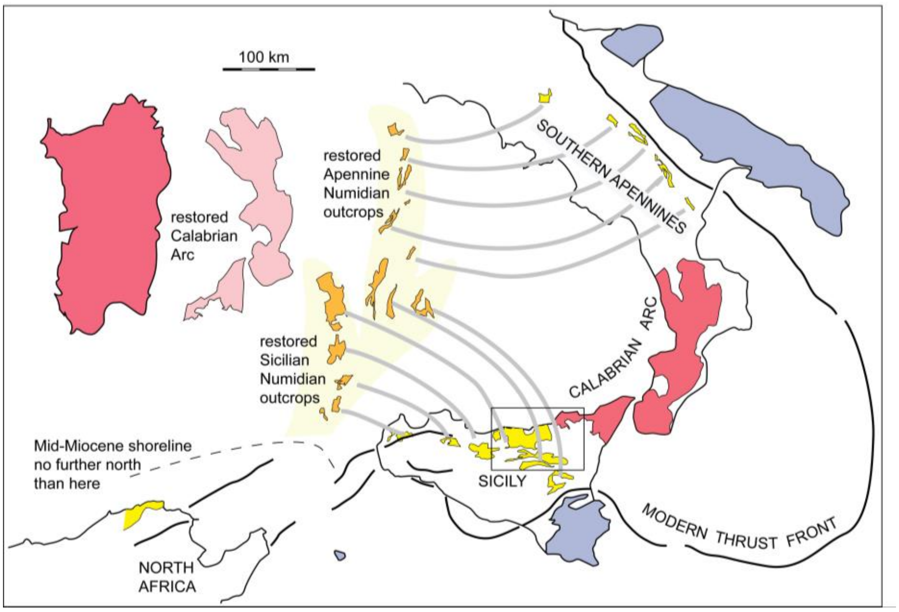

Fig. 1. Palaeogeographic restoration of Numidian outcrops in the Central Mediterranean (based on tectonic rotations of Maffione et al. 2013, Tectonophysics). The boxed area contains our principal study sites on Sicily with further work undertaken on the outliers in the Southern Apennines.

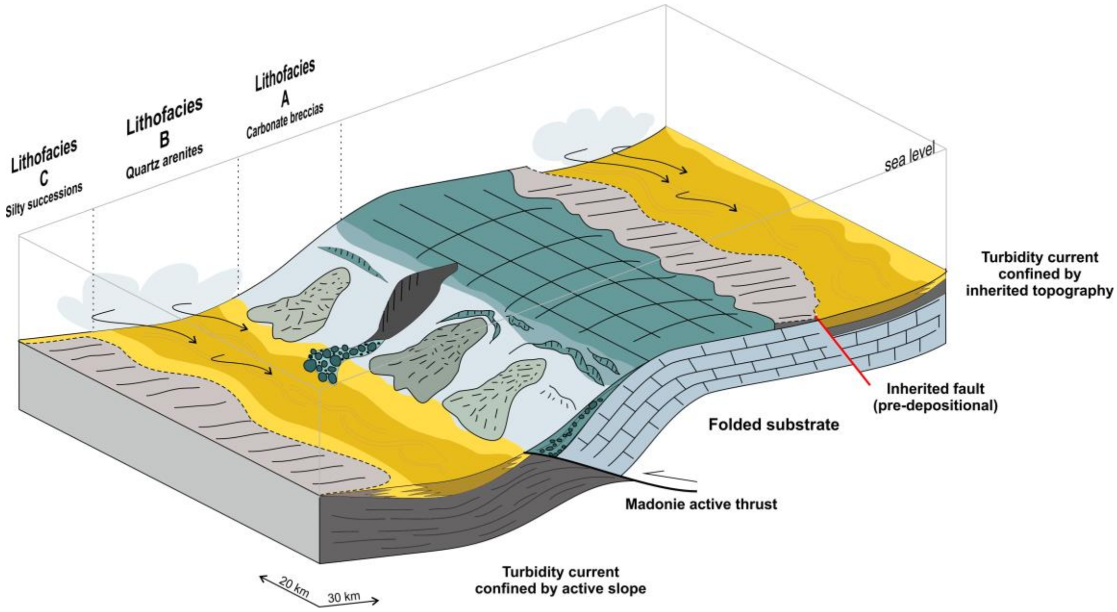

Fig. 2. Schematic block diagram illustrate facies variations in the Numidian associated with local basin floor structures – based on field relationships in northern Sicily.

NOTES:

Comparison of outcrop and subsurface deep-water compressional systems: Late Miocene-Play, Sabah Malaysia and circum-Alpine basins

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Deep-water depositional systems in actively-compressional tectonic regions display markedly different tectono-stratigraphic development from more passive tectonics basin regimes or in active basins with high sediment flux (Stanbrook *et al*, 2014; Peel *et al*, in prep). These differing settings give rise to different basin margin onlap relationships that have an impact on how the architectures of subsurface reservoirs in similar systems are organised. This can have a significant impact on how architectures are modelled and a substantial effects on calucualted volumes and economics forecasts. To eludicdate these architectureal elemnts we compare the thrust-front compressional deep-water system of a Late Miocene play in Sabah, Malaysia to two outcrop, and one subsurface deep-water system, from around the European Alpine chain (Figure 1).

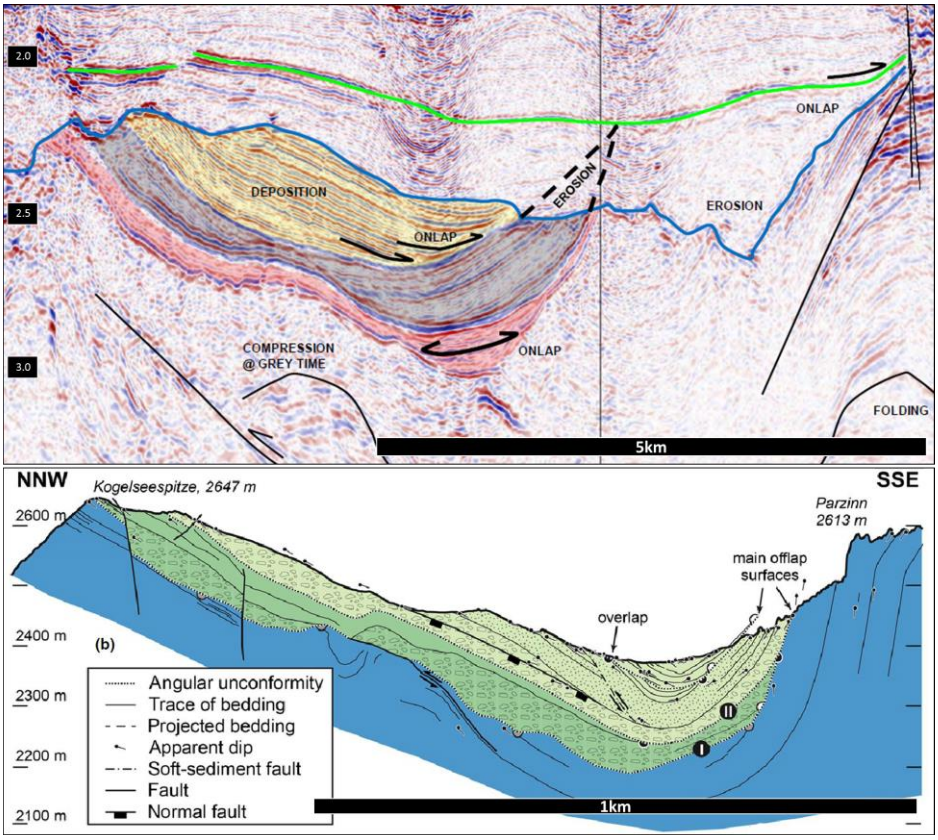

Figure 1. Comparison of two deep-water compressional systems in fold and thrust belts. Subsurface Miocene-Compressional system, Sabah, Malaysia (upper image, from Jones et al, 2016). Outcrop Molasse Basin system (lower image, from Ortner et al, 2015.)

The Late Miocene play in northern Sabah (Jones *et al*, 2015) is a high net-gross deep-water clastic system that comprises a series of linked mini-basins that formed in response to syndepositional tectonism along the Sabah thrust front. The complex bathymetry of the system is in part a function of inherited multi-phase tectonic regimes with widely varying principal stress directions (Jones *et al*, 2015). Across the European Alpine system there are at least three deep-water systems of a similar geometric and basin-fill nature. The Eocene-Oligocene Grès d'Annot Formation deep-water clastic system has exposures along the length of a series of linked mini-basins in a variable, but generally very high net:gross, and confined system (Stanbrook & Clark, 2008). The complex topographic nature of the Grès d'Annot system is a function of inherited multi-phase tectonic regimes with widely varying principal stress directions (e.g. Apps 2004). The Cretaceous Muttekopf-Gosau basin exposes a high net:gross deep-water clastic system in a strongly compressional setting (Paton *et al*., 2007a,b). Syn-thrust sedimentation was controlled by active folding and tear faults that set up both angular unconformities and progressive unconformities (Ortner *et al*, 2015). The Oligocene-Miocene Puchkirchen Formation of the Molasse Basin, Austria is a subsurface example of thrust-front constrained deep-water clastic system (De Ruig & Hubbard, 2006). The Puchkirchen Formation turbidites responds through time to changes in basin morphology resulting from the entry along the basin margin of mass transport complexes driven by changes in compression along the thrust front (Masalimova *et al*, 2015).

Comparison of these systems indicates that deep-water clastic depositional systems in compressional basin settings may exhibit several or all (Table 1) of the following criteria 1) basal portions of basin fill tend to be dominated by mass transport complexes; 2) the compressional nature of the basins leads to high degrees of lateral confinement and therefore high net:gross expression; 3) syn-depositional basin reconfiguration changes sediment depocentres through stratigraphic fill (Figure 1); 4) main axial transport direction tend to be normal to the thrust front; 5) gullying of the thrust front provides entry points for mass transport complexes; 6) considerable reworking of basin margin deposits occur; and 7) erosional angular unconformities of early to late basin stratigraphy at basin termination (Figure 1).

Criteria	Sabah	Annot	M-Gosau	Molasse
Basal MTC's	Inferred	Yes	Yes	No
High net:gross	Yes	Yes	Yes	Where channelized
Mobile depocentres	Yes	Minor	Yes	Yes
Transport normal to thrust	Yes	Yes	Yes	Yes
Thrust front gullies	Yes	Basal & terminal	Inferred	Yes
Reworked basin margins	Yes	Minor	Yes	Moderate
Angular unconformities	Yes	Yes	Yes	Moderate

Table 1: Comparison of sedimentary/tectonic features of the basins discussed.

NOTES:

Sedimentology and architecture of late syn-rift to early post-rift transition in a deep-water half-graben, Neuquén Basin, Argentina

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The early post-rift period of many rift basins are characterized by deep-water conditions due to thermally-driven subsidence after rapid, large-magnitude, syn-rift subsidence. The transition from syn- to post-rift, which in subsurface data is defined by a post-rift (PRU) or breakup unconformity stage, can lead to major changes in sediment dispersal patterns and processes, conditioned by inherited rift basin topography (i.e. underfilled or overfilled rift basins). Generic tectono-stratigraphic models for deep-water rift basins do not capture this complexity, especially in early post-rift systems fed by multiple sources. To assess the impact of evolving post-rift physiography on stratigraphic architecture, a rare example of an exhumed post-rift deep-water system has been documented. The study area is the Chachil subbasin, a 17 km long and 17 km wide NW-SE trending half-graben in the SW Neuquén Basin, Argentina. The exposures permits the controlling factors on the paleogeographic organization from syn- to post-rift transition to be assessed. Ten measured sections were physically correlated along a >10 km long transect across the width of the southern border of the Chachil half-graben. The subbasin is filled by Triassic, volcano-sedimentary, syn-rift deposits, which thicken northeastward from 100s m to >2 km. The syn-rift deposits are overlain by an early Pliensbachian-late Toarcian syn- to post-rift marine succession that dips and thickens towards the hangingwall, and thins and onlaps towards a major granitic footwall bounding the southwestern margin of the subbasin.

The syn- to post-rift succession comprises two major stratigraphic units. The first is a fining-upward succession (up to 50m thick) of slope-to-platform, mixed carbonate-calcareous clastic deposits, which are strongly influenced by rift-related relief (Chachil Formation) (Fig. 1-2). The second stratigraphic unit is a coarsening-upward succession (up to 2000m thick) of slope-to-basin floor, deep-water clastic deposits emplaced across gentler basin relief (Los Molles Formation) (Fig. 3). The gradual sedimentary infill indicates drowning of the carbonate system by a turbidite system in a subbasin dominated by subsidence. The turbidite system is composed of (i) a lower calcareous-rich mud-prone succession and (ii) an upper carbonaceous-rich lobe-dominated succession with abundant plant material and intrabasinal mudclasts (cm to dm). The lower mud-prone succession corresponds to massive mudstones with rare thin to medium beds of structureless siltstones and medium to fine-grained sandstones with shell fragments. The upper lobe-dominated succession corresponds to thick beds of poorly sorted, massive or normally graded very coarse to fine-grained sandstones, with planar or low angle-cross tangential stratification, intercalated into dark organic shales and pelagic mudstones, or thin bedded successions of fine to coarse-grained, structured or structureless sandstones and siltstones.

The architecture and thickness patterns of the syn- to post-rift succession presents local variations of accommodation and readjustment of sedimentary systems across structures, expressed by abrupt facies changes. The evolution of syn- to post-rift sedimentation, from a shallow-water carbonate- to a deep-water clastic-dominated regime, record a transition from intra- to extra-basinal processes that occurred with a change of sediment yield, source provenance and climate. The development of predictive stratigraphic models that incorporate outcrop data is necessary to improve prediction of subseismic facies distribution in early post-rift sequences. This will allow us to better predict reservoir distribution and trap type for analogue systems developed under the influence of similar factors of control in underexplored post-rift basins.

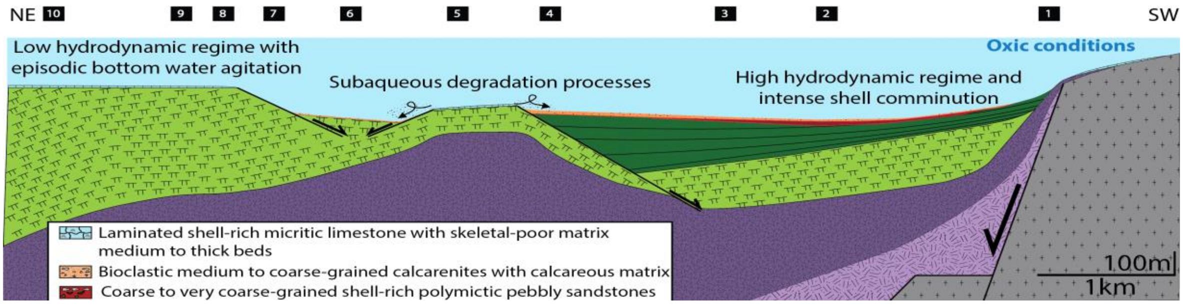

Figure 1: Early Pliensbachian section of the Chachil hemi-graben showing shallow-marine sedimentation from footwall to hangingwall (SW-NE), with transgressive lags and proximal carbonate patches on structural platforms. (Grey unit: basement; purple units : andesitic lava flows and breccias ; green unit : ignimbrites and resedimented pyroclastic deposits)

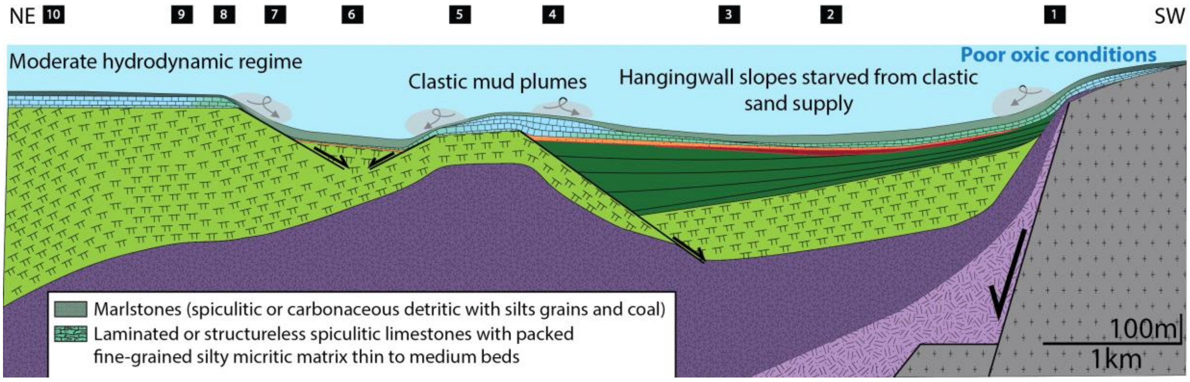

Figure 2: Late Pliensbachian section of the Chachil hemi-graben showing deep-water sedimentation from footwall to hangingwall (SW-NE), with distal carbonate ramp across slopes and restricted downthrown topographic lows.

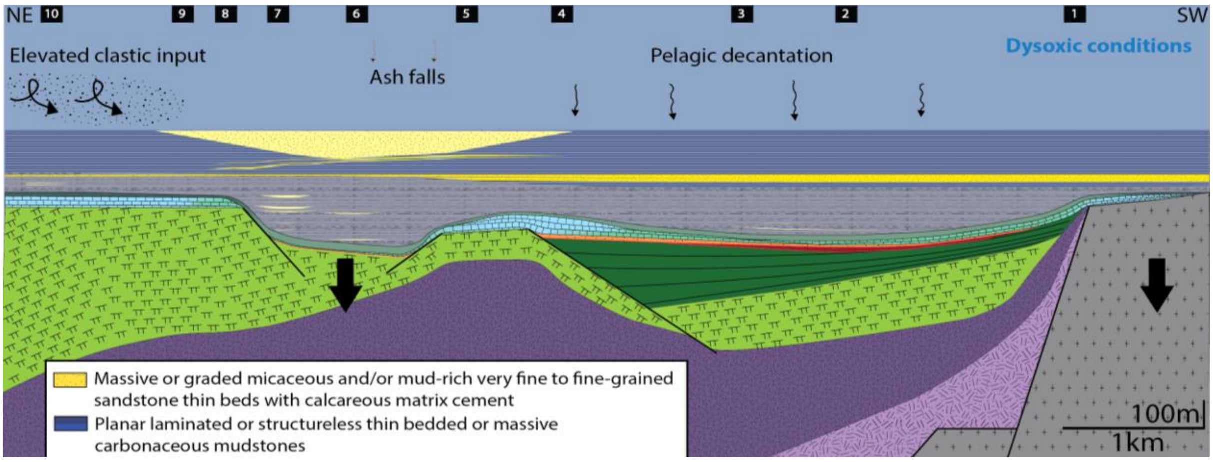

Figure 3: Toarcian section of the Chachil hemi-graben showing deep-water sedimentation from footwall to hangingwall (SW-NE), with calcareous mudstones and sand-poor succession overlain by organic shales and sand-rich succession.

NOTES:

Thursday 26 January

Session Five: Mass Transport 2

Neogene Turbidite and Mass Transport Sedimentation in the Arabian Sea Revealed by the International Ocean Discovery Program (IODP)

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The Indus Submarine Fan is the largest repository of clastic sediment eroded from the Western Himalayas since the start of India-Eurasia collision, likely around 50 Ma, at least in the Indus catchment. Interpreting this sedimentary archive is central to understanding how the Asian monsoon and Himalaya have evolved together. Drilling by International Ocean Discovery Program (IODP) Expedition 355 in the Laxmi Basin of the Eastern Arabian Sea recovered two submarine fan sections spanning the last ca. 11 Ma. The Indus Submarine Fan has received materials from Himalayan high-grade metamorphic rocks since at least ca. 14–17 Ma via a palaeo-Indus River. Results also indicate that there was a direct connection with the Indus-Yarlung suture, likely close to the western syntaxis, since the late Miocene. The two drill sites (U1456 and U1457) cored the center and edge of the Laxmi Basin, which has funneled sediment between Laxmi Ridge and the Indian passive margin at least since the late Miocene. Each site recovered packages of sandy turbidites with short, infrequent interbedded intervals of muddy carbonate. These likely represent times when avulsion diverted Indus-derived material to the west into the central Arabian Basin where it was deposited in lobes and channel-levee complexes. Seismic data show that the sequence is largely flat-lying, with some incision by migrating channels, but that major channel-levee complexes did not develop so far (>750 km) from the river mouth.

The turbidite section overlies a giant mass transport deposit, the Nataraja Submarine Slide, that runs from the Gujurat-Saurashtra coast to the Laxmi Basin and is over 330 km long and a maximum of 190 km wide. Drilling shows that this was emplaced before 10.8 Ma. This slide covers $5 \pm 0.2 \times 10^4$ km^2 and represents a volume of $19 \pm 4 \times 10^3$ km^3, exceeding in volume all but one previously described mass-transport complex on passive margins worldwide. This slide circumvented large seamounts of the Panikkar Ridge, thus highlighting the capacity of the flow and its potential energy during emplacement in a funnel between the slope of the Western Indian passive margin and the Laxmi Ridge. Drilling verifies that the slide is composed or one or two discrete events and is >800 m thick at its maximum but ca. 300 and ca. 190 m thick at IODP Sites U1456 and U1457 respectively. The slide deposits comprise an upper sequence of slump-folded muddy and silty rocks, with underlying calcarenites and limestone breccias, together with smaller amounts of volcanic clasts, all of which were derived from the western Indian continental shelf. Presently the trigger to the slide is unknown but could be linked to enhanced sediment delivery to the shelf edge following a time of intense monsoon, or to falling sealevels.

NOTES:

Entrainment of substrate sediments by submarine debris slides: insights from blocky MTDs of the Eocene Ventimiglia Flysch Fm, NW Italy

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Submarine mass wasting is recognized as one of the main contributors to deepwater deposition. A number of transport mechanisms, including block and debris slides, slump and debris flow or any combination thereof are reported in the literature, reflecting the degree of disaggregation and the rheology of materials involved. The degree to which debrite runout and character are determined by the nature of the initial failure, vs. the erosional character of the flow and the composition of any eroded substrate remains a key area of study.

This contribution describes multiple MTDs from the Ventimiglia sub-basin of the Alpine foreland basin, NW Italy. This tectonically active, N-S elongate depocentre was predominantly filled by southerly-sourced turbidites of the Upper Eocene Ventimiglia Flysch Fm (VF), deposited unconformably onto hemipelagic marlstones of the Middle Eocene Olivetta San Michele Fm (OSM). Metre to tens of metre-thick blocky MTDs of resedimented OSM occur at different levels and locations within the basin fill, suggesting they resulted from repeated mass wasting events affecting basinal slopes. Typical features of these MTDs include from bottom to top: i) a basal surface locally cutting up to 30minto a variously deformed turbidite substrate; ii) a megabreccia comprising changeable proportions of metre to hundreds of metre-scale blocks of either OSM with intact internal stratigraphy or folded turbidite sandstones and mudstones of VF; iii) a crudely graded conglomerate of dominantly OSM clasts that tends to become increasingly rich in VF clasts distally and may either sit onto the megabreccia or directly upon the turbidite substrate. Typically the MTD top has nested wavelengths of rugosity (a few to a few tens of metres over lengths of hundreds to a few thousands of metres), forming confined accommodation space for post-mass wasting turbidites.

Based on correlation of multiple sections through the best exposed of the studied MTDs, the shape and internal heterogeneity of these blocky deposits was detailed over an outcrop of ca. 5 by 15 km distinguishing: i) an inner/proximal region with high positive relief and deep, though localized, basal erosion consisting of a clast-supported OSM megabreccia (thickness in the range 30 to 75 m); ii) a dual-layer medial region (thickness in the range 5 to 30 m) lying on a distally-shallowing basal surface which comprises a bottom layer of intensely deformed to sheared turbidites and an upper discontinuous layer of either sparse OSM megaclasts or conglomerate and iii) an outer/distal region of the MTD where only the conglomerate is to be found, sitting conformably onto the substrate with no discernible erosion. The most plausible process interpretation of such depositional architecture is one of an initial debris slide of OSM (possibly with a focused mass-flow axis) eroding deeply into the substrate upon reaching the basin floor and undergoing a significant compositional and rheological modification as result of entrainment of unconsolidated sediments from the substrate. It is suggested that development of pore water overpressure in the newly entrained turbidite material may have played a leading role in controlling flow mobility, thus resulting in a longer run out and an increased capacity to transport megaclasts. Finally, the conglomerate is interpreted as the deposit of a trailing debris flow that was cogenetic to the initial slide and capable of outrunning the main deposit of the MTD with minor compositional hybridization. This study potentially provides facies architecture constraints on so-called "detached" MTDs (*sensu* Moscardelli and Wood, 2008), that are common in the subsurface, but whose internal characteristics often cannot be imaged seismically.

