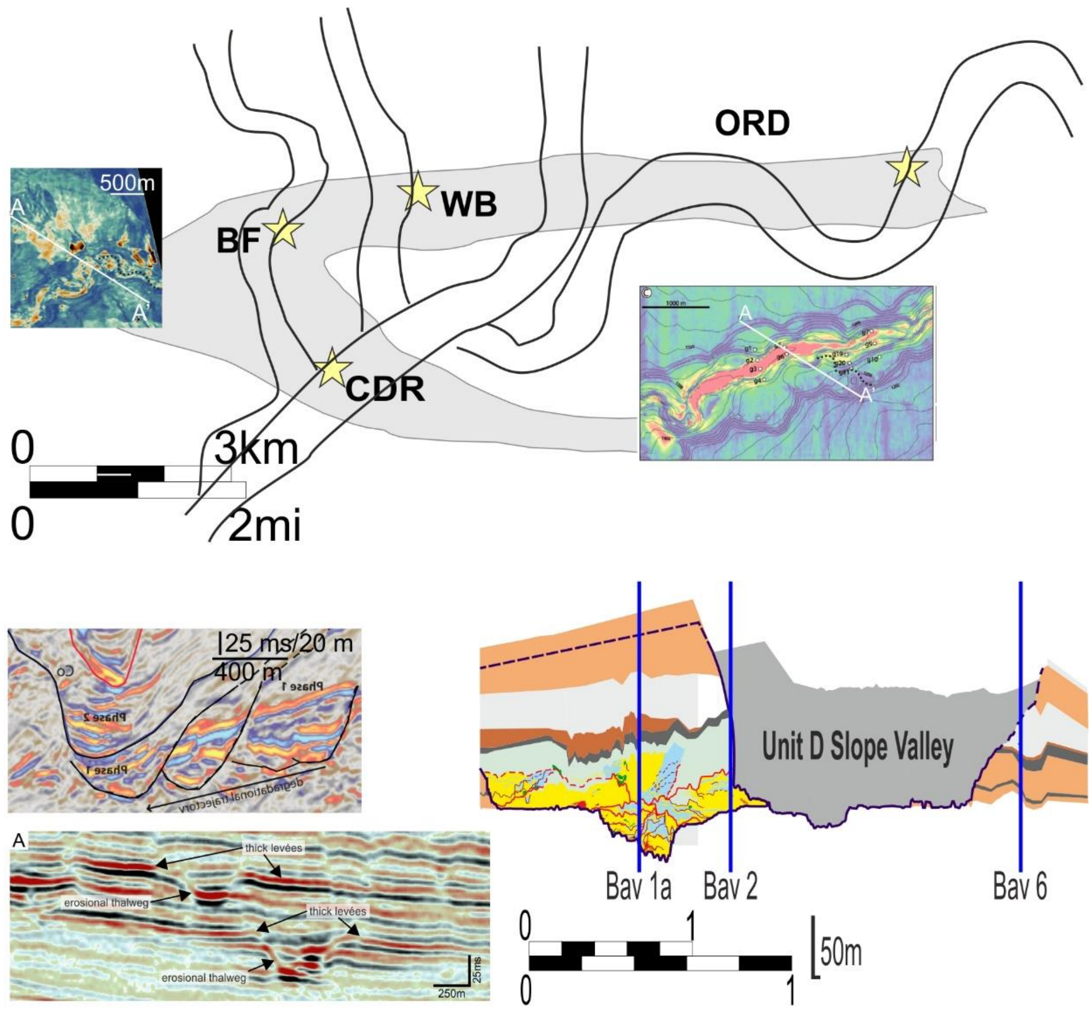
SLOPE Phase 5
Deep-water slope systems:
a globally calibrated model for exploration and development



Theme 1: Global exportability of slope system architecture

Theme 2: Multiscale analysis of slope channel related stratigraphic traps

Executive Summary

SLOPE Phase 5 is a 3-year research project, which leverages the knowledge and insight developed during earlier phases of the SLOPE consortium. SLOPE Phases 1-4 saw the development of powerful predictive models for deep-water reservoirs from exploration- to development-scales, including quantitative datasets on architecture, geometry, facies, net:gross and reservoir connectivity. Outcrop studies of exceptionally well exposed seismic-scale systems in the Karoo Basin, South Africa, have included direct calibration to research boreholes (core, image logs and wireline logs) at depositional sequence and composite sequence scales. The conceptual models of Phases 1-4 are being used across the industry worldwide to reduce uncertainty in exploration and development projects.