NOTES:

Mechanisms of mass-transport erosion and associated controls; insights from the Magdalena Fan, offshore Colombia and the Santos Basin, offshore Brazil

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Mass-flows can be highly erosive, and a significant proportion of their volume can be acquired through substrate entrainment. The entrainment of substrate can affect the rheological evolution of mass-flows and introduce heterogeneities in the associated deposits, thus affecting the sealing capacity of mass-transport complexes (MTCs). Furthermore, basal erosion may also modify the connectivity of underlying reservoirs. Despite the importance of mass-flow erosion, the factors controlling these processes are poorly understood. We use 3D seismic reflection volumes from the southern Magdalena Fan, offshore Colombia and the Santos Basin, offshore Brazil to investigate the mechanisms and possible controls on substrate entrainment by mass-flows.

The slope on the southern Magdalena Fan is characterised by folds associated with a thin-skinned fold-and-thrust belt and high-relief channel-levee systems. Nine syn-to-post-tectonic Pleistocene MTCs overlie and erode into six seismic units composed of channel-levee systems and older MTCs. The local morphology of the MTC basal surfaces reflect interpreted compositional changes in the underlying seismic units, with deeper erosion occurring above likely sand-rich channel axes and more subtle changes occurring across different, likely mud-rich levees. Relief generated by tectonic structures and channel-levee systems influenced debris flow pathways, the final geometry of the MTCs, and the internal MTC seismic facies distribution.

In the Santos Basin, seismic data image three Oligocene-Recent MTCs. The MTCs contain large (up to 10 km^2) coherent blocks. The stratigraphy underlying the MTCs is characterised by parallel, continuous reflections. However the reflections directly underlying the MTC basal surfaces are parallel yet discontinuous. The lateral and frontal margins of the MTCs are typically sharp and well-defined. Locally, however, they are more gradational. Transition zones are characterised by a 0.3-3 km wide area within which discontinuous, parallel reflections become progressively more continuous away from the chaotic seismic facies of MTCs. The transition zones at both the base and margins of the MTCs are interpreted as substrate deformation by the passage of debris flows and ultimate emplacement of the overlying MTC.

This study contributes to our understanding of mass-flow process evolution by demonstrating that: i) seabed morphology and composition are important controls on debris flow dispersal and substrate entrainment, and ii) deformation and weakening of the substrate may facilitate entrainment, and could explain the presence of kilometre-scale megaclasts within MTCs. Because bathymetry can determine flow pathways and erosional fairways, and substrate entrainment can affect the dynamic evolution of flows determining their ultimate runout distances and the characteristics of their deposits, our results have implications on hazard assessments, sub-MTC reservoir presence and continuity, and sealing capacity of MTCs.

NOTES:

The impact of intra-slope salt controlled structures on the character and distribution of mass transport complexes, offshore West Africa

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Department of Earth Science and Engineering, Imperial College London
[1] Now at BP Exploration, Sunbury-upon-Thames

A high-resolution, three-dimensional seismic dataset over a salt-controlled mini-basin allows the identification of two types of mass transport complex (MTC) deposit within the mini-basin fill; local, detached slides and regional debris flows. These two mechanisms transport very different volumes of sediment and, as such, have very different internal morphologies and distributions.

Local slides are observed throughout much of the history of the basin and cover areas of 11-28 km^2. They consist of translated material which can clearly be sub-divided into an extensional domain and a compressional domain: the former containing the headwall scarp which cuts down into the stratigraphy and extensive normal faults, and the latter dominated by thrust faults, folds and ramps cutting up through the stratigraphy. The frontal and lateral ramps are up to 200 m high. The structures within the MTCs create topography, infilled by younger sediment, at the top of the body with depressions up to 40 m thick, 50-210 m wide and 150-400 m long. These slide deposits can be clearly traced back to their source area on the flanks of anticlines that bound the basin.

Regional debris flows are sourced from at least 100 km east of the mini-basin, near the shelf of the continental margin. At least eight can be identified deposited within a 5.38 Ma interval. These MTCs are up to 300 m thick and cover an area of up to 1300 km^2 within the limits of the study area. They are mostly comprised of chaotic material carried within the flow with some discrete high amplitude transported blocks of sediment, from 50-250 m in size.

Rates of movement of the intra-slope salt structures which bound the mini-basin, determined by shortening analysis, can be correlated to observations of the dimensions, characteristics and distribution of the MTCs. Local MTCs have a variable relationship to the rate of structural movement, with the location and frequency not necessarily corresponding to high periods of growth. On one structure the timing of the MTCs clearly corresponds to high rates of structural uplift. However on a different structure, the timing of the MTCs corresponds to a period of quiescence following a higher rate of uplift. In this area, onlapping stratigraphic relationships indicate that the slope was exposed on the sea-floor for some time which may have led to greater sediment instability on the flanks of the exposed structures.

In general the regional MTCs tend to infill the topography within the basin, depositing further down the flanks of actively growing structures and with significantly thicker deposits found in the centre of the mini-basin. The thickness of the deposits also influences their relationship with the topography; the thicker regional MTCs deposits extend further up the structural slope of the salt structures than the thinner MTCs.

NOTES:

Thursday 26 January

Session Six: Regional and Field Studies

Keynote Speaker: Source-to-Sink Methodology for Prediction of Deep-Water Depositional Systems

Ole J. Martinsen and Tor O. Sømme
Statoil Exploration, Norway

Over the last decade, Source-to-Sink (S2S) methodology has proven itself as a powerful tool in the analysis of sedimentary basins. It was initially applied to qualitatively predict the quality and nature of deep-water depositional systems in offshore sedimentary basins weakly modified by tectonics. Early examples include the Cretaceous and Paleocene successions in the North Sea and Norwegian Sea basins (Fig. 1), as well as offshore Brazil.

Subsequent refinement of the methodology was made by developing a concept (Fig. 2) rooted in a semi-quantitative and globally robust database of modern and Recent S2S systems and testing the methodology against known subsurface deep-water depositional systems, such as the uppermost Cretaceous – lower Paleocene Ormen Lange reservoir system in the Møre Basin, offshore mid-Norway (Fig. 3).

In the last 5 years, focus has been on applying the S2S concept to new exploration acreage globally as well as refining the existing methodology. While there is extensive specific information to be gained from applying S2S analysis, the methodology also allows for understanding sedimentary systems in broader and more complete ways than sequence stratigraphy. Nevertheless, S2S analysis complements sequence stratigraphy rather than replacing it. Detailed analysis of basin fill sequences based on seismic and well data requires sequence stratigraphic analysis.

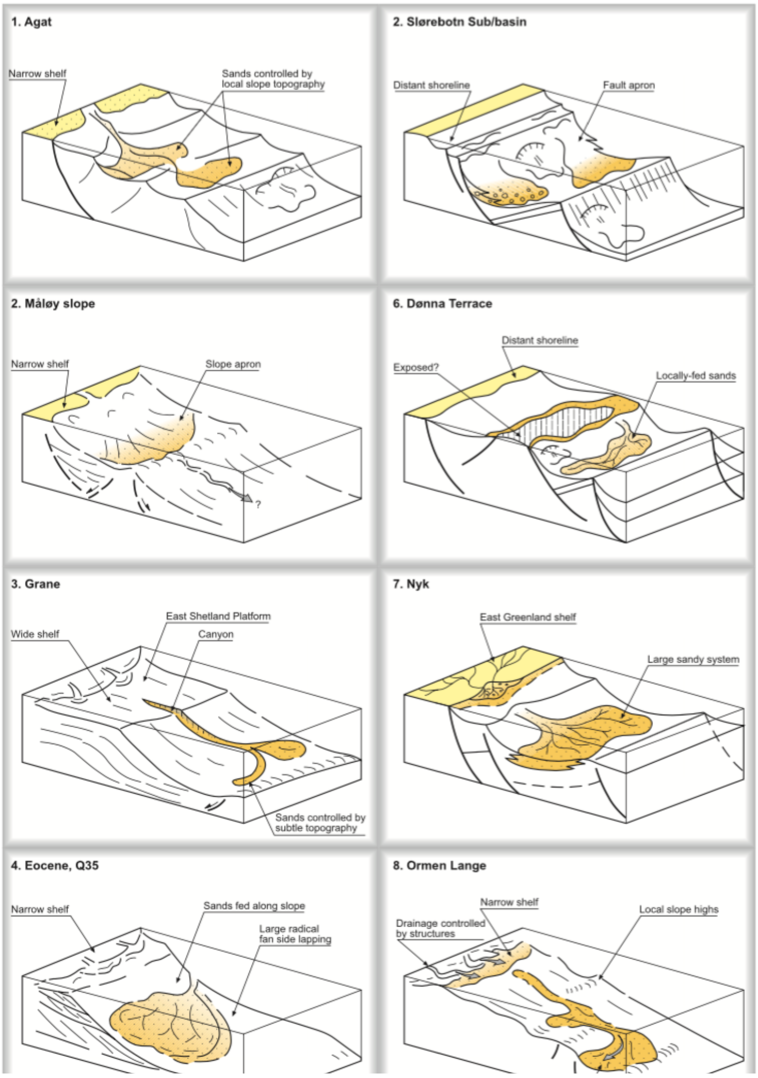

Figure 1: Early application of S2S methodology to Cretaceous and Paleocene deep-water systems, Norwegian Continental Shelf (from Martinsen et al. (2005)

A late development of the S2S methodology is to outcropping basin fill successions. Both foreland basins with continuous onshore, shallow-marine and offshore systems, and particularly well exposed extensional complete basin-fill sequences lend themselves well to such analysis. The analysis is based in the global statistics and key data, such as slope lengths and shelf widths are inverted from decompacted thickness data. For the Carboniferous Shannon Basin, western Ireland, such analysis has been performed, and a full S2S profile was reconstructed. In addition, a reliable prediction of the areal of the deep-water fan complex in the area was made. An important modifier for such S2S analysis is to honor external controls such as tectonics and paleoclimate for the local basinal setting and time period analyzed.

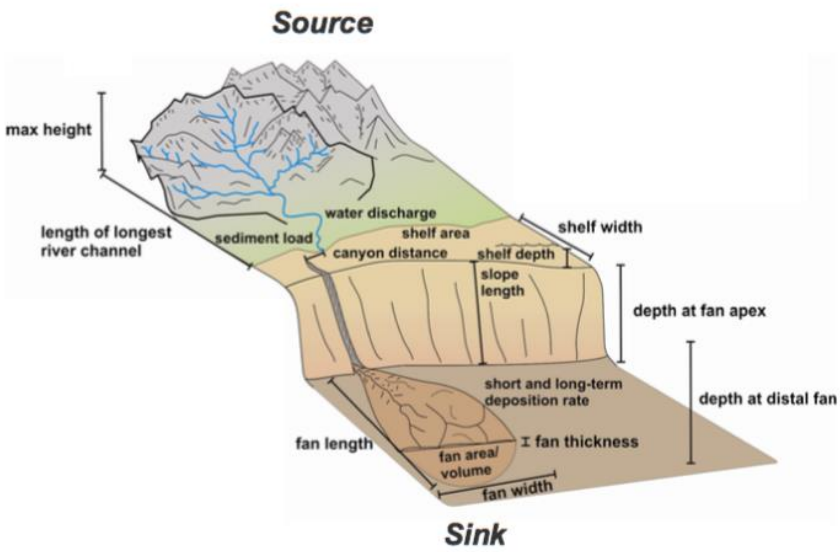

Figure 2: The Source-to-Sink concept (from Sømme et al., 2009a)

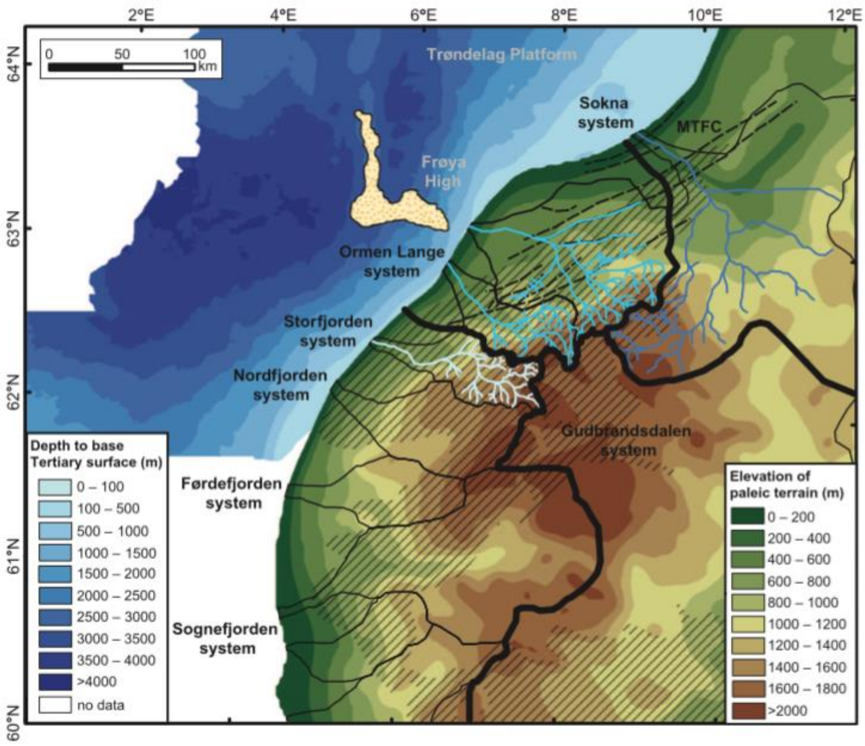

Figure 3: Reconstructed paleo-topography for the onshore-offshore relationship between catchments, shelf and deep-water slope and basin floor for the Paleocene Ormen Lange deep-water system (from Sømme et al., 2009b)

NOTES:

Source-to-sink system analysis of a modern submarine sedimentary system, West of Shetlands, UK – A potential analogue to Paleocene subsurface sedimentary systems

Kjøller, H.E.[1,2], **Larsen, M.**[3], Hamann[3], N.E[3] and Boldreel, L.O.[1]

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Source-to-sink system analysis is a method of analysing an entire depositional system and establishing a linkage between the onshore erosional system and related ultimate, offshore depositional system. This study presents an analysis of a modern, complete source-to-sink system in the West of Shetland region, UK, through mapping and visualisation of 2D and 3D seismic reflection data, bathymetrical and topographical digital elevation models (ArcGIS). The results from the modern West of Shetland source-to-sink system are finally discussed in relation to the understanding of ancient source-to-sink systems in the basin.

Deep marine fan systems (ancient and modern) are recognised in the offshore West of Shetland region. The Paleocene fan systems form prolific reservoir units and have for decades been the focus for oil and gas exploration in the region. Seismic reflection data also reveals the presence of a modern day basin-floor fan system, associated with several slope canyons (Fig. 1). Both the ancient and the modern fan systems are believed to have been sourced mainly from the uplifted highlands of the Shetland Islands and the Scottish mainland and thereby provides an opportunity to compare the source-to-sink systems through time.

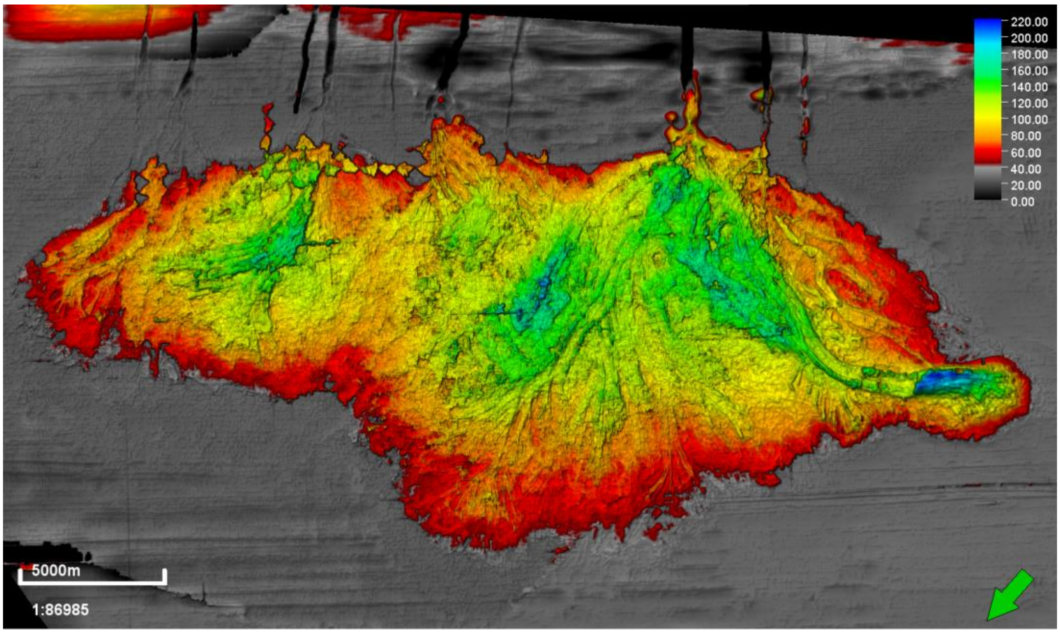

Fig. 1. Isochore map of a modern submarine fan system in the Faroe-Shetland Basin, West of Shetlands. The fan system represents the sink element of a complete source-to-sink system analysed in this study.

The high-resolution data of the modern submarine fan system makes it possible to make a detailed investigation of the modern fan system. Based on seismic mapping and analysis of the digital elevation models a number of key parameters including fan area, fan length and catchment area etc. have been established for the modern fan complex and may be compared with established semi-quantitative scaling relationships of published source-to-sink systems (Fig. 2). The analysis of the modern fan complex demonstrates an excellent match with most of these scaling relationships, providing evidence of the applicability of the source-to-sink approach to the study area. The methodology is then applied to nearby, incomplete source-to-sink system represented by Paleocene submarine fan systems and producing fields in the basin. This allows for estimation of missing key parameters and to achieve a better understanding of the ancient fan systems and their relations to sediment source areas.

Ultimately, the results of the study may improve understanding of the ancient depositional system and support predictions of reservoir presence and quality in future exploration forming a screening tool,. It may give an indication of where to allocate the search for slope and basin floor depositional systems and estimate for example fan areas, from onshore catchment areas. The method may be especially useful for the petroleum industry within unexplored basins or explored basins where missing data or a lack of a detailed understanding of the sediment source area and transport system is contributing to a high play risk.

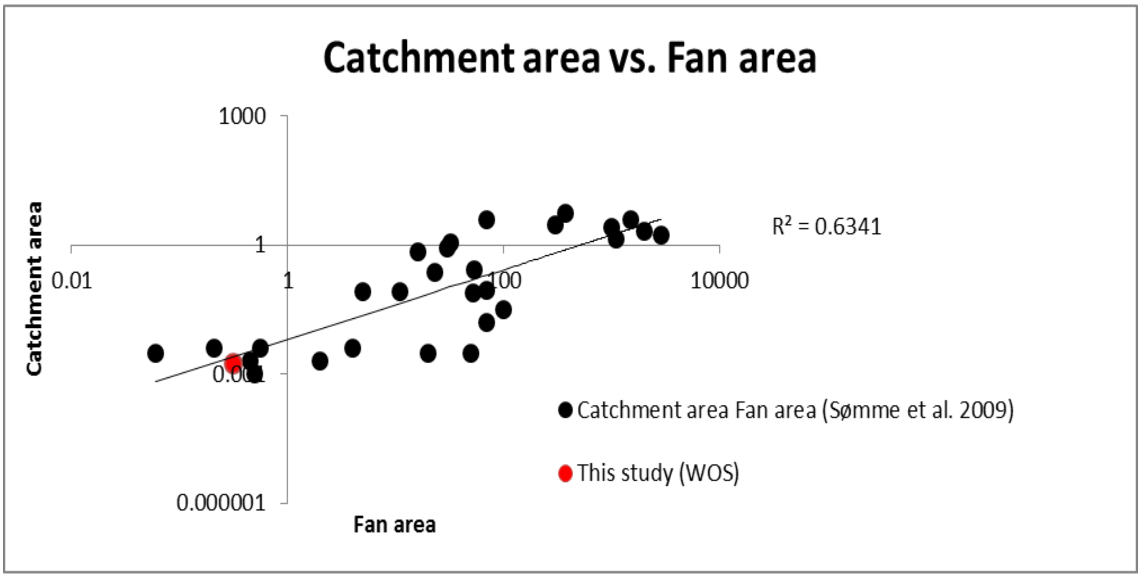

Fig. 2. Catchment area vs fan area relationships of published source-to-sink systems based on Sømme et al. (2009). The quantitative analysis of the modern fan system presented in this study shows an excellent match to the established correlation.

NOTES:

Integrated seismic attribute analysis for reservoir characterisation of the Marconi/Vorlich discovery CNS UK

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The Marconi/Vorlich oil discovery made in 2014 by ENGIE E&P UK Limited and its joint venture partner group (Dea, Maersk, BP and Total) was defined as an Eocene Rogaland basin floor fan prospect characterized by a Class III Amplitude Versus Offset (AVO) signature.

Pre-drill ENGIE E&P UK Limited followed an integrated workflow to characterize the Rogaland fans using inputs from 10 offset wells and a combination of amplitude extractions, AVO analysis, Extended Elastic Impedance (EEI), seismic inversions, and High Definition Frequency Decomposition (HDFD) calibrated to NMO gathers *(*Figure 1). The results suggested fan limits, net to gross distribution, probability of hydrocarbon bearing sands and fluid type distribution within the reservoirs.

The discovery well and its side-tracks 30/01f-13 A, Z, Y proved the pre-drill model by finding excellent quality oil-bearing sandstones in the Sele Formation. This therefore gives good confidence that we have an integrated geoscience workflow that can be used successfully for the appraisal and development of the Marconi / Vorlich discovery and also help define future exploration targets.

NOTES:

The Raven high pressure gas field in the West Nile Delta: evolution of subsurface understanding from Project Appraise to Execute

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The Nile Delta is a world class gas and condensate province. In 2010, the USGS estimated means of 1.8billion barrels of recoverable oil, 223 trillion cubic feet of recoverable gas, and 6 billion barrels of natural gas liquids in the Nile Delta basin.

Shallow Pliocene-Pleistocene plays are relatively easy to identify as a result of advances in seismic 3D imaging and the utilization of DHI. The deeper Pre-Pliocene plays are more challenging to image due to lower seismic data quality and complex overburden geology.

The Raven field is located in the West Nile Delta (WND) province in about 600m water depth, offshore Egypt, 60km to the North of Alexandria. The hydrocarbons are mainly contained in Upper Burdigalian to Middle Miocene aged sandstone reservoirs within a number of turbidite channel complexes draped across a NE plunging anticline.

The field was discovered by the Raven-1 exploration well in 2004 and subsequently appraised by three additional wells and 8 geological sidetracks during 2004 to 2008. At a depth of 4-4.5km Raven is a near high pressure high temperature (HPHT) gas and condensate field with temperatures of about 140°C and initial reservoir pressure of about 10,700 psi.

The Raven Field forms part of the WND Phase 1 gas development project. The other fields in WND project are TL (Taurus/Libra) and GF (Giza-Fayoum). These consist of normally pressured Pliocene reservoirs that are stratigraphically younger and partially overlying Raven. The Pliocene reservoirs are interpreted to be depositionally similar to the deeper Raven channel complexes. The WND Project has been sanctioned and project execution began in 2015. The Raven development plan involves 7 subsea wells and two subsea manifolds.

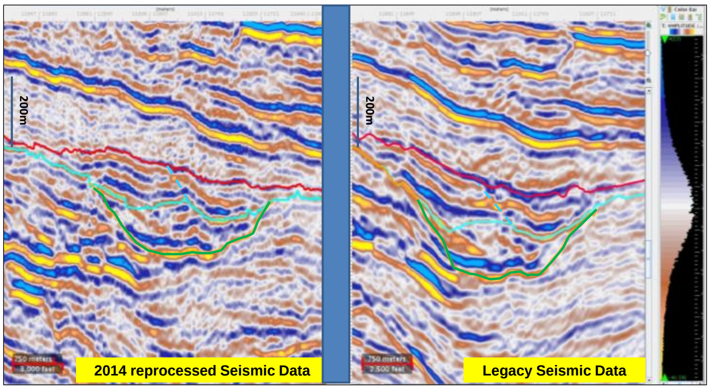
Raven is covered by a multi-azimuth seismic streamer dataset processed in 2009. The seismic image at reservoir level is affected by a geologically complex overburden (Rosetta canyon, shallow turbidite systems with different fluid fills, slide scars, mass transport complexes (MTC) and the complex Messinian evaporitic sequence). In 2014 the seismic data was reprocessed to preserve the low frequency content which is vital for full wave form inversion. This was followed by a multiscale 3D full waveform inversion (FWI) and five iterations of reflection tomography. This approach has led to a significant improvement in reservoir imaging and allowed the building of a high resolution earth model which was used for both imaging and depth conversion.