SLOPE Phase 5 has two themes, each delivered via a series of inter-related work packages.

Theme 1, **GLOBAL EXPORTABILITY OF SLOPE SYSTEM ARCHITECTURE**, will critically compare and test the models developed in Phases 1-4 against key variables found in other sedimentary basins, to measure the generic applicability of the Karoo analogues globally and therefore to constrain uncertainty and reduce risk. These variables include a wider grain-size range, different tectonic settings with different subsidence mechanisms/rates, and combinations of syn-depositional tectonics and residual structural topography; a wider range of flow processes, including systems dominated by supercritical flows, and systems inferred to have been fed by hyperpycnal river input; greenhouse climate settings (Karoo was icehouse-greenhouse transition) and wide palaeo-latitudinal settings. Particular attention will be paid to thin-bedded pay, by extending the recognition criteria for distinguishing different thin bed depositional environments and developing machine-learning approaches based on core and image log data from behind-outcrop wells. The effect of permeability distribution on likely recovery will be investigated using fluid flow modelling.

Theme 2, **MULTISCALE ANALYSIS OF SLOPE-CHANNEL RELATED STRATIGRAPHIC TRAPS**, will work from system-scale pinch-out down to sub-seismic bed-scale facies changes, including Karoo and Ainsa core datasets, to better understand requirements for trap development and preservation of trap integrity. Fluid flow simulation of the outcrop architecture will investigate strat trap integrity and leakage potential. Seismic forward modelling integrated with outcrop studies will constrain the actual facies and architecture at and below the resolution of seismic mapping.

Three principal outcrop study areas include 1) the Cretaceous Punta Baja Fm. and Rosario Fm. canyon and channel-levee systems of Baja California, Mexico; 2) the Austral Basin, Tierra del Fuego, Argentina; and 3) the baseline control of the Karoo Basin, South Africa. We will also integrate key results from recent work in other deep-water basins such as the confined Annot, Ainsa and Jaca systems.
Four work packages have been designed to cut across scales of observation and data types in the programme themes:

- **WP1. Slope-channel related stratigraphic traps**
- **WP2. Controls on slope channel architecture and hierarchy**
- **WP3. High resolution seismic and fluid flow modelling of facies and connectivity**
- **WP4. Embedding project results in sponsor workflows**

Principal Investigators Stephen Flint, David Hodgson and Ian Kane will be supported by a post-doctoral researcher, two PhD students and experienced deep-water researchers (Brunt, Hubbard and Poyatos-Moré). The project will run from March 2019. Cost per company will be UKP 33K per year for 3 years and a minimum of 8 sponsors are required for the project.

Background

The last 15 years have seen major advances in our understanding of submarine slope processes and stratigraphy. These have led to increased success in exploration worldwide and better strategies for field development and late field life recovery. These advances have been driven by a combination of increased resolution 3-D and 4-D seismic reflection datasets, continued modern seabed surveys, new generations of both physical and numerical modelling of deep-water processes, and data-rich outcrop analogue studies. Crucially, the last 5 years have seen the convergence of these different strands towards unified models to bridge the scales of spatial and temporal variability inherent in these disparate approaches. Examples of the positive feedback between integrating different approaches include the current interest in supercritical flows, and finding outcrop evidence to support observations from seabed mapping, flow monitoring and physical laboratory models. There has also been good progress in understanding how lateral (across-strike) variability in shelf edge geomorphology and process regime affect sand transfer over the shelf edge to develop deep-water reservoirs.