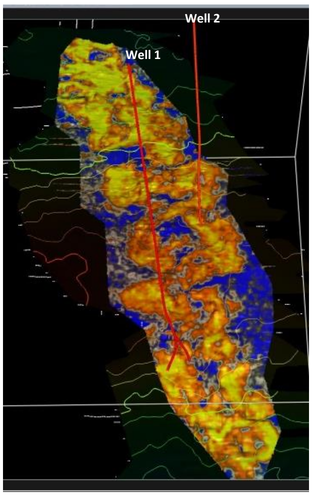
The initial reservoir description for Raven during field appraisal was largely based on the well dataset including a significant amount of core and log information. These data were supplemented by local and regional analogue information including from the shallower Pliocene reservoirs. Each channel complex has been broadly divided into a lower sharp-based, erosional high N/G (net to gross) , laterally confined aggradational channel sand system overlain by a low to moderate N/G fining upwards, abandonment and constructional system. This interpretation was adequate for the early stages of project planning and for managing subsurface uncertainty.

The significant advance in seismic quality and the use of different seismic AVO products has revealed some of the reservoir heterogeneity. The new seismic has played an important role in the evolution of the reservoir description from being predominantly well and analogue-based to being much more integrated, based on well, seismic and dynamic data .The degree of lateral variability in the reservoir between close spaced wells highlights the high degree of reservoir heterogeneity. Even with the improved seismic data, this heterogeneity is present at a spatial scale considerably below seismic resolution.

Dynamic data acquired during the appraisal phase implies a high degree of connectivity between different parts of the reservoir within a particular channel complex. Dedicated production wells mitigate the risk of poor connectivity between channel complexes and spread the ultimate recoverable volumes between a number of offtake points.

Raven development drilling began during 2015-2016 with the first three wells suspended above their target reservoir. One well provided a new reservoir penetration in a channel complex above the target interval and confirmed the presence of reservoir sand in both constructional and aggradational parts of the channel complex. The drilling of the remaining production wells and completion of the suspended wells will be carried out in 2017-2018. First gas for Raven field is expected in 2019.





The above two seismic cross sections show the improvement in seismic data quality resulting from the 2014 seismic data reprocessing. The uplift has resulted in better imaging of internal channels architecture as well higher resolution velocity field used for time depth conversion.

The picture to the right represents a 3D view of an amplitude extraction using the seismic gradient impedance volume and represents the aggradational (Lower) section of one of the Raven Langhian channels. Distance between wells 1 and 2 is 4 km. Contours represent top channel depth map (red=high and Green=deep). The yellow colour in the map is interpreted to represent the axial high quality sand fairways of the channel lower aggradational section.

NOTES:

Thursday 26 January

Session Seven: Turbidites and tectonics 2

Keynote Speaker: Structural controls on sand fairways in submarine thrust systems: examples from the Annot and other Western Alpine systems

Rob Butler
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Tectonically active submarine foredeeps are characterised by folds and faults that deform the seabed, directing and deflecting turbidity currents entering and transiting these confined systems. Intra-basin structures can serve to separate distinct sand fairways of distinct provenances – an important feature if craton-derived mature sands are an exploration target that might otherwise be contaminated by sediment derived from less mature hinterlands. However, while structural highs within the basin may inhibit mixing of distinct sand fairways, these highs and their slopes may also provide intra-basinal sources of contamination if they are eroded, either by flows or by mass-wasting processes. Therefore, understanding the kinematic evolution of intra-basinal structures and their impact on sediment routing can assist in predicting facies variations and sand quality. For subsurface examples this integrative approach may assist and de-risk hydrocarbon exploration. Reconstructing flow pathways from ancient deposits can yield important information on the structural evolution of the basins that host them together with their underlying tectonic structures. The aim of this presentation is to examine these different roles of intra-basin structure in influencing the routing and content of turbidity currents and thus explore the structural controls on sand fairways in turbidite successions.

The Eocene-Oligocene deepwater deposits of SE France provide the case history for this presentation (Fig. 1). They include the Annot Sandstone (Gres d'Annot), which accumulated in and adjacent to the fledgling Western Alpine orogenic belt. The bulk of the sediment entering these systems was derived from a landmass (ancestral Corsica and Sardinia) that formed a southern prolongation of the European continent. From these terrains came two distinctive sand assemblages that were delivered axially from the south into the broadly N-S-trending foredeep basin system. Much of the sand was sourced from a weathered granitic basement terrain (generally characterised as "Corsica") and this is represented in the main Annot fairway. In parallel, immature volcanic sands entered the basin area, most-probably sourced from earliest Oligocene igneous complexes (chiefly "Sardinia"). Their deposits include those of the Western Champsaur basin.

Although significant work has focussed on the main Annot strata, within c 50km of their type area, and addressed the depositional architecture of the volcaniclastic turbidites of Western Champsaur, there has been little attention paid to the more deformed sequences down-system in the Alps or to the complexities resulting from interactions between distinct sand sources. The critical ground lies either side of the uplifted Ecrins crystalline basement massif. Traditional interpretations propose that the massif occluded this part of the ancestral Alpine foredeep so that the southerly derived Annot turbidites pond against it. Recent work (Vinnels et al. 2010; Butler in press) shows this to be false – turbidity currents passed across the massif, with local deflections. The Ecrins formed an intra-basinal high but not a barrier. Thus the Annot system's northern continuation is the so-called Aiguilles d'Arves "flysch". Although the bulk of this succession has similar quartz rich sand compositions as within the main Annot fairways, the lower parts contain coarse, immature, basement-derived sands and gravels. These testify to local erosion of the intra-basinal high of the Ecrins. Similar facies are described for the upper part of the Annot succession that was deposited locally down-system from the Argentera basement massif (Mulder et al. 2010).

In the southern Ecrins the Annot sand fairway is separated from the volcaniclastic turbidites of the Western Champsaur by the syn-depositional Selle Fault zone. This thrust created a dynamic intra-basinal ridge that kept the two fairways apart. The volcaniclastic turbidity currents continued over the ancestral Ecrins but their ultimate sink is unclear. Likely candidate include the Taveyanne system of the NW Alps.

The Annot system illustrates the need to address the more strongly-deformed and dismembered stratigraphic sections in orogens to achieve better whole-system understanding. These examples show that growing intra-basinal structures can both separate distinct sand fairways and provide local coarse clastic contamination that reduces sand quality. It is likely that similar processes operated in many other systems within the ancestral record, including some used as part-analogues to inform subsurface interpretation for hydrocarbon exploration. The uncertainties in applying structural-stratigraphic relationships from these deforming foredeep basins to other tectono-stratigraphic settings remain unresolved.

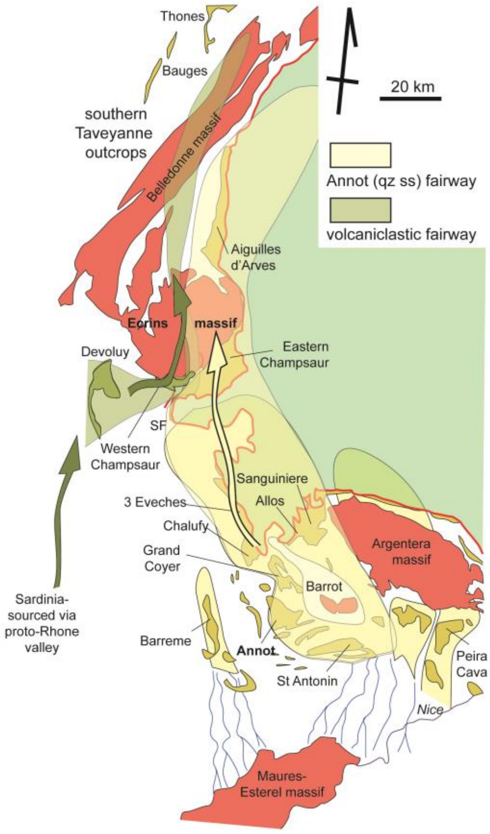

Fig. 1. The Annot and associated sand fairways of SE France, with locations.
SF – Selle fault.
Modified after Joseph & Lomas 2004 (GSL Spec Publ 221).
Note that the Taveyanne outcrops restore to the East of the Belledonne massif, into the volcaniclastic fairway as depicted. Likewise the two fairways have been partly overlapped across the Ecrins by post-depositional contraction on the Selle Fault.

NOTES:

Modelling paleobathymetry of real world, structurally active, basins in outcrop and subsurface

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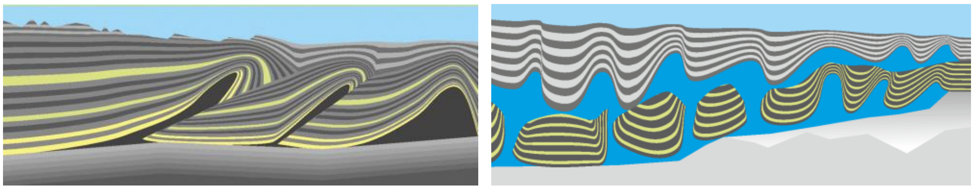
The transport and deposition of sand by turbidity currents is critically dependent on basin-floor slope. We need to have a model of the basin-floor topography at the time of deposition in order to understand the distribution of turbidite reservoir units and seals in the subsurface. In some regions, where there is excellent quality seismic imaging, this can be deduced by direct imaging of the sediments. Elsewhere, even if we cannot image the reservoir, we may have sufficient resolution to see detailed onlap/offlap/thickening relationships which indicate the paleotopography on the target horizon.

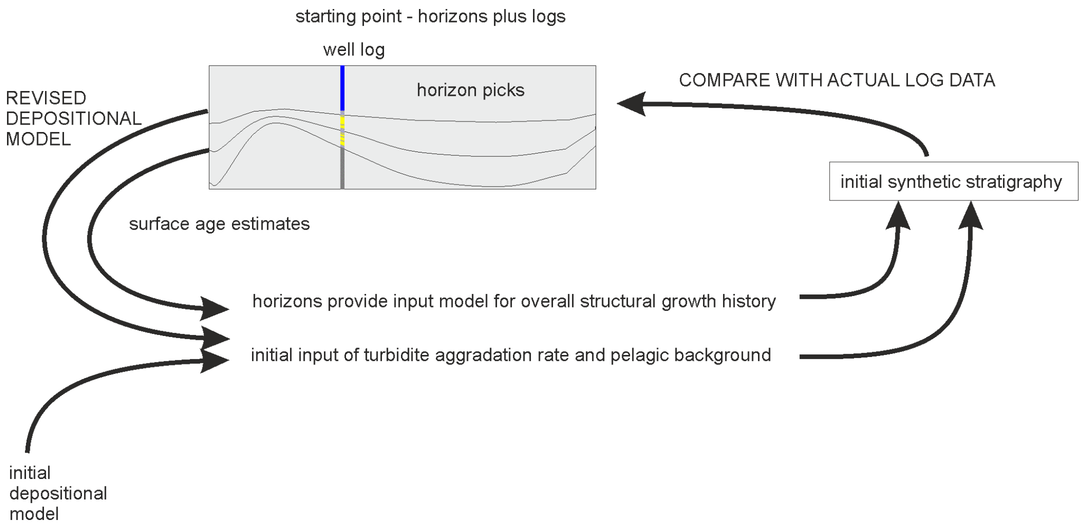
However, in many real exploration or development areas, like the Paleogene of the US Gulf of Mexico, the subsurface image is imperfect and the structure is complex.



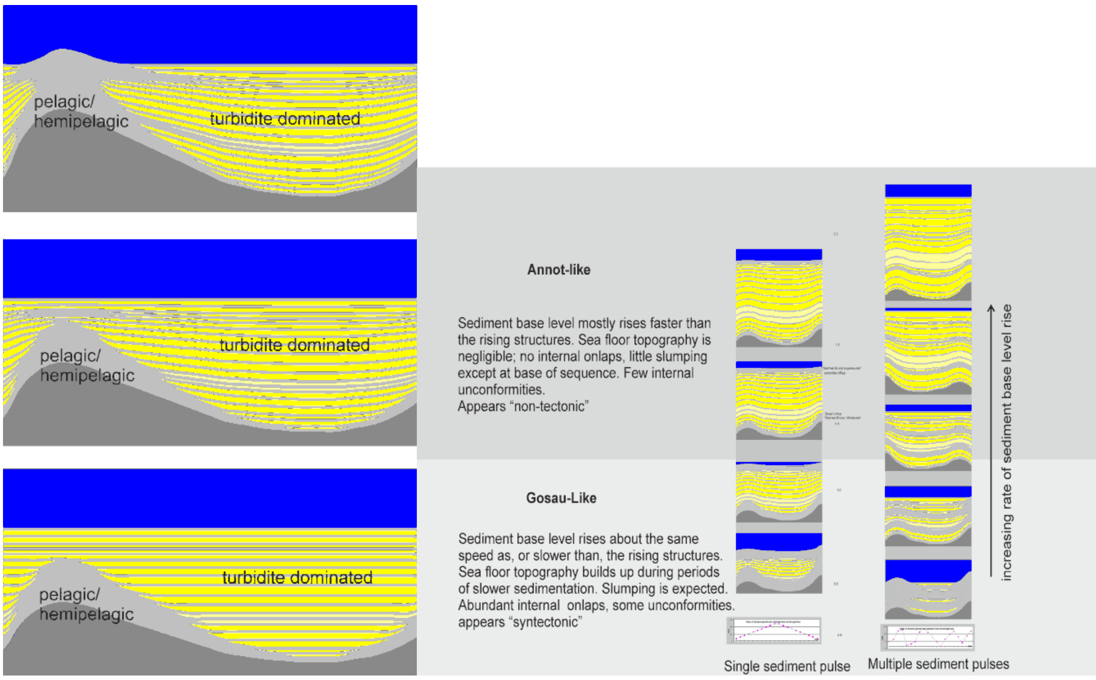
In such settings, we may be able to map a limited number of seismic surfaces, and we can obtain isopachs of broad units, and we may have some indications of onlap/offlap, but not enough to constrain the paleotopography.

Depositional systems are commonly drawn with transport directed down the axes of isopach thicks, with ponding of turbidite fans within the thickest party of the basin. However, this is not consistent with what we see at the sea floor. Where sedimentation is fastest, there is only a weak relationship between surface topography and isopach, and within the core of a major clastic system, the two can be completely independent. The blanketing of mini-basins by the modern Mississippi Fan is a very good modern example of this. Using the gross isopach can give a significantly misleading result. In other words, the isopach method is only a good method of predicting topography when there is no major reservoir system. Where there is a major clastic system, the method fails.

We have developed a proof-of-concept method, which creates a synthetic stratigraphy in 2D section using these principles. Our objective is to develop a 3D equivalent, designed for use with typical exploration data, which will take as its input existing seismic horizon interpretation to use as the basis for the structural template. We have applied this method in the subsurface (Miocene of the US Gulf of Mexico) and in the Grès d'Annot, S.E. France, and Muttekopf-Gosau, Austria outcrop areas. We believe this approach will be beneficial in a number of active hydrocarbon provinces; for example, Miocene of Sabah Malaysia (Stanbrook *et al*, in prep)



This approach illustrates important principles that throw light on well known outcrop areas. For example, it is generally assumed that the Grès d'Annot turbidites were deposited in a relatively quiescent basin, when compared with Muttekopf-Gosau, due to the rarity of features caused by slope failure. We show however, that the development of steep sea floor topography is critically dependent on the balance of structure growth rate and sedimentation.



When the model delivers a reasonable match to the well data, we not only have a synthetic stratigraphy which covers the whole mini-basin, but we also have a full evolutionary model which includes the amount of paleotopography at each stage in its development.

We acknowledge other modelling approaches are available (eg. Sylvester *et al*, 2014), but it is all too easy to produce precise but wrong outputs from such models. We rarely have the basic information required to constrain parameters in these existing, published models; for example, sediment flux.

NOTES:

Exhumed Deepwater Clastic Systems along the 1000 km Gondwana Margin: Lessons from Outcrop Studies

Miquel Poyatos-More, **Stephen Flint,** David Hodgson and Rufus Brunt
Stratigraphy Group, Universities of Manchester and Leeds, UK

Over 15 years of outcrop studies integrated with 20 cored research wells and radiometric dating has constrained the time-stratigraphic evolution of the Permo-Triassic Karoo-Falklands Gondwana margin. The stratigraphy is remarkably similar along the margin but with important difference in thicknesses, volumes and partitioning of sand between basin floor and submarine slope. A consistent hierarchy is applied based on depositional sequences (recognised in outcrop and well data) that stack into composite sequences (mappable at seismic scale) and composite sequence sets (CSS).

The Tanqua Karoo depocentre includes 800 m of silty mudstone overlain by 4 basin floor fans, each up to 50 m thick with dip lengths of 40 km+, showing a progradational stacking pattern. Grain size never exceeds fine sand. The submarine slope section is only 120 m thick, above which are shelf edge clinoforms and a 500 m of mixed influence shelf edge to shelf deltas. Some 80 km along margin the 1200 m thick Laingsburg succession comprises distal basin plain turbidites punctuated by 3 MTCs. A 300 m+ basin floor fan composite sequence set is overlain by an 800 m thick muddy slope succession with slope valleys feeding fan system 80-100 km long and up to 60 km^3. Shelf edge clinoforms mark eastward progradation of a 500 m thick mixed influence delta system. The Prince Albert area 100 km east is characterized by large MTCs likely derived from a southern lateral non-depositional section of margin, which alternate with undeformed 20-40 m thick lobe complexes. Overlying shelf deposits are sand-poor.

Some 400 km further east, the 1700 m Ecca Pass section includes a 300 m thick basin floor fan complex overlain by a 100 m thick siltstone and slope channel deposits. Grain size is coarse sand. The shelf section is sand poor, suggesting a switch in sand delivery location between deepwater and shelf. The Falkland Islands lay 250 km east of Ecca Pass in the Permian and the 3 km+ succession includes a similar basin floor fan complex and a 100 m siltstone cap, then 500 m of slope channel levee complexes with no slope valleys. The shelf succession is wave-dominated.

The exhumed Karoo-Falklands margin provides a well exposed example of lateral variability in basin margin physiography convolved with late icehouse to greenhouse transition glacio-eustatic sea level and long wavelength subsidence to control spatial and temporal variability in deepwater systems architecture and overlying shelf delta style.

NOTES:

Structural growth rate and impact on deep-water depositional systems in deepwater fold belts: Gulf of Mexico, West Africa and Niger Delta

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Examples of slope channels being diverted or deflected by growth folds, salt walls or thrusts are found both at the modern seabed and in the subsurface in deep-water fold and thrust belts. Most previous descriptions of the interaction of deep-water depositional systems with growing structures have tended to be descriptive. We have quantified the shortening rate of thrust-related folds, salt-cored anticlines and faulted salt-detachment folds in each area, with the aim of investigating whether there are any predictive
relationships between structural parameters such as structural relief, growth rate versus sediment accumulation rate, and depositional patterns.

In each of the three study areas, we observe slope channels that modify their downstream course as they interact with growing structures. Ponded deposits, and local slumping associated with structural relief are observed in all three areas. Our work shows that the Pleistocene to Recent Niger Delta slope channel systems behave comparably to the older buried channels studied in deep-water West Africa and Gulf of
Mexico.

Shortening rates in the thrust-related folds of the Niger Delta and the faulted saltdetachment fold in the Gulf of Mexico are comparable, with maxima of between 120-400 m/Ma. The maxima recorded for the West African salt walls and salt-cored anticlines are lower, ranging from 30-100 m/Ma. The rate at which channels can cross folds or keep pace with fold growth is very similar for Miocene Gulf of Mexico Channels and the Pleistocene- Recent Niger delta channels at ~50m/Ma. However we note that the buried Miocene channels in West Africa, are diverted and deflected by growth rates as low as 30-50 m/Ma. In general, during periods of higher growth, channels are forced to deflect or divert around growing structures. However, channels that already have established a route through a fold or salt wall (e.g. at a relay position) can continue to exploit that route down slope as long as the turbidity flows continue to have enough erosive power to keep pace with the growth of the structure. Our data suggest that a strain rate of -0.005 Ma-1 is the threshold for channels to cross active fault-related folds.

NOTES:

The long-term evolution of an exhumed deepwater stepped-slope profile

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The effects of changes in slope angle and orientation on turbidity current behaviour have been investigated in many physical and numerical experiments and interpreted in outcrop, subsurface, and modern systems. However, the long-term impact of subtle and dynamic seabed topography on stratigraphic architecture of deep-water systems is more challenging to constrain. Extensive detailed fieldwork in the Karoo Basin, South Africa, has demonstrated the presence of a stepped slope profile, which provides opportunity to investigate the stratigraphic record of interactions between turbidity current behaviour, sediment dispersal patterns and subtle seabed topography.

This study focuses on the Permian Laingsburg and Fort Brown formations, where multiple large sand-rich systems (Units A-F) have been mapped from entrenched slope valleys, through channel-levee systems to basin-floor lobe complexes over a 2500 km^2 area. Here, we investigate thinner (typically <5 m in thickness) and less extensive Units A/B, B/C, D/E and E/F, which are developed stratigraphically between the larger scale systems. Typically, these units are sharp-based, and sand-rich, with scours and mudclast conglomerates that indicate deposition from high-energy flows. The mapped thickness and facies distribution suggest a lobate form. These units were deposited in similar spatial positions within the basin-fill, and suggest formation of accommodation on the slope prior to the larger B, C and E systems. That areas of increased slope accommodation were maintained throughout the deposition of successive deepwater units suggests an underlying structural control. The larger-scale systems were also affected by the development of this slope accommodation, but this is poorly recorded as they significantly modified the slope profile as they evolved. This study shows that the smaller systems are a more sensitive record of evolving seabed topography; they can be used to recreate more accurate palaeotopographic profiles and provide better understanding of the dynamic topography of evolving slope systems.

Thursday 26 January

Session Eight: Lobes and Contourites

Exhumed Basin-floor Fan Pinchouts: Implications for Stratigraphic Trap Architecture

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Stratigraphic traps occur due to changes in rock character at the pinchouts of sandbodies, and are problematic during development phases due to unpredicted sub-seismic scale issues of rates of facies changes, capturing transition zones in reservoir distribution and compartmentalisation. Detailed mapping of basin-floor fans in the SW Karoo Basin has documented a wide range of up-dip, down-dip, and lateral sandbody pinchout configurations. These are analogous to stratal pinchouts identified on seismic data, but the sub-seismic analysis of the sedimentology and depositional architecture indicates that not all configurations are suitable stratigraphic trap targets.

Up-dip terminations occur where the physical passage from the erosional submarine slope to the basin-floor results in a complicated stratigraphic record of process change from confined channels to unconfined lobes. Predicting the degree of up-dip sand connectivity is critical when assessing stratigraphic trap potential in this transition zone. In a sand-detached system, such as Units E and F in the Laingsburg depocentre, a widespread area dominated by erosional processes and coarse sediment bypass can lead to the formation of an up-dip stratigraphic trap. The facies associations preserved in these sand-poor areas are thin-bedded, but their top surface includes megaflutes, rip-up clast lags, and soft-sediment deformation, indicating a high-energy erosional bypass-dominated setting. In reflection seismic datasets, a physical connection might be imaged, although the degree of reservoir connectivity, and the stratigraphic trap potential, will be less clear. Oblique up-dip pinchouts from axial to off-axis settings, such as Fan 3 in the Tanqua depocentre, fine- and thin- abruptly, and include minor soft-sediment deformation features. Lateral and frontal stratal terminations are sand-rich, particularly in mature systems, but have contrasting sedimentology and stratigraphic architecture. However, these settings commonly contain large numbers of argillaceous hybrid beds and low porosity sandstones with complicated geometries that increase the heterogeneity of pinchout, and the rate of facies change controls the lateral extent of the thief zone.

Although up-dip and proximal pinchouts are the best targets as stratigraphic traps in terms of sandstone quality, there will be uncertainty in terms of their 3D connectivity with sandstones, and these bodies could suffer from fluid leakage. Furthermore, abrupt stratal pinchouts in basin-floor settings are commonly associated with widespread post-depositional clastic injection. This study indicates that sub-seismic analyses of a range of basin-floor pinchout styles are needed to help in the prediction of stratigraphic trap potential in the subsurface.