However, a fundamental challenge remains that of scale – both spatial and temporal. The modern seabed provides unequalled spatial but limited stratigraphic control. Latest generation 3-D seismic provides a good mix of both, but suffers from finite resolution limits and variable lithology calibration. Seismic-scale outcrops supplemented by cored boreholes remain a powerful way to close the scale gap and reduce uncertainty in predicting sub-seismic net:gross and connectivity, thus optimising initial development planning.

Key outcrop study areas that have contributed to our increased understanding of these systems include the Brushy Canyon area of West Texas, the Tres Pasos system of southern Chile, the Neuquén Basin of Argentina, the Ross Fm., Ireland, and the Karoo Basin, South Africa. The SLOPE project, based in the Karoo Basin, has completed 4 phases and provides an integrated holistic understanding of simple and stepped slope systems and overlying shelf edge/shelf deltas over a 2500 km^2 area, within a 2 km thick basin margin succession deposited over 6 Myr.

The 20 years of Stratigraphy Group work in the Karoo Basin (originally based at Liverpool and since 2012 at Manchester and Leeds) has included 8 Post-doctoral workers and 10 successfully completed PhDs, leading to 40 papers published in academic journals. These studies have provided data-driven models for the development of early deep-water basin plain systems with mass transport complexes (e.g. Van der Merwe et al., 2009; 2010; Brooks et al., 2018), distributive lobe systems (e.g. Johnson et al., 2001; Sixsmith et al., 2004; Hodgson et al., 2006; Prélat et al., 2009; Kane et al., 2017; Spychala et al. 2017; Hofstra et al. 2018) and a mud-dominated submarine slope characterized by cycles of erosion, bypass and deposition (e.g. Hodgson et al., 2011; Kane & Hodgson, 2011; Di Celma et al., 2011; Hodgson et al., 2016; Poyatos-Moré et al., 2016; Brooks et al., 2018), with major along-margin differences between the Laingsburg and Tanqua areas. The nature of the shelf edge and the mechanism of shelf construction in both areas have been characterized (Wild et al., 2009; Jones et al., 2015; Poyatos-Moré et al., 2016; Gomis Cartesio et al., 2017; 2018) with both down dip and across strike studies (Fig. 1).