NOTES:

Deep water turbidite deposition ponded by mobilised mudstone

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The Vaila Fm sandstone, of the mid-Paleocene, in the northern part of the Faroe-Shetland basin, is characterised by turbidite deposits ponded by mobilised mudstone. The recent study has focused on the complex interaction between sedimentation and mobilisation of the substrate. The Vaila Fm sandstone is present in the entire basin, which otherwise shows a mud prone deep water setting, and is represented by important discoveries like Laggan, Tormore, Glenlivet and Cragganmore. In 2012-2013 two exploration wells Glenrothes (208/11-1) and Cragganmore (208/17-3) were drilled by DONG Energy, in the northern part of the Flett Sub-basin. They both targeted and found Vaila Fm turbidite sandstone deposits. The sandstone deposit was anomalously thick but with limited lateral extent in the otherwise mud prone area. The Cragganmore well found 55 m of reservoir sandstone, drilled only 3.5 km from the completely shale prone well 208/17-1. The Glenrothes well encountered 500m of sandstone, much thicker than predicted. Typically, in this part of the basin the lower Vaila Fm sandstone show excessive thicknesses of more than 250m indicating ponding. During the Vaila Fm, large amount of coarse sediments were shed from the Shetland platform and transported rapidly to the deep water. However, the sand seems to have been unevenly distributed in the area. The turbidite deposits were trapped in some extremely deep ponds, formed by shale walls and mud diapirs but also diverted by topography.

It was clear from seismic interpretation and well penetration that some of the present day topography was created post or syn-deposition. Attempts to model the distribution of the turbidite deposits on a reconstructed paleobathymetry failed since mobilisation of the mudstone substrate was not taken into account. The observed sandstone distributions could not be modelled with a fixed topography prior to deposition. The underlying Danian and Maastrichtian section in the northern Flett Sub-basin form a very thick mudstone package. The thickness and characteristics of this mudstone provides a ductile substrate, which is mobilised when loaded by turbidites creating or exaggerating the topography.

A numerical 3D model of turbidite deposition on to different substrate was created to investigate the effect of the substrate quality on the distribution of the sandstones. Several scenarios were tested with rigid substrate, normal compaction, without buoyancy and with ductile substrate. The results of the investigation showed that the mobilisation of the mud where initiated by the deposition of the turbidites, creating shale walls and diapirs. Modelling without turbidite deposition resulted in a scarp-flat topography. The model also clearly showed the effect of the mudstone mobilisation creating ponds for further trapping of turbidity flows, which results in deep but narrow and confined ponds with large sandstone thicknesses. Tested scenarios without ductile substrate created broad, widespread or backfilling fan systems. Further on, by modelling the syn-sedimentary ductile deformation, the observed sandstone distribution in the area could be reproduced.

Turbidites deposited onto a ductile substrate activate mobilisation of the underlying strata, with the right conditions. Especially thickness of underlying mudstone has a large influence. This leads to ponding and capture of further turbidity flows, resulting in excessively deep but confined deposits of turbidites. The turbidite deposition is creating accommodation space for the next turbidite flow and the mobilised mud will create positive topography diverting later turbidite flows. Low density turbidites will not have sufficient impact to generate mobilisation, therefore ponds limited by mud diapirs are very likely filled by high density turbidites as seen in the Glenrothes well.

NOTES:

Sedimentary Structures in Deepwater Paleogene Wilcox Core Data, Gulf of Mexico, USA; Some New Insights into Deposition of Sands from High Magnitude Turbulent Flows

Andy Pulham[1], Nathan Blythe[2], Art Trevena[1], Ryan Murphy[2], Truitt Smith[2]
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Recent acquisition of petrophysical and rock data in the deepwater, Paleogene Wilcox Formation, offshore Gulf of Mexico, USA has delivered many 100s meters of conventional core that record a broad variety of mass flows, turbidite and hybrid event beds. A wide spectrum of sedimentary structures are exquisitely expressed in Computed Tomography (CT) data volumes and extracted images. These high resolution (voxel size less than very fine sand) volumes can be orientated via well data and provide a means to catalog the spectrum of sedimentary structure types, their internal architecture, vertical motifs and their paleocurrent trends. The potential to advance our understanding of deepwater depositional processes, document rock properties by sedimentary structure and place patterns and organization of the sedimentary structures in an environmental context is presently unlimited via these new data. This is also true of other deepwater CT core data in younger Gulf of Mexico deepwater reservoirs and in ongoing deepwater development projects worldwide. The Wilcox is not an unique case study. Near future analyzes will enable 3D mapping of sand grains in real space and add another thick layer of data to deepwater sedimentological characterization.

This presentation will share some of the findings from our Wilcox data, including laminated sands that are considered enigmatic by the authors and may comprise a 'new' class of upper flow regime sedimentary structures. Data presented are operator and partner approved, but will not be displayed in actual x,y,z space.

Wilcox deepwater sands are very fine to fine grained, averaging commonly very fine upper (88-125 microns). Sand composition is lithic arkose-feldspathic litharenite with a mixture of sedimentary, metamorphic and volcanic rock fragments. Sediment source is from the North American continent with a potential for Appalachian to Laramide Rockies drainage that fed deltaic shelf margins in SE Texas and Central Louisiana (see Blum and Pecha 2014; Blum 2016). Deepwater transport distances to the location of the core data is 600-700 kilometers and via a slope underlain, in part, by shallow buried, mobile salt.

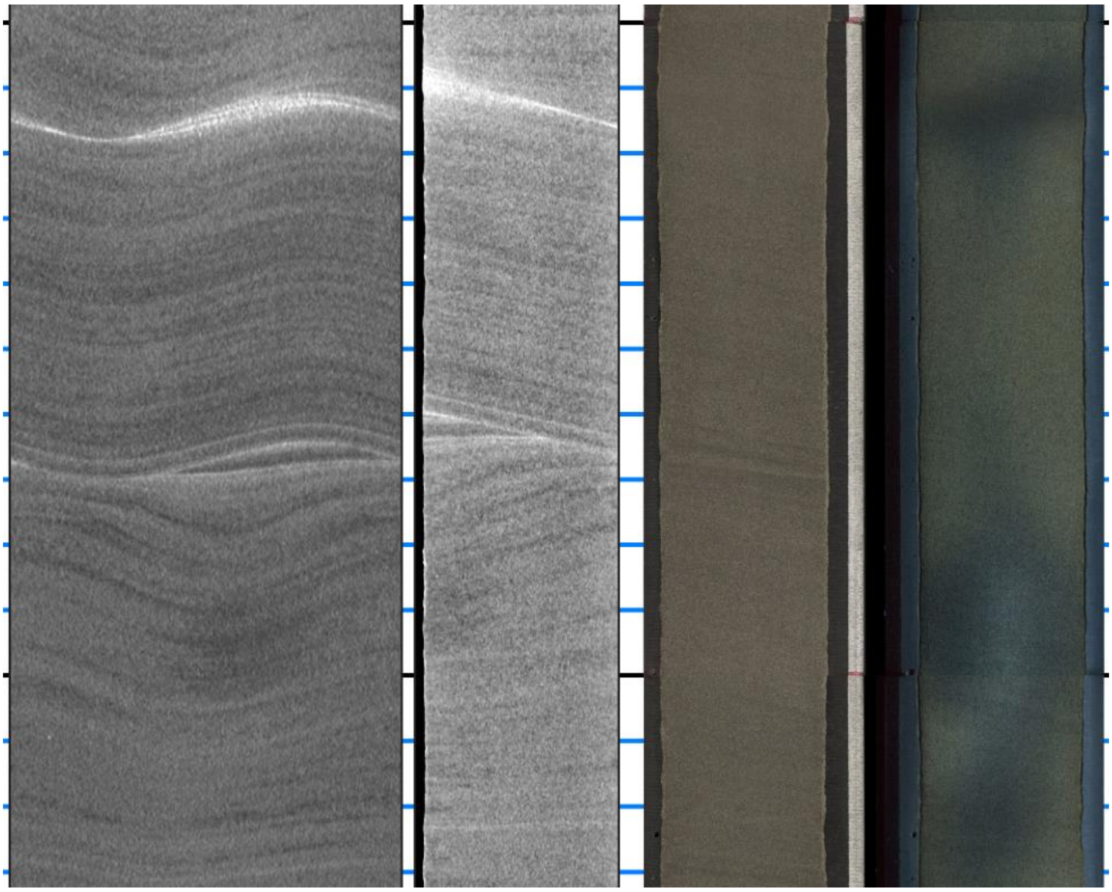
Our focus is on sedimentary structures in sands that are interpreted as the depositional products of high magnitude, fully turbulent to dominantly turbulent, sediment gravity flows. Context of the sedimentary structures are thicker sand intervals (commonly 10s feet) and in stratigraphic sections interpreted as submarine channels and/or proximal and axial deepwater lobe settings.

A part catalog of structures are:
(1) Scour and Fill - sensu Elliott, Gardner and others; documented and described in field guides from numerous outcrops of deepwater successions. Sand in sand scours draped and filled by dipping laminae.
(2) Horizontal and near horizontal laminated - a variety of lamination styles; weak to extremely well, graded and diffuse.

(3) Inclined laminated - above erosion surfaces, steep at base (up to 10-15 degrees max, but commonly much less), flattening and rotating dips upwards, and in sets that can be many 10s centimeters in thickness.
Massive or structureless sands are very rare to absent in these core data. Past descriptions of deepwater sands in the Gulf of Mexico commonly record structureless sand intervals. CT data reveals that the majority of sands comprise laminae.

We suspect that our description and initial classification of these high energy sedimentary structures includes bedforms that are operating at the threshold of flow velocities capable of entraining and suspending fine sand; the uppermost flow regime and a realm classically of upper plane beds and antidunes. Should these structures be fully explained by flow types and depositional setting within the myriad of deepwater sub-environments, then considerable value will be added to future deepwater reservoir characterization.

Unwrapped Helical CT - a reflected 'borehole image' | Pseudo Core CT | White Light Core | UV Light Core



Example interval of laminated Wilcox deepwater sand. Depth intervals are 0.1 foot.
~40 centimeters of core. CT images are gray scale 'density'. Darker shades are lower density and are coarser sand. Note the 'sets' of laminated sand have dips that steadily rotate upwards in a counterclockwise sense.

NOTES:

A new model of plastered drift formation from hydrodynamic modelling, geophysical and sedimentological data

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Contourites are sedimentary bodies related to bottom currents, commonly found along continental margins at all depths, from the continental shelf to the abyssal zones. Despite their ubiquity, the physical processes controlling the formation of this type of deposits are still not well constrained. By coupling a hydrodynamic model of the NW Mediterranean Sea with seismic and sediment core data, we aim to understand which are the current velocities, bottom shear stresses and the position of water masses related to these depositional systems. The circulation in the NW Mediterranean Sea is modelled with the MARS3D code of IFREMER in its MENOR configuration, with a special focus of the currents near the seafloor. We modelled three months of winter and three months of summer 2013 in order to represent two periods of maximum and minimum circulation, respectively. The cell size of the model is 400 m in the Northern Tyrrhenian Sea and 1.2 km in the whole NW Mediterranean Sea. The computed hydrological results are coupled with geophysical and sedimentological data: multibeam bathymetry, High-Resolution-72 channel (50-250 Hz) and CHIRP (3200-5200 Hz) seismic profiles and Calypson piston cores.

Plastered drifts are convex-shaped muddy contourites that were previously related to broad non-focused bottom currents along slopes with slow rates of deposition. But in this study we demonstrate that the development of these sedimentary bodies is controlled by a more complex oceanographic context, using as an example a plastered drift along the Pianosa Ridge in the Northern Tyrrhenian Sea. The upper and lower parts of the plastered drift are characterised by lower sediment accumulation due to faster along-slope bottom currents in these areas (Figs. 1a,b). These faster bottom currents (mean velocities 7-12 $cm \cdot s^{-1}$ for March 2013) are coincident with two pycnoclines: (i) at 150-200 m water depth (w.d.), corresponding with the mixing layer between the surface water mass (Atlantic Water, AW) and the intermediate water mass (Levantine Intermediate Water, LIW); (ii) and below 400 w.d., where the salinity and the temperature of the LIW start to decrease. The main drift growth is constrained between these two zones in an area of lower bottom currents (mean velocities below 2 $cm \cdot s^{-1}$ for March 2013) that mainly have an across-slope direction, favouring the sediment transport on the drift.

The heterogeneous distribution of bottom current intensities on the plastered drift has also an influence on the grain size distribution and on the generation of incisions. The upper part of the drift commonly contains sands while the central and lower parts are mainly muddy (mean grain sizes of 5-10 µm). In the lower part of the drift the percentile 90th of the bottom shear stress is up to 0.1 $N \cdot m^{-2}$, enough to generate the erosion of unconsolidated mud (Fig. 1c). This could explain the presence of moats at the foot of the slope that separate the plastered drift from the separated mounded drift located in the basin (Fig. 1f).

Hydrodynamic modelling is a very powerful tool to improve the understanding of the sediment dynamics in deep environments, where measurements are more limited. With this first attempt we found that plastered drifts are deposited in zones of constant low bottom-current velocities, constrained between zones of faster bottom currents, that are more intense during winter.

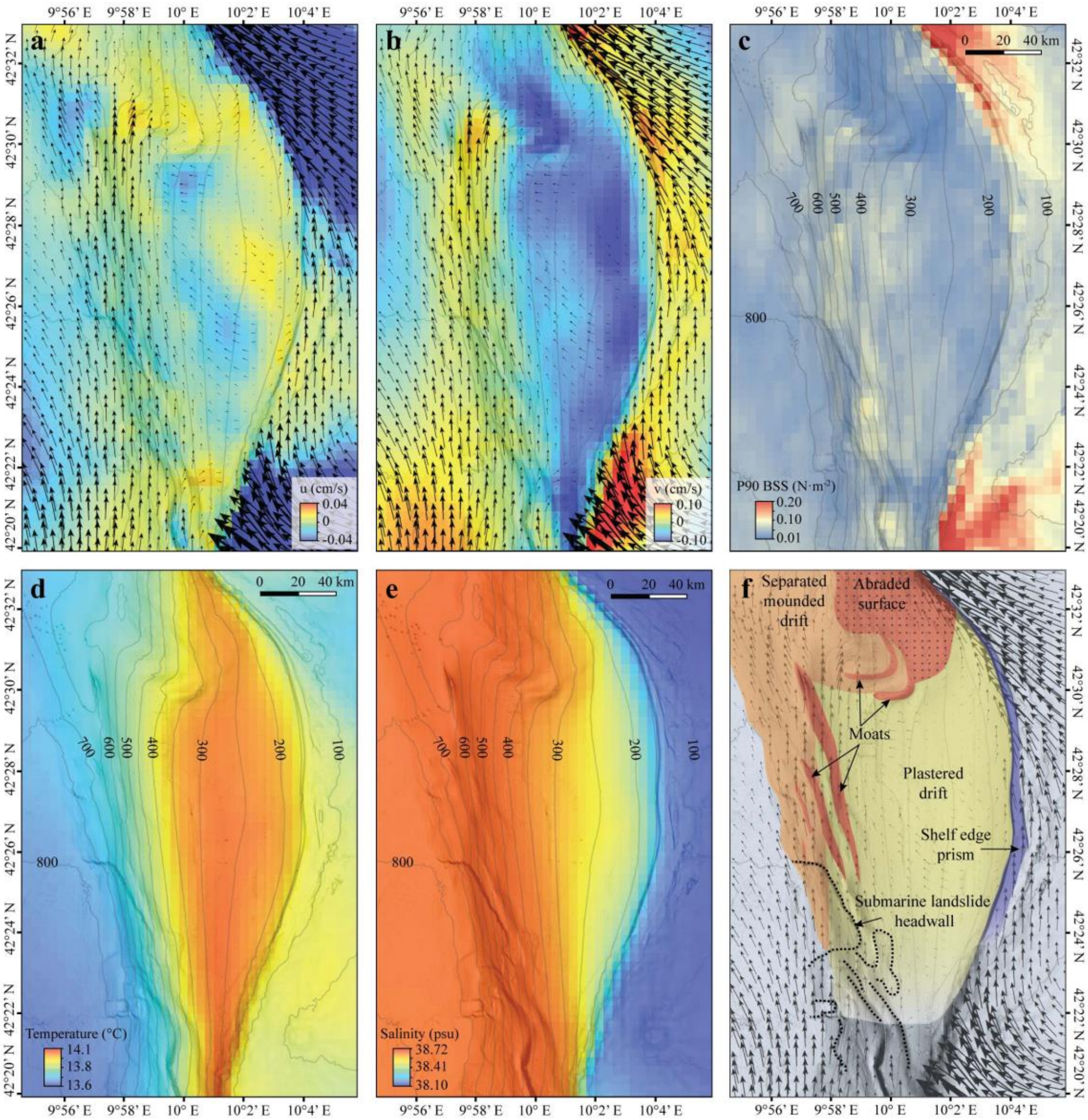

***Fig. 1.** Results of the MENOR model with the 400 m zoom near the seafloor during March 2013 in the Pianosa Ridge (eastern flank of the Corsica Trough, Northern Tyrrhenian Sea): **a)** Zonal component of the mean current velocity; **b)** Meridional component of the mean current velocity; **c)** 90th percentile of the Bottom Shear Stress (BSS); **d)** Temperature; **e)** Salinity, **f)** Morphosedimentary map. The arrows represent the velocity vectors with their size proportional to the velocity intensity.*

NOTES:

Deep-water large bedforms on contourite terraces: sedimentary ad conceptual implications

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Over the last decade, numerous large-scale depositional, erosional and mixed features have been recognized in deep-water settings within the world's oceans, which provide diagnostic evidence for both modern and ancient bottom water circulation patterns and sedimentary processes. Whilst most of these features are mud-rich, extensive sand-rich deposits have been determined, predominantly in high-velocity bottom currents settings. The use of high-resolution 3D seismic data along with modern seismic attribute analysis has allowed the distribution and geometry of these sand-rich deposits to be more easily recognised. Deep-water sands have come a long way. Usually, deep-water sand deposits are interpreted as a product of submarine gravity flows, whose facies model is derived primarily from the ancient record. Deep-water sandy deposits generated or reworked by bottom currents are still poorly studied, but adopting new perspectives should be explored and evaluated, since these deposits are of great scientific and potentially economic significance.

Buried contourite terraces associated with large plastered drifts from the Paleocene to Miocene in the Uruguayan continental slope have been recognised. Large erosional (*channels*, *scours* and *furrows*) and depositional (*sand ribbons*, *2D sedimentary waves* and *barchans dunes*) bedforms along these terraces have been identified with 3D seismic, and compared with similar bedforms identified, at different depth and ages, on the Brazilian, Gulf of Mexico, Canadian and Northern European margins.

The observations from Uruguay suggest that the bottom-currents are associated with two water masses: one vigorous deep current flowing toward the NE along the lower slope and a weaker intermediate water mass flowing toward the SW along the middle and upper slope. The interface between these two water masses is related to contourite terraces in the middle slope, and its vertical shits conditioned the formation and distribution of bedforms through time. Downslope processes were reworked and distributed by these bottom currents along the terraces generating sandy deposits concentrated in certain places in three distinct depositional settings: a) high bottom current velocities (> 0.4 m/s); b) weak bottom current velocities (< 0.4 m/s); and c) mixed systems where down-slope processes dominate developing channel-levees, but shifted alongslope due to the bottom current influence. Our evidence demonstrates that most of these bedforms are common but still unknown features in deep-water environments. Some of these features pose questions about our fundamental understanding of margin morphologies and bedforms development in the deep marine environment. They are essential as palaeoceanographic markers and might represent potential hydrocarbon reservoirs, thereby being of potential interest to petroleum explorers.

NOTES:

Friday 27 January

Session Nine: Channels and Canyons 2

Keynote Speaker: Waterflood Performance Outcomes Across a Set of Deep-water Turbidite Reservoirs

Peter Clifford
Reservoir Engineering Senior Advisor, BP

Many Angola deep-water reservoirs now have a production history of at least a few years, and up to 15 years. In most cases, reservoir sweep has been tracked with one or more 4D seismic surveys, in addition to pressure and production data. The information has been integrated into reservoir simulation models. A set of waterflooded turbidite reservoirs is discussed, with deposition ranging from well-developed channel complexes to sheet-like sands. Some fields have significant quantities of thin-bedded pay, and there is varying influence from fault baffles. Aquifer strength is another important variable between reservoirs.

This presentation discusses the relationship between waterflood sweep and the geological setting. It presents 4D seismic images and discusses dynamic pressure and watercut data. However it does not include specific information on named fields, their recovered volumes or recovery factors.

In channelised reservoirs, early well performance is dominated by water sweep in channel axes. 4D seismic and material balance support a view of efficient sweep through high net-to-gross channel axes. However, in lower net-to-gross channel margins and overbank regions, the story is less clear. It is normal to see significant levels of production-influenced pressure depletion in margins, which provides proof of connectivity, but it is much more difficult to demonstrate water sweep. 4D interpretation is more challenging in marginal facies but history-matching allows cases with very limited margin sweep. Understanding recovery with relation to facies becomes an increasingly important issue as the field matures. Sheet-like sands tend to show a high degree of vertical communication and efficient sweep in the absence of structural complexity.

Most of the fields considered have initial pressure and fluid data which suggest lateral and vertical communication on geological timescales, even when major shale intervals are present. However, there are fields or field segments which are dynamically dominated by fault-baffling. In more highly faulted fields, there are some faults which behave dynamically as sealing barriers, while others behave as baffles with varying degrees of transmissibility, and others enable communication between intervals or may even act effectively as conduits. Numerous wells have pressure transient data influenced by seismic or sub-seismic faults in the vicinity of wells, with impacts on performance.

Major shales commonly act as barriers to vertical communication, though pressure interference and 4D seismic demonstrate communication through some apparently continuous shales. However, sand-to-sand contact does not guarantee good dynamic communication. Stratigraphic features within sands, such as channel interfaces in stacked channel complexes, mud-filled channels, and regions of thin-bedded pay, are responsible for baffles which can have an important influence on well and reservoir performance.

Aquifer strength normally plays a significant dynamic role in these fields, particularly in mitigating pressure decline during periods of low injection. However, there are few fields in which aquifer strength is sufficient to make waterflood redundant. Aquifer strength is a function of rock compressibility and connectivity as well as volume.

NOTES:

Quantitative description of submarine channel fills: Identifying the stratigraphic expression of variations in channel evolutionary history.

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Slope-channel fills are a composite product of a spectrum of sedimentary processes (e.g. erosion, bypass and deposition) that are variably recorded by a series of channel-fill characteristics. Proportionally, thick-bedded sandstones dominate channel fills yet they provide a biased record of channel-filling processes via deposition from collapsing high-density turbidity currents. The significance of other channel processes is more cryptic as they are recorded by features that are proportionally subordinate or less readily preserved. These include: (1) the geometry of the channelform basal scour that records the inception and earliest phases of conduits (Fildani et al., 2013; de Leeuw et al., 2016); (2) chaotically bedded units containing discrete blocks of remobilized strata that record mass-wasting and scour (Gardner et al., 2003); (3) draping mudstone-prone units and clast lags that record sediment bypass (Mayall et al., 2006; Hubbard et al., 2014; Stevenson et al., 2015); (4) intra-channel fill erosion surfaces that record punctuating phases of incision and sediment bypass (Hubbard et al., 2014; Clarke et al., 2014); and (5) relatively thin-bedded units in the margins that record the focusing of stratified flows largely within the channel thalweg (Hansen et al., 2015).

We use an exceptional exposure of outcropping submarine slope channel fills from the Cretaceous Tres Pasos Formation, southern Chile, to document the varied stratigraphic expression of these formative processes. The outcrop comprises >25 stacked channel elements (~300 m total thickness) from a ~3 km-long segment of a lower slope channel system. Over 5000 m of measured section and detailed GPS mapping of three-dimensional exposure enabled the development of a well-constrained correlative framework for individual channelfills. Such context provides a unique opportunity to glean insight into the channel infill history, both from channel fill architecture and quantified sedimentological characteristics (i.e., bed thickness, sandstone-to-mudstone ratio, amalgamation ratio, grain-size, number of sedimentation units), which were determined for sub-environments within the channel (i.e. axis, off-axis, and margin).

Quantification of sedimentological characteristics from channel fills of the Tres Pasos Formation generally confirm more qualitative assessment of axis-to-margin variations; such trends include an axis-to-margin increase in the number of sedimentation units and decreases in amalgamation ratio, sandstone-to-mudstone ratio, total channel fill thickness, bed thickness and grain size. When compared to the axis, margins exhibit the greatest variability in terms of the values of sand-to-mud ratio and total number of sedimentation units, as well as in channel-fill architecture. From these observations we recognize three discrete styles of channel fill (Fig. 1), and inferred channel history, which exhibit variation in one of more of the following channel-fill attributes: (1) gross channel architecture and facies proportions; (2) the geometry of the basal channelform surfaces that was cut during inception of the conduit (i.e., stepped or smooth); (3) the presence and proportion of heterolithic strata preserved in the channel margin; (4) the relation of heterolithic strata to thicker-bedded sandstones (interleaved or discrete packages); (5) the relative distance from the channel edge at which thick-bedded amalgamated sandstones in the axis change to thin-bedded strata in the margin; and (6) distributions of bed thickness and grain size in the channel margin.

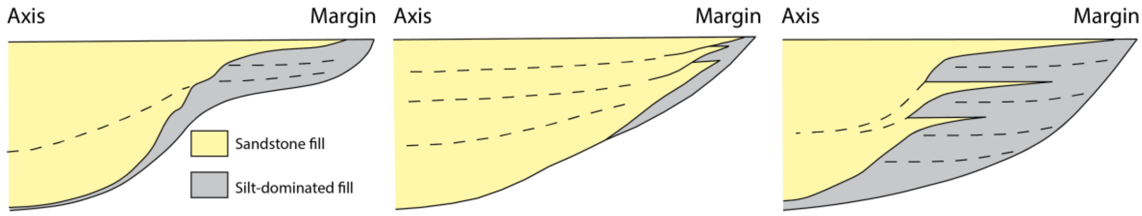

Figure 1) *Two-dimensional schematic cross sections depicting the various styles of channel fill and axis-to-margin transitions observed in the Cretaceous Tres Pasos Formation, southern Chile.*

The various styles of channel fill are inferred to record the influence of the geometry of the basal channel incision surface, and variation in the sequencing and relative magnitudes of discrete channel processes during channel evolution. For example, the occurrence of a stepped incision surface is thought to favour the development and preservation of heterolithic deposits in the channel margin. Such heterolithic deposits record the interaction of focused and stratified flows with the channel geomorphology; a stepped basal channel incision surface is thought to encourage focusing of the flow in the axis, whilst enhancing the deposition and preservation potential of heterolithic strata in the channel margin above this step (i.e., depositional terrace). The data compiled provides insights into the discrete ways channel fills are developed and preserved, the characterization and prediction of reservoir, and informs interpretations of channel stratigraphy and processes from less-constrained datasets.

NOTES:

Anatomy and multiscale heterogeneity of a deepwater fan – constraints on architecture from core and virtual outcrop, Ross Sandstone Formation, western Ireland.

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Introduction

The 495 m thick Pennsylvanian Ross Sandstone Formation is a well-exposed deep-water succession forming part of the overall shallowing-upward fill to the Clare Basin of western Ireland. Despite detailed study from the 1950's onwards a series of conflicting models have been presented accounting for the evolution and architecture of this enigmatic, sandy deep-water fan system. The thickest deposits of the Ross are centred on the region of the present day Shannon estuary where accommodation space was created by subsidence (probably related to extension, thermal subsidence and sediment loading) along the trace of the Iapetus suture zone. The most intensively studied coastal exposures of the Ross Fm. encircle the Loop Head Peninsula, just north of the Shannon in Co. Clare. This study presents the key insights gained at multiple scales in the Ross Fm. at Loop Head, through the integration of behind and below outcrop core, virtual outcrop and traditional data collection techniques. The primary aim was to integrate detailed bed-scale observations from cores with a re-analysis of the adjacent outcrops to better understand the depositional processes, resulting architecture and longer-term evolution of a deep-water system subject to high-frequency 'ice-house' forcing. The data from Loop Head captures a rare, fully-cored insight into the vertical evolution of a stacked submarine fan system from system inception overlying deep-water shales to the arrival of unstable toe-of-slope deltaic facies.

Dataset

Data from a combination of eight separate behind-outcrop boreholes providing slabbed PQ core and eight discrete virtual outcrop models (VOMs) (acquired via photogrammetry) have been integrated. The grouped dataset allows for detailed pseudo 3D analysis of previously inaccessible cliff-outcrops within the context of a new stratigraphic framework. A suite of wireline log data run for each of the wells provides a link to the petrophysical properties of the analysed elements. The virtual outcrops provide quantitative constraints on element geometries and facies distribution where interpretations are extended from borehole logs and accessible outcrop to inaccessible cliff outcrop sections. Bed types, element proportions, net:gross and amalgamation ratios as well as lateral and down dip trends within various cliff sections can be mapped onto the 3D virtual outcrop panels. This unusually rich dataset is augmented by a detailed re-examination of the classic Loop study sites via traditional field data collection techniques. A new stratigraphic framework for the Ross is underpinned by a combination of legacy and new biostratigraphic data, core-to-cliff correlations, interpreted photomosaics and the use of marker beds (extensive mass-transport deposits, distinctive thin-bed intervals and condensed sections). Three additional condensed sections internal to the Ross have been identified and these allow a higher resolution subdivision of the formation that has been possible heretofore. The framework constrains the Ross within up to ten discrete cycles of deposition within which a major system adjustment can be recognised splitting the system stack into two.

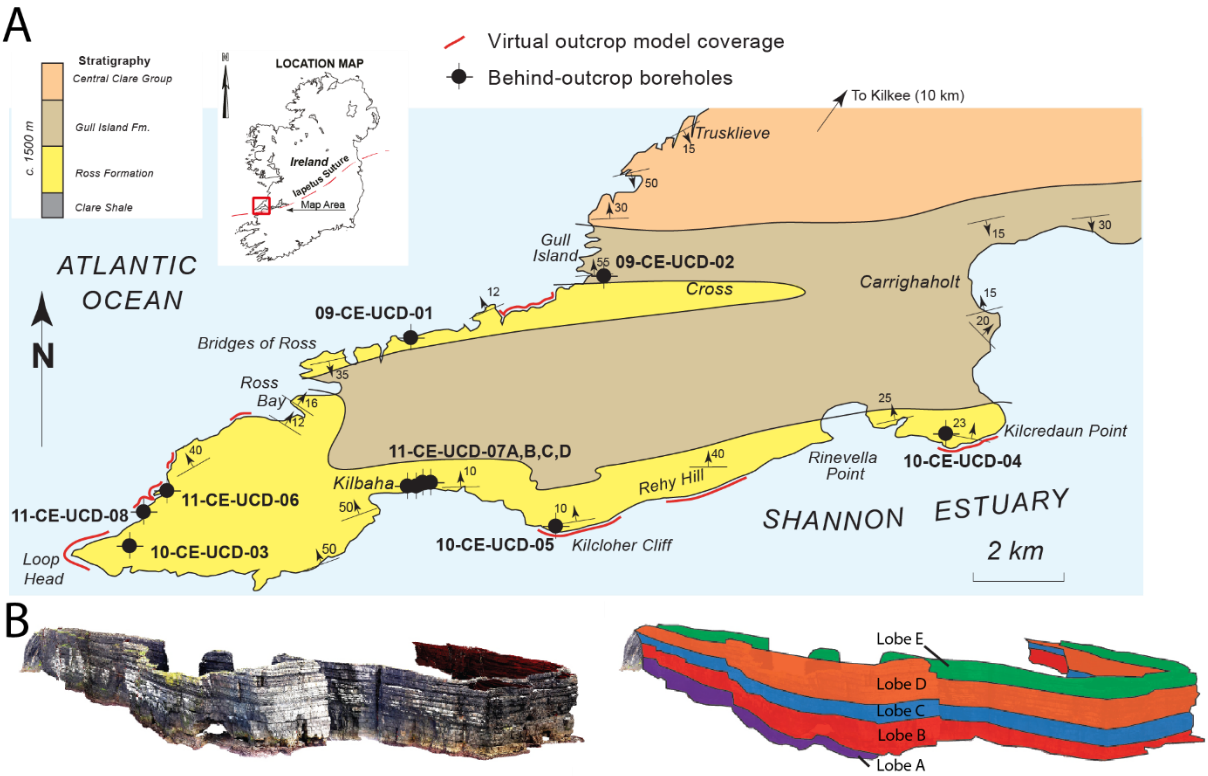

Figure 1 ***A****) Geological summary map of the study area showing the location of the virtual outcrop scan sites and the behind outcrop borehole distribution* **B***) A virtual outcrop panel from the tip of Loop Head with an un-interpreted version left and the lobe scale subdivision of the outcrop right.*

Beds to System Architecture

The slabbed core has revealed a previously unsuspected diversity of event beds and these have been catalogued using a custom bed classification scheme. The scheme acknowledges the key importance at many levels in the Ross of various types of hybrid event bed (HEBs; 27% of the formation, by thickness), in addition to the more familiar turbidites and mass-transport deposits. At least nine mass-transport deposit >1 m thick are recognised, some spanning the Loop area and extending to Kerry.

The main Ross system was constructed by a series of distributive lobe bodies fed by shallow channels. Rare leveed channels can also be recognised. Two types of lobe are identified; those comprising compensationally-stacked lobe elements conforming to lobe structure in other basins, and m-scale thickening-upward sandstone packages capped by erosion surfaces. The latter are interpreted as accommodation-limited lobes that evolved to bypass and incision, with channels distributing sand to compensationally-stacked lobe elements further down dip. The distinctive megaflute surfaces in the Ross are interpreted as bypass surfaces above accommodation-limited lobes and lobe elements.

Key cliff sections spanning different fan cycles provide worked examples showing the evolution of Ross architecture in space and time. The multiscale analysis (at bed, sub-element and element scale) within the individual fan cycles of the progradational Ross system stack allow for the characterisation of heterogeneity and reservoir quality in discrete sectors of the fan ranging from distal to proximal.

NOTES:

The evolution and significance of different type of canyon systems

Mark McKinnon
BG Group

A complex array of deep-water canyon systems exist offshore Tanzania. On the modern day seabed, we are presented with a unique snapshot in time of the margin configuration of these systems. This allows inferences to be made on the interaction between the canyons themselves, how they interact with major structures and the processes which allow these canyons to form. In additional, we have the opportunity to study canyons that are actively being formed and make inferences on the local scale erosional processes acting on the floors of these canyons.

Three distinct types of canyon systems exist: Shelf edge canyons are low sinuosity systems that cut the shelf edge and feed coarse-grained splays on the continental rise. They are steep sided with the greatest vertical incision situated at the shelf edge break. Canyon margin failure is relatively common. The second type are well established, highly sinuous leveed systems that can cut obliquely across the slope feeding out to the basin floor. These systems are characterised by abundant margin failure, multiple generations of terraces and an extraordinarily smooth equilibrium profile along their Thalweg. As such, they are interpreted as mature systems active for an extended period of geological time providing a pathway for flows to access the abyssal plain. Finally, immature, low sinuosity, 'headless' systems with headward migrating knick points on the canyon floor are the least typical canyon features on the margin. This type of canyon is interpreted to result from structuration of the basin floor and headward erosion upslope from features with relief at the seabed. Curiously, evidence suggests that these canyons are eroded by fine grained, low density turbidity currents.

The reservoir implications are significant; it is often thought that sand-rich fan/lobes must sit at the terminus of heavily incised systems. This can only be if the canyon connects updip to a coarse-grained source which is not the case in type 3 systems. Therefore, it is important to distinguish these headless canyons from those connected to the shelf. Additionally, systems that are at grade with the slope profile (type 2) are efficient at transporting sediment across the slope; sands associated with these systems occur beyond the channel mouth on the abyssal plain. Type 1 canyons typically encounter a negative break in slope at the continental rise often resulting in sand-rich splays that backfill the canyon.

Not only is the Tanzania example a world class dataset in which to study a modern day canyon dominated slope apron system, it can clearly provide a direct analogue to the reservoir potential in the subsurface and in similar settings around the globe.

NOTES:

Deep-Water Channel Trajectory Control on Connectivity

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Deep-water channel fill comprises thick-bedded sandstone in the thalweg that transitions laterally to thin-bedded deposits toward the margins. Channel fills stack to form composite channel systems, which commonly exhibit an evolution of early channel incision and lateral migration to late-stage aggradation. This stratigraphic evolution ultimately controls three-dimensional (3D) facies architecture (i.e., facies heterogeneity and stacking patterns). We developed a suite of 3D object-based reservoir models based on incising-to-aggrading trajectories of 21 deep-water channel systems in order to compare the static connectivity of channel deposits. Channel form and facies trends are held constant in all models. Preliminary results suggest distinctively different connectivity depending on the degrees of aggradation and lateral migration. More aggradational channel trajectories result in more continuous and vertically connected sandstone-rich facies in the thalweg. A higher rate of lateral migration results in a complex architecture of cut-off and eroded remnant sandstone-dominated channel deposits. Future work will evaluate different fluid flow behavior during hydrocarbon production depending on channel trajectory.

NOTES:

Friday 27 January

Session Ten: Hybrid Beds

Hybrid Event Beds in Channelised Systems – Insights from Outcrop and Subsurface Case Studies

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[2]*University of Manchester, England*
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Hybrid event beds are an enigmatic group of deep-water gravity flow deposits that preserve elements of both turbulent and laminar flow behaviour during the passage of a single flow event. The causal mechanisms, including updip flow-substrate interactions, as well as the timing of flow transformation that produce these bed types (i.e. whether this occurs proximally or distally along the flow path) remains an active theme of research and of particular relevance to the interpretation of such deposits in prospective hydrocarbon regions. Many studies have described HEBs in the distal parts of fan systems where the change in flow rheology is variably linked to changes in confinement or slope gradient with flow runout length also an important parameter; in the Wilcox System, for example, it has been proposed that rheological stratification is driven by flow expansion and transformation at the channel-lobe transition zone (CLTZ). New analysis carried out in this current study combines analysis of subsurface and outcrop data from the more proximal parts of turbidite systems where HEBs have been documented in and around erosional channels in order to examine the distribution and implications of their occurrence in these settings. In both examples the turbidite systems are interpreted to have formed within a structurally-complex intra-basinal setting, where fill and spill-type processes were likely to have been active and flow-substrate interactions occurred in response to seafloor irregularity.

The first case study uses North Sea subsurface data from a channel ~10 km long, 1 km wide and 70 m deep and is based on core and seismic interpretations. The lowermost axial deposits show a typical channel fill character of pebbly lags and amalgamated high density turbidite (HDT) sandstones; similarly, stacked HDTs characterise the upper fill. These deposits are, however, separated by a thick HEB-prone interval, interpreted to be extensive across the channel area, we interpret these in terms of a channel axis association. Additionally, HEBs are also present within the upper, generally more thinly bedded channel fill which we have interpreted to represent a channel margin association. The distribution of HEBs within this system indicates a trend of increasing HEB frequency and increasing dominance of the upper matrix-rich interval, both marginally and distally along the length of the channel system. Additionally the proportion of matrix-rich to matrix-poor sandstone also appears to increase when stacked vertically and we ascribe this to the effects of knickpoint migration as erosion back-steps upslope and progressively further from the point of deposition.

The second study uses outcrop data gathered from the Grès du Champsaur, SE France. Here we document the distribution of bed types across a series of erosional channels, at least 6 km long, and ranging up to 1 km wide and 120 m deep. These channels generally have a more typical turbiditic fill, with amalgamated High-Density Turbidites (HDTs) exhibiting bypass features dominating the axial areas, less amalgamated HDTs in the upper fill and off-axis and with a range of thinner bed types marginally. HEBs are again documented in two associations in this system. The first is as sheet-like deposits cut by channels or beneath thick sandstone packages; we interpret this as a frontal splay association, linked to the onset of waxing flow cycles. The second is a channel margin association, where HEBs occur in coarsening/thickening upwards cycles; we interpret this as a waning flow overbank association, deposited by flows that escaped during late-stage channel filling.

These analyses indicate that although most occurrences of HEBs have a relatively distal environmental association, the mechanisms of ‘hybrid flow’ formation and deposition may also be active within the proximal, channelised parts of turbidite systems, where they may be linked to cycles of knickpoint migration and erosion of updip minibasin fill. The occurrence of HEBs within the axial channel fill sequence further suggests that flow transformation may occur over a relatively short distance, local to the point of erosion and upstream of the CLTZ. The occurrence of thinner and finer grained HEB-types in the channel margins, lateral to increasingly amalgamated deposits within the axial region serves to highlight the importance of preservation in their distribution.

NOTES:

Is hybrid bed distribution in basin-floor fans predictable?

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Hybrid beds, which are the deposits of flows that show more than one flow regime (turbulent, transitional and/or laminar), have been recognized as important elements of submarine lobe deposits. The range of hybrid bed types has been widely documented, however, quantitative analyses of the distribution of these deposits are rare. Extensive exposures supplemented by research borehole data from Unit A of the Laingsburg Formation and Fan 4 of the Skoorsteenberg Formation, South Africa, provide the means to examine geographical and stratigraphic patterns over a range hierarchical scales (from lobe to lobe complex set). For this purpose, >23,000 individual beds have been evaluated for deposit type and bed thickness.

It has been shown that hybrid beds make up <15 % of all events in a lobe complexes. A prominent geographical trend shows that hybrid bed deposits become more prevalent towards the frontal fringes of a lobe complex with up to ~35% of all the events and ~80% of the deposit thickness. Stratigraphic trends in the lobe successions are dependent on the dominant stacking pattern (aggradational, compensational, progradational and retrogradational) of lobes within a lobe complex as this controls the vertical stacking of clean sandstones, thin-bedded heterolithic deposits and hybrid-bed prone deposits. Rather than being dominantly controlled by processes on the slope as suggested hitherto, the occurrence and distribution of hybrid beds is interpreted to be controlled by flow transformation processes on the basin-floor.

These new insights have implications for reservoir evaluation and the recognition of lobe stacking patterns in 1D core data sets and 2D outcrop analogues.

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Hybrid event bed character and distribution in a deep-water fan and confined basin plain system: the North Apennine Gottero Sandstone (NW Italy)

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Hybrid event beds (HEBs) are increasingly recognised as an important component of many deep-sea fan and sheet systems. HEBs are sediment gravity flow deposits comprising a basal clean (H1) and/or banded (H2) sandstone overlain by a muddier sandy facies (H3) emplaced during the same transport event. Their recognition and prediction is important in both hydrocarbon exploration and appraisal phases because their presence and character can compromise reservoir performance.

The Cretaceous-Palaeocene Gottero turbidite system of NW of Italy developed on the Ligurian convergent margin, evolving from a basin-floor fan to a progressively-confined trench system. Detailed fieldwork, including collection of >5000 m of graphic logs, has shown that HEBs are abundant in the outer fan and confined basin plain portion of the system, where they comprise more than 57% of the total thickness. In more proximal sectors, HEBs occur interbedded with mid-fan sandstone lobes, and comprise up to 20% of the total thickness. They are not observed in the inner fan, channelized area. The origin of HEBs in the outer and mid-fan sectors is different, and is thought to be controlled by the flow magnitude and the loci and mechanisms of mud entrainment and turbulence damping.

The confined basin plain sector is dominated by thick (max 9.57 m; average 2.15 m) and tabular HEBs (Fig. 1a), the H3 divisions of which can include very large substrate slabs and blocks, evidence of extensive auto-injection and clast break-up, and abundant mudstone clasts set in a sandy-matrix with slightly elevated interstitial clay (~20%). These beds are thought to have been generated by highly energetic flows capable of delaminating the sea-floor locally, sometimes detaching large pieces of substrate by basal injection, and carrying them relatively short distances before arresting. A number of genetically-related bed types can be recognised in which progressive disaggregation of the mud clasts and rafts along longitudinal facies tracts leads to the development of the H3 divisions.

The unconfined lobes of the mid-fan sector (Fig. 1b) are dominated by thinner (average 0.38 m) HEBs, which have H3 divisions characterised by higher levels of dispersed clay (>25%), floating mudstone clasts, and matrices that are enriched in hydraulically-fractionated components (mica, organic matter, clay flocs). Those beds can also occasionally show a banded H2 division. HEBs are present in the muddy inter-lobe intervals between amalgamated sandstone lobes, or are stacked into thickening-upward or symmetrical sequences, and interpreted as individual lobe fringes. This HEB association is thought to have been produced by less energetic flows that underwent early turbulence damping following incorporation of mud from proximal lobe locations or flow expansion points and may include depositional phases from transitional flows. At the base of a few lobe units, mudstone clast and raft-bearing HEBs (similar to the types found in the distal basin plain sector) can be present and are interpreted as originating by local delamination of the underlying inter-lobe fine grained substrate.

In the Gottero system, no large-scale stratigraphic relationships are apparent linking the development of hybrid event beds to system evolution, relative sea level oscillations or phases of tectonically-induced slope instability. Instead, the variable character of the hybrid events is linked to sub-environment (fan lobe vs basin plain), flow magnitude and type of substrate (presence of muddy inter-lobes and ponded mud caps). Although this tectonically-active system was prone to hybrid flow generation, local HEB occurrence was strongly controlled by autogenic rather than allogenic processes.

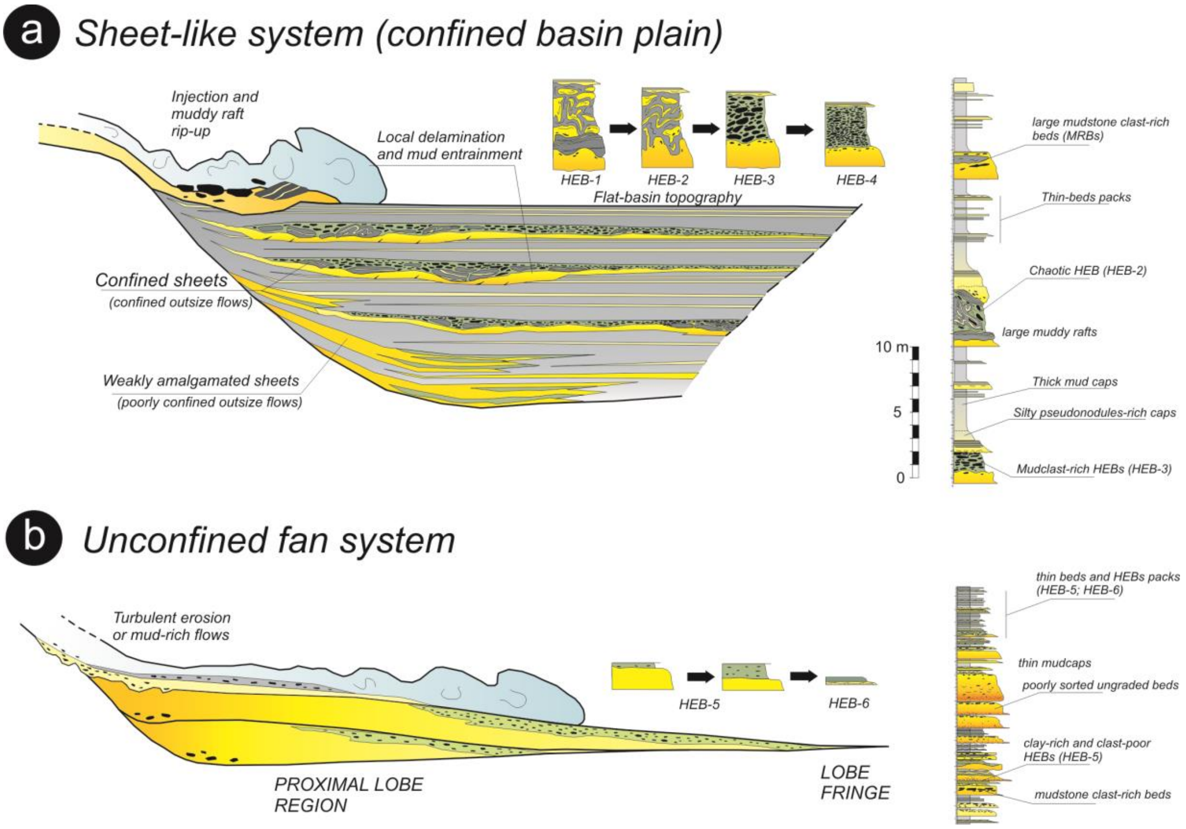

Figure 1 – Diagram summarising the basic stacking patterns, bed types and flow processes recognised in the Gottero system. (a) Confined basin plain characterised by thick tabular and lateral extensive mudstone-clast and raft-bearing HEBs interbedded with thin-beds packages and thick mud caps. (b) Unconfined fan system characterised by depositional lobes and clay-rich and clast-poor thin HEBs forming in the lobe fringes.

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Abrupt down-current shift from channelized sandbodies into a hybrid event bed dominated domain: the Bordighera turbidite system (NW Italy)

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In order to improve predictions on the efficiency and productivity of clastic deep water petroleum reservoirs, studies of small- to basin-scale facies heterogeneities within comparably exposed systems have gained increasing attention in the last decade. In particular, the detailed facies distributions of sand-rich turbidite systems deposited in trench settings have only been analyzed in a limited number of ancient systems, with no previous documentation of the presence of abundant hybrid event beds (HEBs). The coarse-grained, elongated Bordighera turbidite system of the Western Ligurian Flysch of NW Italy has been chosen to document such occurrence by a multi-scale approach. Integration of traditional methods such as high-resolution bed-scale facies analysis, amalgamation ratio (AR) analysis and paleocurrent orientation determinations with basin-scale statistical analyses of horizontal and vertical trends in facies distributions allowed determinations of system-scale cyclicity, sub-depositional environments and along current quantitative assessment of facies heterogeneity.