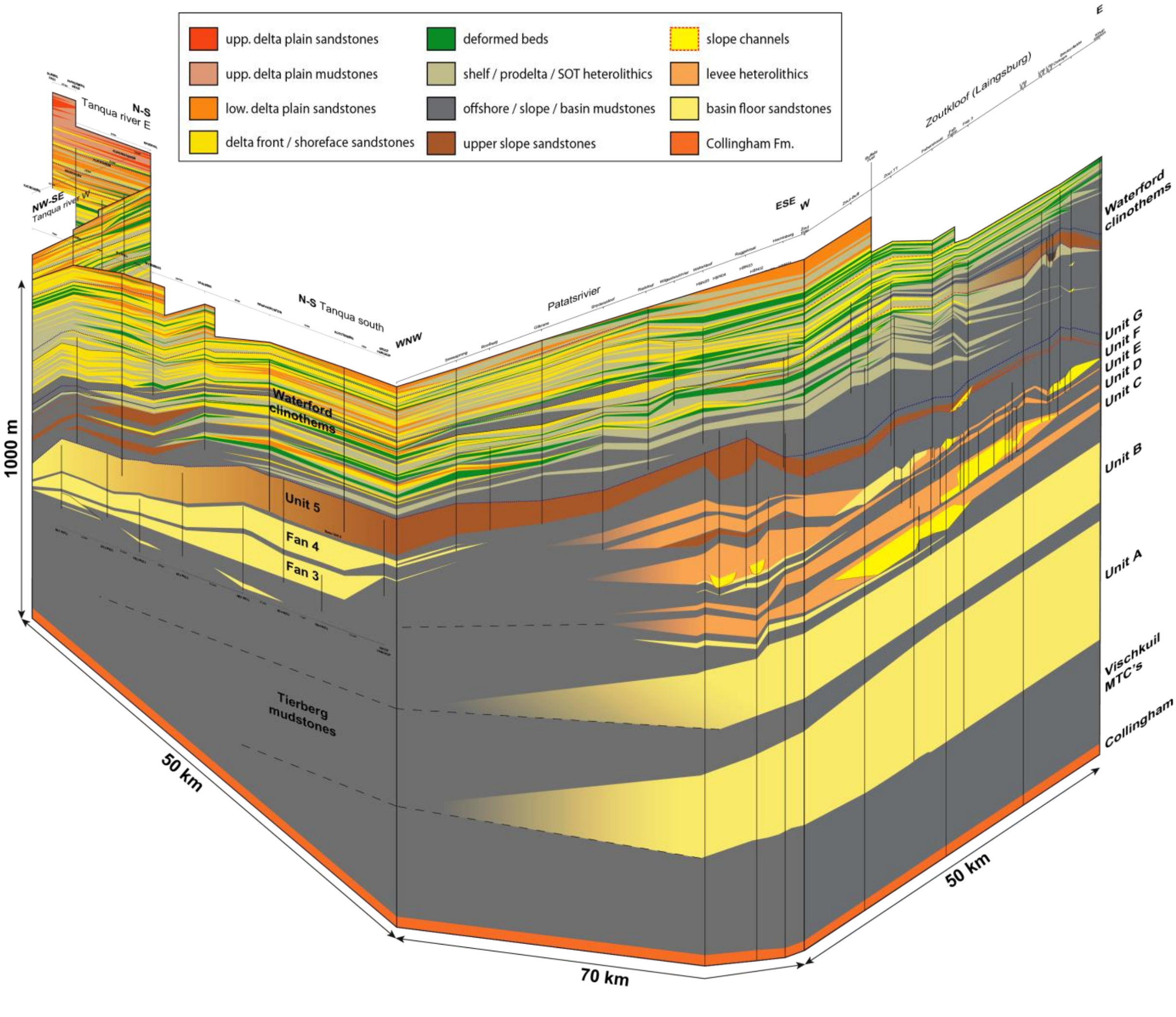


Figure 1: Correlation across strike (70 km) between the Tanqua and Laingsburg depocentres achieved in SLOPE Phase 4. This allows highly detailed reservoir-scale analyses to be set within an exploration scale context.

Slope Phase 4 has synthesised all of the Karoo work into Petrel-based data repositories containing quantitative information for use in reservoir modelling (e.g. Pringle et al., 2010). In addition, research boreholes with over 2 km of core have allowed confident calibration of core and image log facies to outcrop-constrained geometry and position in system (Fig. 2), such as differentiation of levee from channel margin deposits in slope complexes (Morris et al., 2016). The 70 km along-margin correlation now achieved for the Tanqua and Laingsburg depocentres has allowed us to constrain the across strike responses to higher subsidence rate in the Laingsburg area (thicker slope succession) and to fully characterise a stepped slope profile in several composite sequences in the Laingsburg area, compared to a less complicated Tanqua margin (Fig. 3). However, the rich database of over 2 km of core has not been fully exploited for understanding thin bed pay in reservoirs and this will be undertaken in Phase 5. The recent high level of interest in slope system stratigraphic traps will also be reflected in Phase 5 work in the Karoo and other areas.