The Bordighera turbidite system outcrops along a roughly 45 km transect parallel to the mean NNE'-directed paleoflow. In the more proximal segment, constituting roughly 1/3 of the transect, lenticular sandstone bodies are composed by highly amalgamated (AR 55–75 %; off-axis to axial) clean microconglomerates and sandstones (i.e. poor in clay matrix). Within a down-current distance of less than 5 km from this proximal realm the system undergoes an abrupt transformation. This more distal domain is characterized dominantly by laterally extensive, tabular, sandstone bodies (max. thickness ca. 8 m) separated by thin, cm-scale siliciclastic mudstone drapes or thin-bedded heterolithic intervals (generally <50 cm), denoting the limited volume of siliciclastic mud deposited in this domain. The sand sheets are infrequently incised by lenticular, coarse-grained massive sandstones, with the ratio between the lenticular and the tabular sandstone bodies varying throughout the distal domain from 0.1 to 0.4. These composite sandstone bodies have similar high sand-to-mud ratios compared to the channelized domain, whereas amalgamation ratios are reduced (40–65 %). Argillaceous sandstones make up the dominant bed types (43–69 %) and characterize the more tabular sands. Intercalations of thin- to medium-bedded calcareous mud become progressively abundant in the distal domain of the system (making up usually 7-16% of the stratigraphy). Basal grain size shows the repeated occurrence of very coarse-grained sediment reaching well into the most distal sections – in contrast to the general down-dip fining observed in comparable trench systems. Statistical analysis of system-scale bed type proportions show that while the more proximal domain is dominated by massive and clean sand, an increased variability can be recognized more distally. In the more distal domain, moving down-current sandstone beds become increasingly enriched in randomly arranged cm- to dm-scale mud clasts until they are replaced by hybrid event beds showing a distinct clean sandstone base overlain by a mud-enriched chaotic division containing m-scale rafts of heterolithic packages and blocks of incorporated calcareous substrate. The thickness of the mud-enriched chaotic division tends to increase towards the most distal outcrops, prompting the emergence of hybrid event beds that lack a basal clean sand and that can rather be described as clast-rich matrix-supported debrites. Remarkably, most of these generally coarse-tail graded beds show pebbly bases followed by a very coarse sand grain size.

The proximal domain is interpreted as low-sinuosity channel fills while the more distal domain is thought to represent frontal splays, locally incised by shallow distributary channels and minor scour fills. The abrupt system change between the two is interpreted as resulting from the shift from a more proximal environment characterized by channelization and related avulsions, into a rather unconfined more distal realm. The intermittently high-energy and partly by-passing nature of the system shown by basal grain-size trends and the availability of calcareous mud might be speculated as being controlling factors on the abundant HEB development. The observed bed type distribution with the argillaceous sandstones rapidly making up the dominant bed types down-dip of a 'transition zone' has a negative impact on hydrocarbon reservoir quality. Recognition of the location and character of this sharp break in facies distribution is crucial in order to establish accurate reservoir models for this type of systems. The Bordighera Sandstone represents a valuable analog for coarse sand-rich turbidite systems deposited in trench settings, permitting the quantification of proximal to distal facies patterns.

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En-route mud acquisition by sandy gravity flows and the origin of hybrid event beds: insights from ponded turbidite mudstone caps, Castagnola system, NW Italy

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Primary clay in deep water gravity flow deposits can be found as mudstone caps, mudstone clasts or as interstitial (matrix) clay particles. While the majority of clay in turbidites is usually seen in mudstone caps, clay in debrites more commonly occurs in the form of mudstone clasts or matrix clay. Hybrid event beds (HEBs) are bi- or tripartite event beds with a lower clean sandstone division and an upper or central chaotic mud-rich division. These beds include features of both turbidites and debrites and their clay content is split between a mudstone cap, mudstone clasts and matrix clay. When a full inventory of the clay distribution can be made, the processes governing how clay is incorporated and partitioned within the flow and finally deposited can be assessed. In turn, such insight should allow the controls upon the relative abundance of turbidites vs. hybrid event beds to be evaluated. As part of a concerted research effort to describe and interpret hybrid event beds, mudstone clasts and dispersed clay particles have received significant attention over the last ten years or so. However, complementary mudcap studies have received relatively little consideration. This is mainly because in most systems the mud substantially bypasses the areas of sand deposition, and because it is difficult to collect accurate mudcap thickness data in the field.

The Castagnola system of NW Italy was chosen as a study area because it is a fully ponded basin (i.e. mud cannot be lost down-dip) and accurate measurements were undertaken with a new, high-precision Jacob's staff. In the studied ponded interval turbidites have a sandstone to mudcap thickness ratio of around 1:2, while hybrid event beds have a ratio of around 2:1. However, the amount of mud present in the HEBs chaotic mud-rich division is not enough to explain such differences (i.e., the HEBs carry relatively less mud overall than turbidites of similar sandstone thickness taking into account all the mud sinks). Also, there are not significant grain size differences between HEBs and turbidites of similar sandstone thickness. Furthermore, two distinct petrographic sources fed flows into the basin; sandstone beds are usually of one type or the other, but the sandstone to mudstone cap ratio is not dependent on the petrographic type. Finally, preliminary data suggest that the mudcaps have mixed provenance signatures.

The apparently mixed mucap provenance signatures, together with the absence of any correlation between sandstone provenance and the event bed sand to mud ratio (which might be expected to vary between petrographically very different source areas) suggest that the flows were originally mainly sandy and incorporated significant amounts of mud en-route. It follows that the currents that deposited the turbidites must have incorporated more mud than those that deposited HEBs of similar sandstone thickness. It can therefore be argued either that the flows were fundamentally different in their erosional character (e.g. by having different duration and deposition rate), or that they were similar but impacted on substrates with different mechanical properties. The second option is favoured and it is speculated that flows that encountered a less cohesive muddy substrate were able to acquire larger amounts of mud en route and to segregate it (deposited as turbidite mudcap). On the contrary, flows that encountered a more cohesive substrate acquired less mud and deposited some of it as mud clasts as part of the chaotic mudstone-rich division typical of HEBs. This conclusion challenges the view that flows with greater erosional capacity are more likely to develop hybrid character, and may force a rethink on the criteria needed to predict the likelihood of HEB development.

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Friday 27 January

Session Eleven: New Techniques and Approaches

Recent Advances in Seismic Reservoir Characterisation for Deep Water Depositional Systems

Patrick Connolly
PCA Ltd.

Because of their highly variable net-to-gross the largest subsurface uncertainty of deep water reservoir developments is typically net rock volume. This applies both at a reservoir scale for assessment of in-place volumes and more locally for optimising well placements and populating models for flow simulation. For shallower reservoirs with benign overburden seismic amplitudes respond strongly to changes in net-to-gross. This provides a technical opportunity that, when combined with the strong business requirement, has led to much effort being put into the development and application of technology for direct estimation of net-to-gross from seismic data.

Results have improved significantly since the earliest attempts in the 1980's but, until recently, shortcomings in the various methods have remained particularly for thicker channelised reservoirs where often the bulk of the reserves lie. However a new generation of algorithms have recently become available which promise a significant improvement in our ability to characterise these reservoirs directly from the seismic.

The net-to-gross of thinner, isolated reservoir units, say less than about 50ms two-way-time, can be estimated fairly accurately using attribute detuning methods (Connolly, 2007, Meza et al, 2015). However for thicker channelised reservoirs the lack of low frequencies in the seismic render the method inaccurate.

An alternative is to use a 3D inversion. All early algorithms were deterministic, that is they did not account for the uncertainty of the data, either the seismic or the additional data being used to calibrate the seismic. Such methods usually involved the addition of the missing low frequencies in the form of a low frequency model typically created by interpolating well data. This had a number of problems; firstly wells are usually in short supply in deep water so models are inaccurate and, more fundamentally, the failure to recognise the uncertainty of the low frequencies tends to bias the results particularly in the thicker channels; the very location that the attribute methods also fail (Grant, 2013).

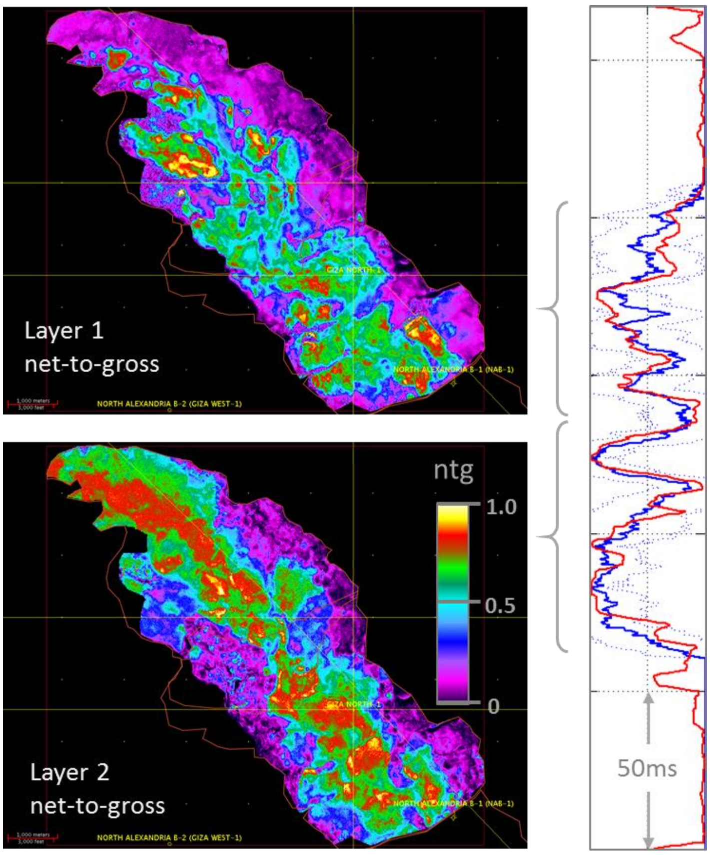

Figure 1. Net-to-gross estimation for a Nile Delta channel showing averages for the constructional and aggradational phases (layers 1 & 2). On the right is the predicted Vshale in blue compared with the actual smoothed Vshale well log demonstrating the accuracy of the method even for thick reservoirs. (Reproduced from Grant & Dutton, 2016.)

So called stochastic methods aim to account for the inherent uncertainties of seismic inversion. Stochastic algorithms first began to appear in the mid '90's but uptake was slow. This is may be due to shortcomings in the algorithms; some were difficult to parameterise, or run-times were too great or workflows, involving multiple-realisations, were too complicated. Others were rather selective with the uncertainties they took into account and often still started with a fixed low frequency model.

In the 2000's Bayesian methods began to emerge (Buland & Omre, 2003). These offered a more rigorous approach to the integration of multiple data types allowing for uncertainties. Until recently these algorithms resided within academia and the R&D departments of larger oil companies but now a number of them, including Pcube, JiFi and ODiSI, have been made available commercially (Riise et al, 2012, Kemper & Gunning, 2014, Connolly & Hughes, 2016 respectively).

Bayesian methods start with a 'prior'; the information that is already known about the reservoir; statistical relationships of facies, rock physics correlations and so on but most importantly this includes a specification of the uncertainty of these relationships. The prior information is then combined with the seismic data, or 'likelihood' in Bayesian terminology, to form the posterior, the final estimate of the reservoir property or facies definition in the form of a distribution i.e. incorporating all uncertainties.

There are several different approaches as to how to solve these problems. The approach used by ODiSI is to randomly select samples from the prior in the form of short stochastic vertical stratigraphic profiles, compare them with the seismic and either accept or reject them. Accepted samples are used to build up the posterior distribution. Figure 1 shows the results of applying this technology to a thick channelised reservoir in the Nile Delta.

ODiSI (One Dimensional Stochastic Inversion) was developed by BP and has now been commercialised by Cegal. In this talk I'll explain in greater detail how the ODiSI algorithm works and show the results from a number of deep-water reservoirs.

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Bed-level clay distribution in deep-water sandstones: insights from continuous XRF profiling

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Emerging evidence suggests clays can modulate turbulence in many sediment gravity flows. This is important because clays that either become hydraulically fractionated or are released by clay-clast break-up near the base of a flow can force deposition of sand and clay together as the flow decelerates. Variable clay distribution has important implications for heterogeneity and associated reservoir quality in many deep-water reservoirs, including those in the distal Forties Fan in the North Sea and the Wilcox in the Gulf of Mexico. However, determining the details of the clay distribution at bed level, accurate clay quantification and understanding the underlying controls in terms of original flow processes remain significant and interesting challenges. High-resolution XRF core scanners have been widely used to capture continuous bed-level compositional trends in shallow sediment cores across a range of environments, including those from the deep-sea. As yet, there has been only limited use of this technology in older rock cores and then mainly to map out mineralization. The present study shows how multi-element compositional profiling has helped to characterise textural profiles for a range of different types of hybrid event bed in the Pennsylvanian Ross Sandstone Formation, western Ireland, an important deep-water reservoir analogue.

The Ross is a useful prototype succession to explore high-resolution chemical profiling using rock cores in that it comprises a relatively simple bimodal mix of dominantly quartz sand and clay. Recent behind-outcrop coring funded by Statoil ASA has identified a wide range of bed types. Previously the Ross was interpreted as comprising mainly turbidites, but the cores establish that hybrid event beds are also an important part of the bed mix (27% of Ross by thickness). Furthermore, a range of hybrid and transitional flow deposits are now identified, implying flow behaviour at different levels in the Ross was forced by different mechanisms (fractionation of clays and low-density flakes, incorporation of substrate clasts, partial transformation of mass transport deposits). A number of key bed types (including hybrid, transitional and conventional turbidites) have been selected for detailed (200 μm) elemental profiling on slabbed core using an Itrax core scanner. In addition, serial thin sections have been cut from plugs in the same beds, and the elemental profiles calibrated against bulk-rock chemistry and compared to high-resolution spectral gamma collected in the open holes. Si and K are shown to be useful textural proxies for silt/sand grains and clay and/or mica respectively, and Ca for diagenetic overprinting. The elemental profiles give new insight into subtle but systematic vertical compositional trends that may reflect differential settling of coarser quartz sand and silt in arresting suspensions and fluid muds, fractionation of micas, and textural interfaces reflecting internal shear and partitioning of the flow. A common pattern, particularly in the thinner hybrid event beds, is a tripartite stack of clean, clayey sandstone and sandy claystone separated by sharp surfaces. Some of the thicker beds show the development of incipient 'banding' and profiling of clay clasts as well as surrounding sand and background mudstones help constrain the likely source of the clays incorporated in the original flows. On a larger scale the elemental data help identify vertical changes in sediment composition and sand input across the Ross Formation as whole; early sandstones are coarser grained, have lower gamma, lower K and higher Si than younger parts of the Ross confirming that the deep-water part of the succession comprises two distinct systems.

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Depositional reservoir quality of a confined deep-water lobe: Jaca Basin, Spain.

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Deep-water sedimentary systems reflect the interplay of allogenic forces (e.g. tectonics and sediment supply) and autogenic factors (sedimentological processes inherent to the system). Accordingly, this interplay controls the intrinsic architectural character and sediment characteristics, and therefore the distribution of reservoir quality, across all scales. Depositional reservoir quality relates to the primary, process-controlled fabric prior to significant post-depositional modification. The secondary, diagenetic, fabric is strongly controlled by the primary texture and mineralogy. Therefore, understanding the primary processes controlling spatial and temporal changes in fabric and mineralogy is key to improved reservoir characterisation and improved predictability of reservoir performance at different hierarchical levels. Results from conventional core analysis are an important data set for reservoir characterisation; however, sampling programmes are typically biased towards thick sandstones, or have inadequate sampling spacing to capture small-scaled heterogeneities. Heterogeneous successions could be incorrectly characterised if outlying thick sandstones in otherwise thin-bedded successions are sampled, or vice-versa. Here, a well-constrained exhumed lobe complex in the Jaca Basin, northern Spain, is used to characterise the depositional reservoir quality of facies in axial to fringe settings at the bed, lobe element, lobe and lobe complex scale. A quantifiable, strategic approach was developed to accurately characterise the succession through hand-sample collection; additionally, representative facies samples were collected at each locality to assess process controls on depositional architecture and facies distribution. The porosity and grain-scale fabric of the samples are analysed in thin-section, the results of which are compared to samples collected at a data resolution typical to that of core. The results indicate that traditional subsurface sampling methods can result in serious under- or overestimates in the reservoir properties, depending on the spatial variability of the lobe complex, which may be a product of basin morphology, e.g., confined or unconfined, and the sediment supply to the basin.

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Timing of coarse-grained sediment delivery to a Cretaceous deep-marine basin, Magallanes Basin, Chile: Insights from zircon geochronology and strontium isotope stratigraphy

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Improved conceptual models of deep-marine sedimentation that link architecture and basin-scale stratigraphy to potential controls require temporal information. However, progradational deep-marine slope systems in the geologic record can be difficult to date because of the high-energy processes associated with sediment transfer and the related lack of preservation of biostratigraphic markers or volcanic ash deposits. Here, we use new chronologic information, including >6300 detrital zircon ages (U-Pb; LA-ICP-MS), two volcanic-ash zircon ages (U-Pb; TIMS), and 80 detrital strontium isotope ages ($^{87}Sr/^{86}Sr$ stratigraphy), from the Magallanes Basin, southern Chile, to constrain the timing and duration of distinct phases of sediment delivery to deep water. Shelf-slope progradation along the axis of a deeply subsided foredeep during the Late Cretaceous resulted in long run-out (>35 km) slope segments that are challenging to correlate across the outcrop belt from mapping alone. We enhance regional correlations with a diverse suite of chronologic information across a ~100 km-long by 2.0-2.5 km-thick depositional-dip-oriented transect.

Results indicate that the history of deep-marine sedimentation is characterized by four distinct phases: (1) A phase of protracted slope oversteepening and readjustment characterized by mass wasting deposits intercalated with turbidite fan units; (2) A phase of pronounced high-relief (500-900 m) shelf margin clinoform progradation with a falling shelf-edge trajectory; (3) Regional transgression, followed by a phase of lower-relief (<400 m) shelf margin clinoform progradation; and (4) A phase of renewed high-relief (>1000 m) shelf margin clinoform aggradation and progradation. Maximum depositional ages (MDAs) are derived from the youngest population of zircons for each sample. The MDA for the onset of slope sedimentation is 80.6 ±0.9 Ma, remarkably similar to a TIMS age from an adjacent ash (80.5 ±0.3 Ma). The four stages of slope development lasted for ~10 Myr, until 70.6 ±1.3 Ma. In addition to depositional age constraints, this data set provides information about provenance and episodes of intra-basinal sediment recycling. Detrital zircon age probability-density plots show that all phases have statistically indistinguishable populations of >90 Ma ages, which suggests there were not significant tectonic changes and/or catchment configuration modifications during shelf-slope deposition. Detrital strontium isotope ages, which are derived from primary calcium carbonate precipitated by shelled marine organisms (in this case, inoceramids and oysters), show that there are two general age populations (~87 Ma and ~79-80 Ma). The prevalence of shells that are up to ~12 Myr older than depositional age indicates reworking via erosional excavation and/or basin-margin uplift.

The combination of extra-basinal and intra-basinal detrital chronology is a novel approach to the examination of how basin evolution impacts deep-marine deposition. U-Pb ages from detrital zircons provide the temporal constraint to estimate rates of coarse-grained sediment flux into the deep basin during discrete phases of basin evolution. The complimentary detrital $^{87}Sr/^{86}Sr$ ages constrain the source of sediment influx to include previously buried intrabasinal sediment. The combination of these data sets provides an important and comprehensive perspective into potential drivers of basin-scale depositional trends.

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Friday 27 January

Session Twelve: Sedimentary processes and products

Keynote Speaker: Sediment flux from source to sink across the Texas continental margin during the late Pleistocene.

Carlos Pirmez
Shell Italia E&P

A series of four intraslope basins linked by submarine channels in the northwestern Gulf of Mexico form part of a source-to-sink depositional system that starts in the headwaters of the Brazos and Trinity Rivers and terminates in a ponded intraslope basin offshore Texas — the Brazos–Trinity depositional system. The system is well imaged with 3D seismic data, and two of the basins have been drilled, with three Integrated Ocean Drilling Program wells and two geotechnical wells. Using an integrated approach, we have combined seismic-litho-bio-tephro-stable-isotope-radioisotope stratigraphic methods to generate a millennial-scale resolution chronostratigraphy for this system. The results enable (a) calibration of the sedimentary record in the deepwater basins and determination of the mechanisms of the sediment partitioning between sub-basins and the resulting stratigraphic geometries; (b) quantification of the sediment fluxes over time; and (c) evaluation of the causes and effects of sea-level changes on the shelf, slope and deepwater sedimentation.

Sediment accumulated in the slope basins at rates which varied over time between 1.4 and 55 million tons per year during the late Pleistocene to Recent. Except for a short time interval when the Brazos River was diverted to the shelf edge, sediment flux to deepwater was on average less than the present-day sediment discharge of the Trinity–Brazos–Sabine Rivers combined. In the period 24-15 ka the sediment sinks comprising the slope basins and shelf-margin delta can be balanced against the fluvial sources if their discharges are somewhat lower than present day, and if the contribution from incised-valley erosion was relatively small. The history of sedimentation on the slope basins is modulated by sea-level changes, but it is strongly influenced by basin topography and by the dynamics of delta development on the shelf. During peak high stands of sea level the slope area receives only pelagic sediments; during low sea-level stands, the sedimentation in each basin results from a complex combination between fluvial input at the head of the first basin, and the rate of subsidence/sedimentation causing basin topography. The ages of sediments in separate basins show that sedimentation occurs at the same time in multiple basins with trapping of sand in updip basins, while mud is preferentially deposited in downdip basins.

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Sediment bypass by turbidity currents and prediction of upslope stratigraphic-pinchout traps

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The abrupt-margin play type has become a prime exploration target for many petroleum companies over the last decade. This play type is high risk owing to its reliance on updip stratigraphic trapping of 'detached' turbidite reservoirs. Seismic is critical for defining such prospects but limited in terms of detecting thin sands and gravels that may extend updip causing hydrocarbon leakage. Here we use a sediment transport model to aid pinchout prediction. Turbidity currents on inbound slopes may erode and bypass sediment forming sand-starved slope conduits and detached reservoir bodies. In contrast, flows that cannot suspend their sediment will deposit on slopes, forming coarse-grained slope conduits and upslope-attached reservoir bodies. Using an analytical diffusion-based model of sediment suspension, erosion and deposition for turbulent flow, we explore threshold shear velocities required for total sediment suspension and bypass. The results are used to estimate the minimum slope gradients required for total sediment bypass in flows of varying grain-size distributions and concentrations. The analysis helps constrain critical slope gradients for sediment bypass required to form upslope pinchouts and may be used to augment the risking of upslope turbidite stratigraphic traps.

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Interaction of multiple turbidity currents – flow dynamics and geological implications.

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Sediment–laden submarine turbidity currents are destructive yet enigmatic. However, their dynamic structures can be studied by interpreting the depositional features they generate. Here we study the processes of multiple interacting turbidity currents and discuss the characteristic signal that such flows may generate in the stratigraphic record. It has been suggested the interaction of multiple turbidity currents may occur during retrogressive slope failure or flow combination at topographic confluence points. It has also been postulated that the deposits generated by interacting flows are distinguishable from non-interacting, or single-event, flows. Such interpretation of turbidity current deposits has been used in palaeo-seismology to link and interpret seismo-turbidites. Of key interest is how the structure of turbidity currents deposits reflects flow dynamics, and thus if and where the mechanics of flow interaction are preserved. Initially flow interaction may result in cyclical waxing and waning of flow velocity, with related oscillations of flow competence and capacity thus resulting in turbidites with discrete grain-size pulses. However, it is not apparent *a priori* if flow dynamics enabling such cyclical variation of flow velocity can be maintained during flow run-out.

Here we present the findings of an experimental study of the flow dynamics of interacting density currents. Lock-exchange density currents were studied, where twin lock-gates allow the generation of interacting flows. Through staggering the release of the flows a cyclical variation of waxing-waning flow velocity is generated. However, experiments show that the front positions of the staggered density currents merge. From the merging of the flows it is inferred that cyclical variation in flow velocity ceases, as one uniform flow is generated. Therefore flow merging is of significant interest in determining how far from source signals of interacting flows may persist, and thus where palaeo-seismic reconstruction from turbidity current deposits may be conducted.

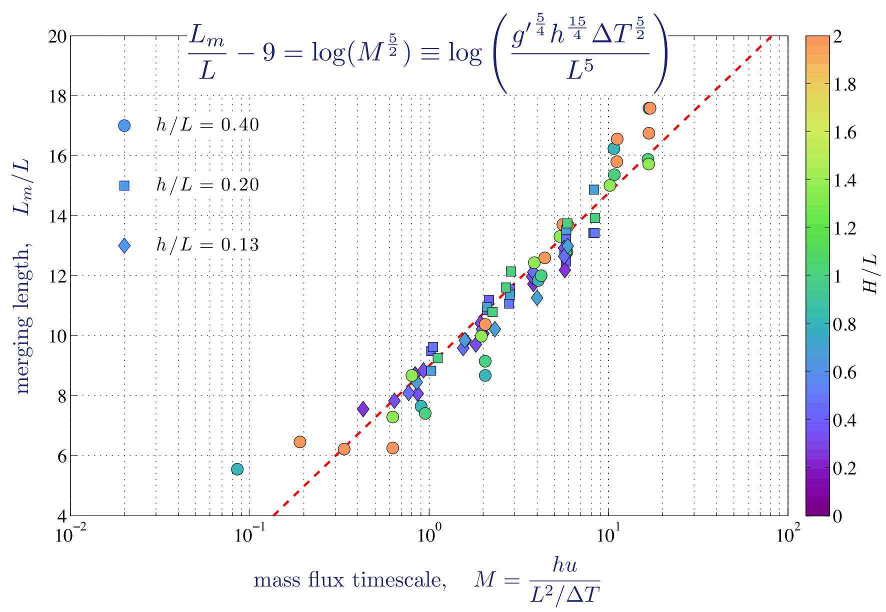

Figure 1. *The merging length scale of staggered release density driven flows. Here g' denotes reduced gravity, h initial flow depth, H ambient flow depth, L lockbox length, L_m merging length and ΔT staggered gate delay time.*

The experiments conducted parameterize flow merging as a distance from source, a feature characteristic of initial experimental conditions. Key initial conditions include the staggered delay time between lock-gate releases, flow depth, density and viscosity and lockbox length and height. Through systematic variation of these initial flow conditions, the experimental study considers a range of values of key dimensionless variables that scale laboratory to real-world settings. From a series of 108 experiments, a remarkable log-linear relationship between dimensionless merging length and dimensionless mass-flux is observed (see Figure 1). From this empirical model the probabilistic range of merging lengthscales in natural systems has been estimated.

NOTES:

A mechanistic model for channel-lobe transition zones: implications for downstream flow dynamics

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Channel-lobe transition zones (CLTZ) have been understood in terms of their planform geomorphology, marked by prominent scattered offset scours, and sediment waves downstream, however the mechanisms for initiating and maintaining these zones have not been clear. Models have typically been restricted to considering a single large hydraulic jump at the base of slope. However it has been unclear how an array of scours forms under such a large jump. Furthermore, experimental studies have shown that such hydraulic jumps are associated with rapid sedimentation of material from suspension, in marked contrast to the extensive areas that CLTZs can extend over. Here we detail the first process model of channel-lobe transition zones, based on a detailed field investigation of a saline gravity current in the southwest Black Sea. In the Black Sea we analysed the three-dimensional flow structure and dynamics of a series of linked hydraulic jumps in stratified, density-driven, flow. These field observations were collected using an acoustic Doppler current profiler mounted on an autonomous underwater vehicle. Field observations suggest a newly identified type of hydraulic jump, that is a stratified low Froude number (<1.5-2) subaqueous hydraulic jump, with an enhanced ability to transport sediment downstream of the jump, in comparison to hydraulic jumps in other subaerial and submarine flows. These novel field data underpin a new process-based conceptual model of channel lobe transition zones that explains the scattered offset nature of scours within such settings, the temporal variations in infill and erosion between adjacent scours, how bed shear stresses are maintained across the CLTZ, and why the locus of deposition, and the formation of sediment waves is so far downstream of the scour zone. The model also suggests that CLTZ flows have Froude numbers below those required for the formation of cyclic steps, suggesting that such features may dominate the continental slope, but are unlikely to be present downstream of CLTZ unless channel slope dramatically increases.

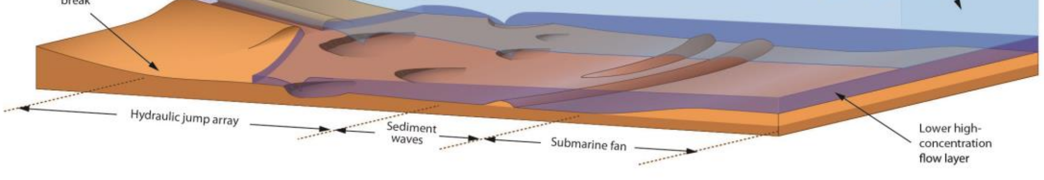

Figure 1. Schematic channel lobe transition zone showing an array of low Froude number hydraulic jumps occurring at a proportion of scours. The position and proportion of active hydraulic jumps likely varies between flows and as a given flow waxes and wanes. Maintenance of bed shear stress, and local enhancement of suspension downstream of jumps, leads to the primary locus of deposition being beyond the scour field.

NOTES:

Poster Presentation Abstracts

Day One

Width variation around submarine channel bends

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Submarine channels occur worldwide on passive and active continental margins with a vast diversity from isolated deep ocean channels to submarine fan channels and from high to low latitudes. They are involved in a wide range of deep-water processes from continental margin evolution, as conduits for sediment and nutrient transport from the continents to the oceans, and as targets for hydrocarbon exploration. One enigma in submarine channel research is the process of channel evolution in submarine channel bends and hence their associated flow and sedimentation processes. From laboratory experiments and models, it is recognised that submarine channels can have a different flow structure compared to rivers, which leads to different sedimentary deposits and architecture. However, all generic studies of submarine channels, through physical experimentation and numerical stimulations have assumed that bends exhibit a constant channel width. This would be in marked contrast to rivers, where a width variation around bends is typically observed, which in turn is strongly linked to sediment patterns, bend migration, and channel evolution. Here, we report the first analysis of width variation around modern submarine channel bends. Knowledge of width variation around bends would help improve reservoir models. Such knowledge may also address a key paradox in our understanding of submarine bend evolution. Observations of modern submarine fan channels on passive margins from seismic data, suggest that submarine channel bends dominantly evolve via lateral bend expansion. However, process-based models of sedimentation, based on physical experimentation and numerical stimulations suggest that bends should preferentially migrate downstream. One possible answer to this paradox is that submarine channel bends exhibit a width variation around bends, rather than the constant width channel modelled to date.

Continuous Signal Propagation in the Indus Submarine Canyon since the Last Deglacial

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Transport of sediment through canyons on continental margins is one of the primary processes responsible for building submarine fans in many deep-sea basins. These fans are not only of economic interest as hydrocarbon reservoirs but are potentially high-resolution archives of changing environmental conditions in the onshore drainage basins. In addition, submarine fans also form the largest sediment bodies on Earth and are largely supplied through their canyons. Such sediment records could allow the relationships between climate, tectonics, erosion, and
weathering to be investigated on a number of time scales if the sediment transport can be understood, in particular the degree of reworking and "signal shredding". Earlier models for sediment transport through such canyons indicated a dominant role for sea level in controlling this flux, but this largely ignored the role played by climatically modulated sediment delivery.

Therefore, the main focus of our research is to understand how sediment transits through the submarine canyon to the deep-sea basin. Specifically, does sea level or sediment supply modulated by climate dominate in controlling the flux through the canyon into the deep sea?

Assuming this can be established, how can we use the deep-sea sediment archive to understand continental erosion and environmental evolutions?

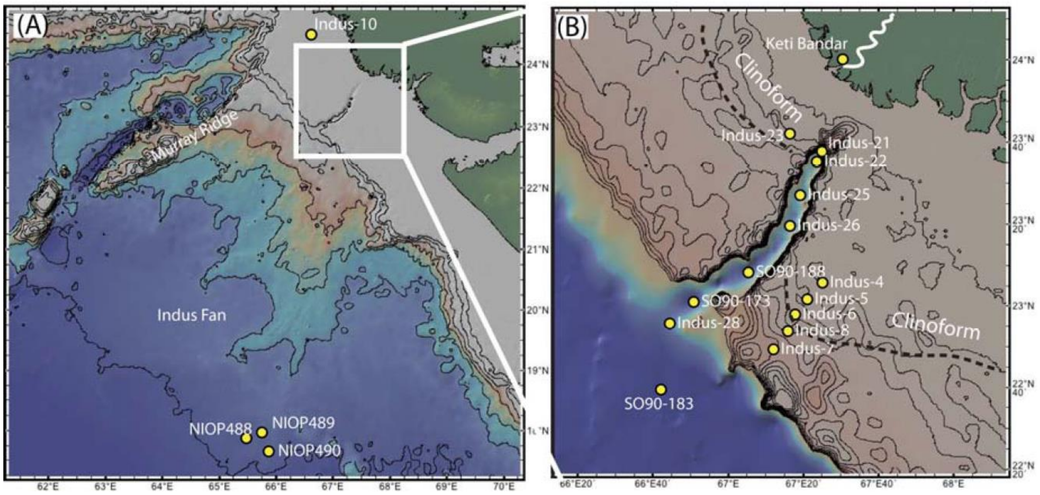

Figure 1. (A) Bathymetric map of the northern Arabian Sea showing the location of the Indus delta, as well as the deep-sea cores already dated from the upper fan [Prins et al., 2000]. (B) Close-up of the region around the Indus Canyon showing the location of the cores collected in the 2008-2008 RV Pelagia cruise, as well as the early RV Sonne cores. Note the much more extensive development of clinoforms on the eastern side of the canyon [Giosan et al., 2006] and the proximity of the river mouth to the head of the canyon. Dashed lines show locations of the top of clinoform foresets.

Sediment supply and sea level interact to control the sediment flux to deep-water submarine fans. Classic sequence stratigraphic models argue that submarine canyons and their associated deep-sea fans should become inactive during periods of rising and high sealevel as accommodation space is generated on the continental shelf. Initial data from the upper Indus Submarine Fan had suggested that this system largely follows this model, as turbidite sedimentation ceased around 11 ka. Cores from the canyon (Fig. 1) now show that the situation is more complex, with sediment propagating deep through the shelf canyon during the entire Holocene. Although worldwide some fans continue to be active during sea level rise, the source of sediment is not always clear and may be dominated by recycling in high energy coastal areas. We present new age and provenance data from a variety of cores covering the last ~20 ka that show continuous deep-water sedimentation through the Indus submarine canyon since at least ~11 ka, despite the cessation of sedimentation on the upper fan around that time. Large volume turbidite flows mantled terraces >200 m above the thalweg throughout the Holocene and their deposits show trends in lithology and geochemistry which coincide both with rising sea level and times of strong summer monsoon in the Early-Mid Holocene. For the first time we use Nd-Sr isotope compositions to show that canyon sediments are similar to the Holocene river mouth suggesting direct supply from the river into the deep water system, with no more than ~8 k.y. of possible buffering (e.g., retention), and likely much less during the Early-Mid Holocene (5.5–12 ka). Significant reworking of older sediments during sea level rise can be excluded, so that the deep-water sediment in the canyon contains a direct record of the Indus River sediment load. Thus signal shredding within the canyon appears to be limited, at least since ~14 ka, suggesting that climatically modulated sediment supply dominates over sea level in controlling canyon sedimentation in high sediment supply settings. Our study allows the difference between reworking within the canyon and direct supply from the river to be resolved for the first time in a major submarine canyon.

Sedimentology and Fracture Characterizations of Kebobutak High Density Volcaniclastics Turbidite as Reservoir Analogue : Quantitative Analysises in Enhancing Reservoir Quality

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Volcaniclastic reservoir is quite challenging in petroleum exploration especially in Indonesia who has vast volcaniclastic product. In order to understand the character of reservoir in volcaniclastic product, it is needed a thourough study of volcaniclastic product. This research is employed by fieldwork at Kebobutak Formation, the northern trend of Southern Mountain Arc approximately 3 km from Jiwo Hill right on Kali Cermo River at Baturagung Mountain. The purpose of this research is to reveal sandstone character of submarine volcaniclastic turbidite for further research which involving volcaniclastic product especially for reservoir analogue.

Measuring section employed to understand the sandstone distribution and sedimentation mechanism. Thin section and laboratory analysis used to determine the composition and diagenetic procces which controlling primary and secondary porosity. Scanline tape section and fracture density measurement also used to identifiy secondary porosity orientation characteristics which caused by tectonic.

Measuring section resulting stacking pattern of coarsening and thickening upward of high density turbidite volcaniclastic sequences. Depostional process initiated from sandstone high density turbidite of Lowe Sequences (1982) with no mud interval and ended on liquified flow of contourite sandstone. Many samples from different lithofacies have been observed, the grain size distribution range from cobble (64 mm/-6 phi) to fine sand (0.125 mm/3.0 phi), poorly sorted to medium sorted, hard to very hard, and angular to sub-angular. Petrographic description shows the Lithic Greywacke composed by 7 % Quartz, 23 % Feldspar, 1 % opaque mineral and 69 %, immature for both textural and compositional maturity. Diagenetic processes showed by clay impurities, secondary porosities and silica cementation. Sandstone with 3-10 % porosity resulted by diagenetic processes and intergranular porosity of volcaniclastic product could not help the reservoir quality. Scanline tape showed the fracture characteristic and orientation are interconnecting fracture ranges from NE-NW orientation. Hydraulic fracturing with sigma 2 orientation of initial fracture is a better option to enhance porosity on volcaniclastic product especially with initial porosity consideration. Keywords: Analogue, Kebobutak Formation, Volcaniclastic Turbidite, Reservoir, Treatment.

The Deep-Marine Architecture Knowledge Store: a database approach to enhance meta-analyses of deep-marine systems.

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A great number of studies of deep marine clastic systems have been completed, with more studies accreting all the time. These studies encompass modern systems, outcrop and subsurface successions, studied through a wide range of approaches. From relatively early in the history of such endeavours, workers have attempted to synthesise models describing how these systems are constructed, linking observations across a wide range of scales. Although many such syntheses have been compiled with great insight and have been highly influential, often they result from subjective analysis, supported by qualitative, or at best semi-quantitative data. A key challenge has been, and largely remains, to devise approaches to data description that allow fully quantitative, meta-analyses of multiple case studies. Ideally, meta-studies permit objective determination of what rules of organisation (if any) deep-marine clastic systems exhibit, and further allow multi-variate analysis to assess how boundary-condition variations – singly or in concert – alter organisational styles.

A new database approach – termed the Deep-Marine Architecture Knowledge Store (DMAKS) – has therefore been developed, which aims to store the variety of deep-marine sedimentological data in a manner that will allow compound analyses between multiple datasets, impartial to the studies original models, data types or scale of observation. Earlier database approaches (e.g., Baas et al., 2005, Petrol. Geosci., 11, 309-320) have demonstrated the utility of database systems that store an array of data on sedimentary architecture along with parameters that describe the depositional systems, particularly in relation to their ability to provide quantitative data outputs. However, previous approaches have been found lacking in their ability to describe the spatial organisation of sedimentary and geomorphic units. The DMAKS has therefore been designed to allow architectural entity relationships to be stored, not only in terms of their position in 3D space but also within a hierarchical framework. To ensure the DMAKS is able to compare consistently defined data from a variety of deep-marine datasets the data-entry procedure also acts as a method of data standardisation. This in turn provides a firm foundation for multi-study analyses of aggregate datasets.

Initial querying confirms the database as a useful predictive tool, for example the databases quantifiable records of architectural-unit spatial relationships allows likely unit transitions to be queried based upon any chosen set of depositional controls. The database approach can be applied to test the effect of boundary conditions on resulting sedimentary architecture. Quantitative data can be derived from the database and employed to assess the range of applicability and accuracy of current models describing sedimentary architecture, e.g. facies models or sequence stratigraphic models. For example, it is possible to test the degree of variability seen within a system's architectural styles and whether proposed facies models can be applied to other similar deep-marine systems. The interrogation of data from a sandy-fan case study in the Golo basin (East Corsican margin, Mediterranean Sea) has allowed the original two-end-member lobe model of Deptuck et al., 2008 (Sedimentology, 55, 869-898), to be tested based upon DMAKS' ability to appraise multi-factor controls as well as integrate data from other studies of the same system. Overall this has allowed a broader study to take place in assessing whether distinct end-member types can be identified within the Golo basin, e.g., through comparisons of width-to-thickness aspect ratios, shape types, grain size, and transition statistics for element type. Such quantitative outputs will also permit more fundamental theories in deep-marine sedimentology to be tested, for example whether architectural hierarchy is scale dependent or whether a recurrent 'hierarchy' does truly exist, in which common discrete hierarchical levels can be identified. As well as facilitating academically focused meta-data enquiries, the database can also be used to characterise likely facies architecture and lithology distributions at the sub-seismic scale given knowledge of the boundary conditions of system formation.

Hierarchy and facies distribution in turbiditic sandstone channel-fills: the Gorgoglione Flysch Formation (Miocene of Basilicata, Southern Italy)

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Turbidite channels are among the most important deep-water hydrocarbon reservoirs currently being explored. Advances in the understanding of these depositional systems result from improvements in modern 3D seismic imaging, showing their three-dimensional stratal and architectural complexity. However, spatial variability of reservoir properties is associated with differences in the nature of channel fill and their stacking patterns, which commonly occur at scales below the resolution of 3D seismic datasets. To improve the characterization of subsurface channel systems, channel-fill properties can be investigated by means of outcrop studies.

A field-based study is presented from the Gorgoglione Flysch Fm, a Miocene turbiditic succession exposed within a piggy-back basin in the Southern Apennines of Italy. Three main coarse-grained sequences of conglomeratic-arenaceous bodies defining channel belts are recognized in the northern proximal part of the basin. The lower belt has a limited exposure and is characterized by a fining-upward succession of amalgamated extrabasinal conglomerates and coarse-grained sandstones, unconformably overlying older tectonic units of the Apenninic orogenic wedge. The central and upper channel belts overlay extensive large-scale erosional surfaces and include 30 to 45 m thick amalgamated sandbodies, systematically stacked to form channel complex-sets that are laterally associated with tabular sand-prone heterolithic overbank deposits. The central channel belt is widely exposed throughout the entire study area and gradually thins from 400 m to 20 m in thickness towards the SE. The upper belt shows a more abrupt SE-ward thickness decrease, punctuated by a lateral and upward evolution from amalgamated channelized sandbodies into isolated and elongated coarse-grained channel-fill deposits, 4 to 35 m thick. This upward evolution is associated with a gradual change in the background sedimentation, dominated by mud-prone heterolithic deposits.

Systematic bed-scale sedimentological logging measurements reveal a recurring motif of five main facies forming a distinctive channel-fill facies-association, allowing the reconstruction of the evolution of turbiditic channels. From base to top, the evolutionary pattern of an ideal channel-fill facies association includes: i) a conglomeratic basal lag documenting significant incision and sediment bypass; ii) normally-graded, structureless or planar laminated, coarse-grained sandstones, associated with the main backfilling phase; and iii) large-scale cross-stratified sandstones with diverging palaeoflow directions, related to a progressive reduction of channel confinement. At the larger scale, the observed stacking pattern can be related to compressional in- and out-of-sequence tectonic pulses (that drove the eastward migration of the Apenninic thrust front during the late Miocene). The tectonically-driven confinement of the depositional system within the narrow basin influenced the sediment distribution and may have controlled the stacking pattern of the turbiditic channels. The limited lateral extent of the lower channel belt is related to the progressive filling of irregularities of the basin floor. The lateral migration of channels within the central and upper channel belts was likely limited because of the narrow available space within the basin and lateral tilting associated with both in- and out-of-sequence thrusting; sedimentation took place under net aggradational conditions without avulsion.

The vertical architectural and grain-size evolution of channel types (from amalgamated sand-filled channels to isolated conglomerate-rich channels), together with the gradual upward change in the background sedimentation (from sand-prone to clay-prone heterolithic deposits), likely reflects a shift along the depositional profile, passing from a near base-of-slope to a slope setting, following the progressive infill of the primary confinement and a general progradational trend. Similar evolutionary histories have been recognized in other ancient turbiditic systems.

The role of mass wasting in the progressive development of submarine channels (Espírito Santo Basin, SE Brazil)

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Mass-wasting processes can have a significant impact on seafloor morphology and sediment distribution on continental slopes. Understanding the interaction between mass-wasting related topography and turbidity flows thus can help to predict the volumes and distribution of sand-prone reservoirs.

A submarine channel system influenced by a localized mass wasting is here studied using high-resolution 3D seismic data from the Espírito Santo Basin, SE Brazil. In a confluence region created by salt diapirs, four channels and an underlying mass-transport deposit (MTD) were recognized in the Pliocene-Quaternary Rio Doce channel system. The cross-sectional area of the channel system in the confluence region can be up to 1.2 km^2, which is 4 to 10 times larger than other parts of the channel system. Such a significant increase in channel size is interpreted to have resulted from the interaction between mass-wasting processes and turbidity flows. An erosional scar was created by mass-wasting processes and was filled by an MTD. The scar was later used as preferential pathways of turbidity flows, which were captured by the headwall and lateral margins of the scar. The captured turbidity flows widened the scar greatly but with small modification in the scar height. Part of MTD within the scar was removed downslope by the turbidity flows, and was replaced by a large amount of channel-fill deposits.

This paper shows that erosional scars can confine and facilitate flow channelization, which are keys to channel initiation. We postulate that the more erosive and frequent flows are captured by the scar, the larger is the accommodation space created for succeeding sand-prone turbiditic sandstones. The replacement of MTD by channel-fill deposits within the scar has profound implications for reservoir volumes and net-to-gross ratios in channel systems. This replacement partly depends on the flow properties of turbidity flows, such as their erosive ability and frequency.

Day Two

Architecture of partial-avulsion channels in the Niger Delta slope

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This study focuses on distributary channels that have been commonly found in deep-water settings. There are primarily two types of distributary channels in the Niger Delta slope: full-avulsion and partial-avulsion channels. Compared with the previously well-documented full-avulsion channels, partial-avulsion channels, as first recognised in this work, remain poor understood. This work uses 3D seismic data from the Niger Delta slope to investigate the architecture, controlling factors, and evolution models of the partial-avulsion channels, to assist in better understanding deep-water channels. The origin of partial-avulsion channels is linked to stripping flows from feeder channels, which leads to fining-grains deposits and fining-upward successions in the studied channels. The varying slope gradients and associated change in the erosional ability of stripping flows, are the dominant controlling factor to the external architecture of partial-avulsion channels. The channels exhibit straight morphology (very low sinuosity) in plan view without outstanding levees. Vertical profiles of channels change from dish, U, V to bowl shape along the flow direction. Linear trains of discontinuous residual pockmarks are another important factors in the external architecture of partial-avulsion channels, which provide not only natural conduits for the stripping flows but also micro-morphology condition for the formation of hydraulic jump. The change in stripping flow parameters with respect to the thickness or density of the stripping flow leads to the development of different internal architectural element types (from erosional to aggradational). The evolution of the interpreted channels experiences four phases: Phase 1 is characterised by partially filled pockmarks, and by steep slope with localised patches of relatively gentle gradients ; Phase 2 is characterised by the formation of flow conduits and backfilling of sandstone and sandy mudstone; Phase 3 is characterised by the enlargement of flow conduits and the deposition of mudstone and sandy mudstone; Phase 4 is characterised by the hemipelagic draping and the deposition of mud turbidites.

Clinoform degradation, mass-transport complex (MTC) emplacement, and the healing of outer-shelf relief: a 3D seismic reflection case study from the Santos Basin, offshore Brazil

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Sediment is typically delivered to submarine slopes by a combination of wave-, tide- and river-influenced deltas that prograde across the slope to the shelf edge, and strike-fed slope mudbelts. Both of these processes drive the construction and progradation of continental margins. However, slope degradation and collapse is a common process on many continental slope margins, resulting in remobilisation of previously deposited material onto the lower slope and basinfloor. Our understanding of how these process vary in time and space, and how they contribute to the long-term development of continental margins, has been greatly enhanced by field-based studies, although such studies are typically limited to observations from broadly two-dimensional, depositional-strike or –dip orientated outcrop belts.

Here we use a pre-stack time migrated 3D seismic reflection survey located in the Santos Basin, offshore SE Brazil to investigate the role that outer shelf-to-upper slope collapse, MTC emplacement, and subsequent slope reestablishment have on margin progradation. These data image a series of early Palaeogene, south-eastward dipping clinoforms, which prograded out into the South Atlantic Ocean. Periodically, large tracts of the outer-shelf-to-upper slope collapsed, resulting in the formation of a strongly scalloped margin. Margin collapse resulted in the emplacement of at least two slope-attached MTCs on the proximal basinfloor. The basal surface of the lower MTC is characterised by deep (c. 10 m), slope parallel grooves, whereas more irregular relief defines the top of the composite MTC body. Within the MTCs themselves, we identify a range of kinematic indicators indicative of extension and compression within the body of the parent flow during translation and arrest. Margin collapse also generated accommodation on the outer shelf-to-upper slope; this accommodation was filled by river-fed deltaic clinoforms that nucleated at the margin-collapse headwall scarp, and which prograded basinwards, downlapping onto the underlying MTCs and facilitating renewed margin construction.

We show that numerous degradational and constructional processes drive net-progradation of continental margins, and that these processes and their products lead to the development of a range of stratigraphic trap types.