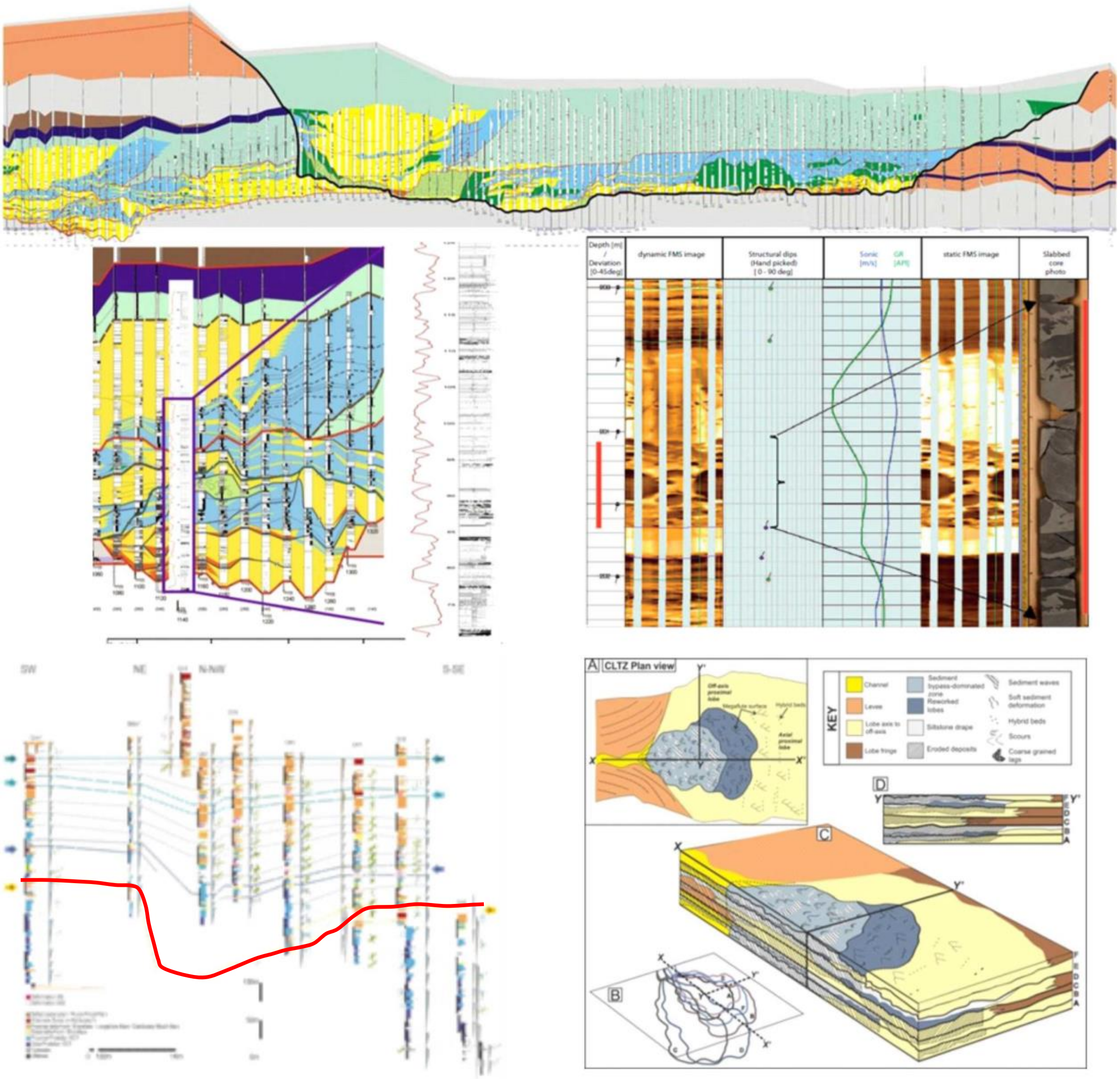


Figure 2: Selected learnings from the Karoo SLOPE project include characterisation of slope valleys, a shelf edge canyon and a preserved multistage channel and levee to lobe transition zone.

The multi-scale Karoo model has been used to guide interpretations of deep-water and shelf plays and field development strategies worldwide. However there remain reasonable concerns around the analogue fit of the Karoo in different types of deep-water system. The Karoo succession is grain size limited (maximum upper fine sand) with a subsidence regime dominated by regional dynamic topography related to far field subduction, prior to transition into a retro-arc foreland basin. The large scale paleoclimate/paleogeography was relatively high latitude, late icehouse during the late Permian.