Various Composition of Miocene Deep Water Kerek Turbidite in Isolated Basin, Western Kendeng: Tectonic Setting during Basin Growth and It's Implication for Reservoir Quality

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Kendeng Zone occupies the North East Java basin as an isolated basin. Kendeng Zone divided into 3 parts consists of Western Kendeng, Eastern Kendeng and Central Kendeng. Physiographically, Western Kendeng located between Sunda Shelf in the northern part and Southern Mountain Arc in the southern part border who took parts as provenance to Kendeng Basin. Miocene sedimentary rocks identified in Kendeng Basin including channelized volcanic lithic conglomerates, volcanic lithic-rich sandstone, tuffaceous mudstone. Western Kendeng stratigraphically consists of Pelang Formastion, Kerek Formation, Kalibeng Formation, Kaligetas Formation, Damar Formation. Important part of our research focused on Kerek Formation which exposed ranges from southern to northern part of Western Kendeng which known to be a potential deep water reservoir.

Provenance study is needed to understand the composition abundance of volcanogenic sandstone. Measuring section from southern to the northern part of western kendeng was employed and granulometry analysis used as additional data for transport mechanism. Thin section analysis also employed to know the signification of composition influence to diagenetic process related to reservoir quality. This paper provides detailed facies and composition abundance of Kerek Formation and it's implication on reservoir quality of sandstone.

Detailed measuring section show that transportation mechanism of sandstone is turbidity current, sometimes found slump and liquified flow. Many samples have been identified for each provenance comperehensively from southern to northern part as Undissected Arc to Dissected Arc province and from Craton Interior to Basement Uplift in southeast basin border. Decreasing volcanic material to the northern part and increasing siliciclastic and calciclastic affected the diagenetic process. Generally, north-south porosity ranges from 7-25 % with classification poor-good porosity. Fossil data showed that the benthic forams lived on neritic-bathyal and planktonic forams have lived from approximately middle miocene to late miocene. By knowing the variation of sandstone composition of Kerek turbidite deposites which ranges within the basin, the best option of exploration target is the turbidite which composition which has both mature textural and composition maturity.

Analytical approaches to modelling the inflation of ponded turbidity currents and implications for forward modelling confined basin fill

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Confined minibasins settings (e.g., salt-withdrawal, structurally-controlled or MTD-related bathymetric lows) can host prolific hydrocarbon reservoirs. In characterising the fill of such basins, key questions include:

- What is the net-to-gross evolution of the basin? When minibasins are fully-confined, all of the material that turbidity currents carry into the basin remains there, potentially decreasing the net to gross, as mud that might ordinarily bypass the areas of sand deposition in unconfined settings will be co-deposited with the sand. Conversely, if flows are only partially ponded then the finer grained component of the suspended sediment load may bypass.
- What is the architectural style of basin fill? Field studies tend to suggest that turbidites deposited within such settings are generally tabular in style, suggesting that autogenic processes such as lobe development and compensation are suppressed in some way by the confinement; yet intuitively at larger basin scales, lobe compensation should be expected. These two scenarios entail rather different lateral connectivity of the basin fill, so it would be useful to know what scaling parameters affect the transition between them. In addition, how abruptly will the transition from fill to spill to bypass be expressed in the record?
- What facies types can be expected in minibasins fill, and will they vary spatially? Any of conventional turbidites, hybrid event beds and locally- and remotely-derived mass transport deposits as well as hemipelagite may contribute to basin fill.
- What is the onlap character of the confined deposits? How far up the slope is sand carried, and can the apparent base-of-slope trajectory in seismic data be inverted to predict basin fill character?

To date, combinations of field, seismic, physical modelling and 1- or 2D statistical approaches have been applied to studying these questions. Here we describe the constraints to interpretation provided by a mathematical modelling approach to turbiditic basin fill.

Turbidity currents entering confined minibasins can be fully or partly trapped by the confining slopes and become ponded. A 'ponded cloud', a sediment bearing cloud thicker than the original flow and characterised by a flat and non-turbulent upper detrainment interface can be generated. The sediment cloud is characterised by an inflation phase (during which the height of the cloud increases), followed by the establishment of a quasi-steady state. The architecture of minibasin fills and the variability of sand termination geometry against the confining slopes is controlled by the interplay of sedimentation and basin subsidence. However, the height reached by the ponded cloud is a key control on the amount and extent of sand deposited on the confining slopes. Here we use numerical modelling to estimate the likelihood of ponded clouds inflation in the full range of realistic field scenarios. Conservation of suspended mass is used to model the ponding and inflation of a topographically confined sediment laden density driven flow. The density driven flow is defined by a fluid flux, given by the mass of suspended material transported into the basin over the duration of the flow. A simplified basin geometry is assumed, with variable sidewall slopes, length, and width; the bathymetric relief of the basin is defined. Upon entering the basin the flow is assumed to rapidly expand to the sidewall width, travel across the basin with a depth averaged head velocity. Net deposition and entrainment are initially assumed negligible. Flow depth is defined implicitly, as is the time taken for the flow to travel across the basin and reflect off the distal slope. On the distal slope the maximum run-up height is defined by the balance of kinetic energy lost to potential energy gained. After the flow has traversed the basin, integration of the mass conservation equation, yields the change in total suspended sediment mass. Initial numerical modelling results suggest that under a broad type and range of flow conditions and of realistic basin and deposit scenarios, significant inflation of a sandy ponded cloud in a deep-water basin is unlikely. It follows that the tabular architecture often observed in the deposits of ponded minibasins is unlikely to be generated by deposition from an inflated ponded cloud. Alternative processes such as deposition from a current reflected off the confining slopes one or several times might therefore be responsible for a significant part of the deposit.

This modelling approach helps forward modelling of confined basin fill architecture, both under unvarying input conditions, and also during changes in characteristic flow size, grain size distribution and frequency (with respect to e.g., the rate of hemipelagic sedimentation). A goal remains to apply this approach to invert the seismic architecture of remotely imaged minibasins fill successions to predict net to gross, architectural style, facies distribution and onlap character.

A global database of subaqueous landslides: A rallying call to the deep-water community

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The global importance of subaqueous landslides

It has been widely recognized that subaquatic landslides are common in lacustrine and marine environments. They pose a risk to coastal communities and offshore infrastructure. They can play an important role in the distribution and diversity of deep-sea ecosystems. Furthermore, their deposits can have importance for hydrocarbon exploration and production activities, acting as potential seals, and in some cases reservoir units. During the past decades geoscientists have made many important contributions towards the improved understanding of submarine landslides. Efforts by the geo-modelling community have helped fill the gap between submarine landslide occurrence, dynamics and tsunami genesis. However, our lack of understanding of the causal mechanisms and timing of submarine landslides has hampered progress in the development of deterministic and probabilistic assessment tools which are essential to implement appropriate mitigation measures.

Significance of Modern and Ancient Submarine Slope LandSLIDEs (S4SLIDE)

Complex issues like these can only be addressed via a multidisciplinary approach. Interest in the study of submarine landslides spans a wide range of sub-disciplines: geologists studying the link between climate change and gas hydrate dissociation, planetary geologists using submarine landslides as terrestrial analogues, petroleum geologists evaluating the seal/reservoir capacity of ancient submarine landslides, and engineers evaluating geotechnical risks. The S4SLIDE project (*Significance of Modern and Ancient Submarine Slope LandSLIDEs*) builds upon the extremely successful E-MARSHAL and IGCP-511 proposals also known as the Submarine Mass Movements and Their Consequences project. As with its predecessors, the IGCP-640 project focuses on facilitating the interaction of scientists, engineers, industry and government representatives, and other parties interested in submarine mass movements and their geohazard potential, especially those from historically under-represented countries. S4SLIDE seeks to create an international and multidisciplinary platform allowing geoscientists from academia, government, and industry to sustain a dialogue conducive to the integration of findings from different fields into a more cohesive understanding of submarine landslides.

The need for a coherent global database of subaqueous landslides

Many developments have been made in the recent years on improving our understanding of subaqueous landslides in a number of different settings, in both modern and ancient timescales. The S4SLIDE community recognises, however, that there is still a large amount of valuable data that is underexploited and stored in many disparate databases. We see much value in building a coherent and peer-curated global database of consistent subaqueous landslide data that can be made available to a large number of end-users, to advance: 1) the understanding of subaqueous landslides, and 2) to support complementary research. Here, we outline the plans to bring fruit to this aim and encourage interested parties to become involved in this truly global initiative.

Initial steps have been taken to understand what existing databases exist. These include multiple formats and delivery platforms, and include a variety of data. Each database type has its strengths and weaknesses; we aim to learn from this. We are keen to hear from individuals whose work concerns any aspect of subaqueous landslides as to how they would use such a database, such that it is built in the most appropriate manner. Key aims of the S4SLIDE database will be to: 1) Make the most of existing databases and compendiums of quantitative landslide data; 2) Identify what is missing from some and that ours is as comprehensive as possible; 3) Ensure inclusion of valuable data that are often excluded (e.g. geotechnical, exploration seismic data); 4) Ensure that the database can be accessed by the widest array of users possible to tackle important scientific, economic and societal questions.

Data within the S4SLIDE Database

High level information held within the relational database will include, but not be limited to:

- Data from both submarine and other subaqueous (e.g. lake) settings. There is much to be learned by cross-pollination between lacustrine and marine studies. This link has been underexplored to date
- Metrics on “recent” mass movements (i.e. those that can be mapped from seafloor survey data)
- Broader information that may be acquired from coring or other vertically well-resolved, but laterally limited data sources (e.g. long term recurrence of landslides)
- Sub-surface geophysical information (e.g. 2D or 3D exploration seismic) that can provide valuable information on ancient landslides or that is not possible from high resolution seismic or core data.
- Geotechnical information, which may include IODP physical properties, in-situ testing, classification and advanced laboratory testing. This will ideally include both characterisation of mass movement deposits themselves, but also of background conditions of unfailed material to enable region or site-specific slope stability analysis, or address why slope failures are different in different areas.
- Links to global tsunami models/databases
- The potential for inclusion of outcrop data from well-studied type examples.

It is recognised that the resolution and completeness of the database will vary, but that is important and will enable a global data gap analysis. Which areas are less well understood, for example, and where should future efforts be place?

Future steps

It is proposed to use an open-access platform for the database; application of the Google Earth Engine is being explored to enable the storage of large file sizes and complex relational functionality. A trial is underway to incorporate an existing database from the Israel continental slope, which features 150 submarine landslides. Here we present some of the recent developments and plans for the future.

Interested parties, from data sharing through to end-users, are encouraged to make contact with the authors.

3D stratigraphic modelling of the Congo turbidite system since 200 ka: towards a hierarchization of factors controlling sedimentation

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If the geometry and internal functioning of turbidite systems are relatively well-constrained, the respective role of autogenic (topographic compensation, dynamics of turbidity currents…) and allogenic factors (tectonic, sea-level variations, climate) governing their architectural evolution is still under debate.

The architecture of the Late Quaternary Congo fan is characterized by successive sedimentary prograding/retrograding cycles reflecting a periodic control of sedimentation (Picot *et al.*, 2016). A strong link with climatic forcing has been proposed, evidenced by changes in fluvial sediment supply consistent with both monsoon intensity variations and glacial/interglacial transitions at the origin of vegetation cover evolution in the Congo catchment area (Picot, 2015).

In the light of these results, the aim of this study is to simulate and investigate the relative impact of internal and external forcing factors controlling, both in time and space, the formation and evolution of depocenters since 200 ka. This work represents the first attempt to model in three dimensions the stratigraphic organization of the Congo turbidite system using Dionisos (IFP-EN), a diffusion process-based software. It allows the simulation of sediment transport and the 3D geometry reproduction of sedimentary units, from deltaic to deep-sea environment, based on physical processes such as sea level changes, tectonics, sediment supply and sediment transport.

Preliminary results confirm that the perennial topographic compensation acts as a key parameter but also reveal that a periodic variation of fluvial sediment discharge is necessary to recreate prograding/retrograding cycles and upfan avulsion events. The ongoing work will decipher the nature and timing of allocyclic factors responsible for water and sediment fluxes changes. In particular, three potential controls will be discussed: (i) seasonal evolution of the water discharge assuming annual dry and wet epochs in the Congo River, (ii) cycles of the West African monsoon in relation with precession of the equinoxes and finally (iii) climate oscillations during glacial and interglacial periods.

The stratigraphic modeling allows us to propose an evolutionary “source to sink” model of the Congo deep-sea fan development, emphasizing the close interconnection through time between drainage basin changes and sedimentary transfers in deep-water basins.

Architectural changes in a coarse-grained deep-water system deposited above a Mass Transport Complex (MTC)

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Local gradient changes and variable accommodation characterize the upper surface of mass transport complexes (MTCs). The associated bathymetric variability can influence the longitudinal and vertical processes occurring within coarse-grained sediment gravity flows, which are challenging to interpret from the rock record alone. Here we document an exhumed deep-water succession from the Los Molles Formation, Neuquén Basin, Argentina to investigate the facies types occurring within and the architecture of, coarse-grained beds deposited above a seismic-scale MTC (20-60 m-thick).

The study area is a 12 km-long oblique downdip section within which individual beds are correlated between 21 measured sections (1:25 scale). The stratigraphic succession comprises a 25-70 m thick, sandstone-rich division (69% sandstone) containing two units (Figure 1). Unit 1 comprises a lower heterolithic succession, grading upwards into a sandstone-prone succession that consists in poorly sorted, very coarse to fine-grained, thin to medium bedded sandstones with pebble-sized clasts. Sandstone beds in Unit 1 have a poor bed continuity, high amalgamation and abrupt lateral pinch-out, with evidence for erosion, sediment bypass and lateral facies changes occurring over short down-dip distances (<100s m). Unit 2 is characterized by three thick and laterally extensive, conglomeratic event beds intercalated with thin to medium bedded very coarse- to coarse-grained or fine-grained sandstones, siltstones and mudstones. Conglomeratic event beds have a very poorly sorted, granular to medium-grained, mud-rich sandstone matrix, supporting polygenic gravels (ranging from pebble to boulder size) and large clasts from the underlying strata (Figure 2). The base of the conglomeratic event beds can be amalgamated over long distance and show local thickness variations related to compensational stacking and enhanced basal erosion.

The vertical stacking of component facies with significant lateral offset, together with the increase of lateral bed extension and thickness upwards, indicates a progressive decrease of confinement from Unit 1 to Unit 2. The MTD-related topography controlled stratigraphic trapping of considerable sand volumes in Unit 1. Once the MTC-related accommodation was filled, relief associated with individual supra-MTC sandbodies produced subtle changes in depositional processes in the Unit 2. The changes of depositional processes and associated spatial segregation of material transported conferred a significant bed heterogeneity downdip local topographic highs and controlled internal bed architecture. We infer that the sandstone-rich division corresponds to a lobe complex emplaced by an out-of-equilibrium sand-rich system. The sand-rich system was fed by unstable flows sensitive to seabed topography and close to an erosional state with intermediate turbulent-laminar behavior. Predictive stratigraphic outcrop-based models can provide insights into spatial distribution and internal architecture of heterogeneous sandbodies able to generate multiscale net/gross variations that make-up the internal complexity of subsurface reservoirs hosted in lobes above MTCs.

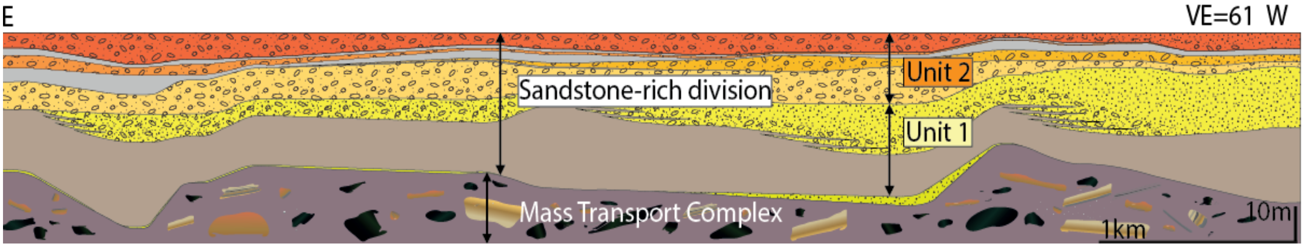

Figure 1 : Sketch showing the stacking patterns of units in the sandstone-rich division of the Middle Jurassic Los Molles Formation.

Figure 2 : Example of a conglomerate event bed in the Unit 2.

Day Three

Prograding Submarine Fans Mark Earlier Deformation in Transitional Kendeng-North Serayu Basin, Java

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Prograding turbiditic submarine fans sequence of Miocene Kerek Formation that outcropped in Kali Pengkol is interpreted from syn-contractional sedimentation in western edge of Kendeng Basin. The interbedded bedding and thickening upwards of sandstone-siltstone consist of Bouma Sequence. The uniqueness of this sequence than another Kerek Formation is the grain composition that recorded in Ta deposit. This research based on petrographic and paleocurrent analysis, emphasize interpretation on provenance that may be a key of tectonic evolution. The Ta deposit (sandstone) is composed by quartz minerals, coal fragments and volcaniclastic materials. The type of quartz that found are angular monocrystalline quartz (in small amounts) and rounded polycrystalline quartz. The composition indicates that there was a mixing from volcanic and methamorphic origin of quartz, so it can be interpreted that this outcrop is a product of progressive uplift in southwestern most of Kendeng Basin. The uplift was reworked older (deeper) than turbiditic of Lutut sandstone and deltaic-transitional sequence that occurred contemporaneously with deformation and sedimentation of volcaniclastic materials from Southern Mountain Volcanic Arc. This implied that deformation in western edge of Kendeng Basin is earlier, and organic matters that reworked to the north can be used as an accountable amount for source rocks.

Confined submarine slope channel complexes of the Cerro Toro: new insights on architectural elements and facies prediction.

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The Cretaceous Cerro Toro Formation, southern Chile, is characterised by thin-bedded turbidites that envelope a coarse-grained, confined slope complex system, interpreted as part of the Lago Sofia Member. This deep-water slope system overlies basin floor sheets of the Punta Barrosa Formation, and is overlain by the sand-filled slope channels of the Tres Pasos Formation.

The 3.5 km x 200 m channel complex sets are contained within topographically irregular bathymetric lows that formed sediment pathway corridors, interpreted to be either the result of tectonism, or contained by poorly preserved, tectonically disrupted or slumped external levee. Syn-sedimentary tectonism, or levee deposits instability led to the development of thick packages of MTDs that collapsed into the slope fairways from their margins, coexisting with other sediment gravity flow deposits.

This work proposes a refined architectural analysis based on the Exxonian model for submarine channels, subdividing the Cerro Toro deposits, at the Silla Syncline area, in at least 4 main channel complex sets, focusing on the recurrent pattern of debrites – conglomerate-filled channel complexes – ponded sheet sandstones. Thus, to avoid confusion in nomenclature with previous works, Pehoe A and B; and Paine A and B are combined forming the four channel complex sets Pehoe AB, Pehoe C, Paine AB, and Paine C.

This pattern recognised in the study area, which triggered the proposed subdivision, is characteristic of most of the submarine channel studies done both for academic and industrial purposes. Recognising these characteristics is critical for using the system as an analogue in hydrocarbon exploration, allowing the prediction of packages with economic interest such as reservoir and seal.

Structural and stratigraphic controls on the architecture of deep-water depositional elements: seismic observations from the toe-thrust region of the Niger Delta slope

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In the deep-water slope areas of the southern lobe of the Niger Delta, gravity-driven deformation has resulted in the development of a fold and thrust belt since middle Miocene times. Over time the interaction between tectonically driven sea-floor topography and sediment dispersal systems have allowed for the formation of structural and combined traps. The typical reservoirs comprise large channel-complex systems and sheet sands, but their distribution, quality and vertical assemblage is ultimately controlled by the rate of structural deformation versus sediment accumulation.

A 3D seismic survey covering an area of 6200 km2 in the outer fold and thrust belt has been used to map the facies and structural evolution of a piggy-back basin bounded between two thrusts-folds.

Within the syn-growth interval of the piggy-back basin three main units, which record the structural and stratigraphic evolution of the basin have been mapped and dated between 12.8 and 3.7 Ma; these units are informally called lower, middle and upper sequences. Four main seismic facies have been interpreted from vertical seismic profiles and seismic amplitude extraction maps; these are channel-complexes, lobe deposits, mass-transport complexes and background slope hemipelagic muds. The relative abundance of these deposits, their assemblage and architecture is seen to vary within the three main mapped units. In general terms, the vertical stratigraphic trend shows predominance of channel-levee complexes in the older section whereas mass-transport deposits are common in the younger parts.

The seismic-stratigraphic mapping has been integrated with measurements of structural strain across the thrusts bounding, and within the piggy-back basin. Results show that periods of relative, low, strain-rate correlate with laterally shifting channel-levee complexes and compensational stacking (lower sequence), whereas during periods of relative, high, strain- rate, channels tend to aggrade and stack vertically (middle sequence). The upper sequence seems to relate to tectonic activity on different structures compared to those which affected the previous sequences. The upper sequence also records the creation of ponded accommodation space, which has blocked sediments in structure-parallel depocentres.

Frequency Distribution of Bed Thickness in Slope-Channel Fills: Insights from the Cretaceous Tres Pasos Formation, southern Chile.

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The frequency distribution of turbidite bed thickness has been interpreted to record information on flow dynamics, initial sediment volumes, depositional setting; it is also an important influence on hydrocarbon reservoirs. Power laws are commonly used to describe these thickness distributions (Carlson & Grotzinger, 2001; Sinclair & Cowie, 2003) and have been linked to initial source volumes associated with earthquakes with comparably distributed magnitudes (Beattie & Dade, 1996; Awadallah et al., 2001). Some turbidities successions have bed thickness distributions that are better described by a lognormal mixture model (Talling, 2001; Sylvester, 2007); a model in which two lognormal distributions are associated with beds of a specific grain-size or Bouma division at the bed base.

We present bed thicknesses from the Cretaceous Tres Pasos Formation of southern Chile, and compare them with published data from channel (Palaeocene Tarcau Sandstone, Romania) and lobe strata (Miocene, Marnoso-Arenacea Formation, NW Italy). The study area encompasses 10 individual channel elements from a well-exposed slope-channel system, upon which a high-confidence correlative framework of channel hierarchy has been developed using over 2000 m of measure section and GPS mapping (Hubbard et al., 2014). This context provides a unique opportunity to consider the distribution of >3000 beds, both in general channelized settings and in terms of channel position (i.e. axis, off-axis or margin).

A mixed lognormal model can be used to describe bed thickness distribution within slope-channel fills of the Tres Pasos Formation. The observed distribution is comparable to that documented for channelized and lobe strata in previous studies (Talling, 2001; Sylvester, 2007); subtle differences in distribution parameters, along with other sedimentological criteria, can offer insight into depositional processes and setting. Subtle differences in the parameters of bed distributions in the channel axis and margin reflect the influence of erosion and channel relief. Quantifying the frequency and variability of bed thickness in channelized strata improves our understanding of these systems and facilitates effective reservoir modeling. Further, our observations support previous studies suggesting that turbidite bed thickness does not always follow a power-law model, and thus cannot be directly related to earthquake magnitudes.

Sequence hierarchy and deepwater sediment delivery in the Giant Foresets Formation, Taranaki Basin, New Zealand

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Depending on accommodation history, shelf margins can provide a staging area for sediment delivered to deepwater and therefore an understanding of staging area evolution through time is required in order to better predict the timing, nature and distribution of deepwater deposits. The Plio-Pleistocene of New Zealand is characterised by an increase in uplift and erosion rates of the Southern Alps. Released sediment was fed north to the Taranaki Basin via longshore drift and oceanic currents, to be deposited as the Giant Foresets Formation (GFF).

The GFF is a set of rapidly prograding continental margin scale clinoforms with up to 1500 m relief and a progradation rate of up to 38 km/Ma. The scale and regional extent of the formation provides an excellent natural laboratory to test sequence stratigraphic models and document the evolution of a rapidly prograding clinoform set and associated deepwater deposits.

Using regional 2D and 3D seismic datasets calibrated with exploration wells, we present for the first time a sequence hierarchy for the Giant Foresets Formation, within which we examine the scale, distribution and nature of deep-water deposits. Nineteen composite sequences have been delineated from 3.0 Ma to present; these composite sequences are each composed of higher order sequence sets. The frequency and scale of composite sequences follows a dominant Milankovitch cyclicity of 41 Ky until approximately 0.9 Ma, after which 100 Ky cycles are dominant to the present day.

Seismic character of deepwater deposits located in the bottomsets of the GFF is consistent with MTDs and a series of lowstand fan deposits. Regional seismic coverage allows along strike variations in these deposits to be mapped and relationships to the sequence hierarchy established.

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Ground Floor Plan of the Geological Society, Burlington House, Piccadilly