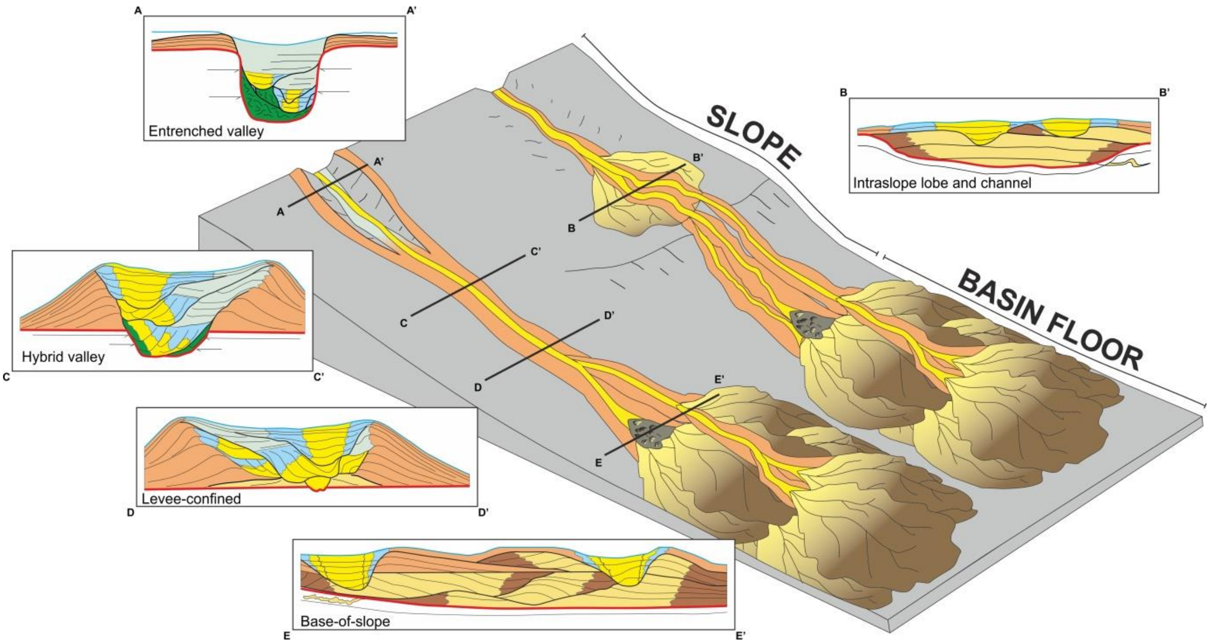


Figure 3: The Karoo-based model for submarine slope reservoir development in systems without the influence of salt or shale mobility but including lateral changes in shelf edge delivery and slope physiography. The cross-sections are all based on quantitative outcrop studies and allow prediction of down slope changes in sand percentage and connectivity.

Key business needs

The two inter-related themes of this research project address important and topical issues in global deep-water exploration and production and will be addressed via a series of work packages (WPs).

Theme 1. Global Exportability of Slope System Architecture (WP 2, 3, 4)

Under THEME 1, the project will critically test the Karoo-based model for prediction and application of stratigraphic hierarchy, architecture, geometries and reservoir sand distribution in submarine slope systems. These differ markedly in key parameters such as grain size range (to include gravel/conglomerate), age, basin type, source-to-sink configuration, subsidence mechanisms and type of shelf edge delivery system (Fig. 3). We will include systems with a range of mass transport deposits (MTDs) in basins with inherited and active structural topography. The final product will allow sponsors to interrogate the dataset, from frontier exploration low-resolution seismic scale, down to the individual reservoir element and its core/well log expression, within a consistent sequence stratigraphic hierarchy. It will be a globally calibrated model for deep-water exploration and development (Fig. 4).

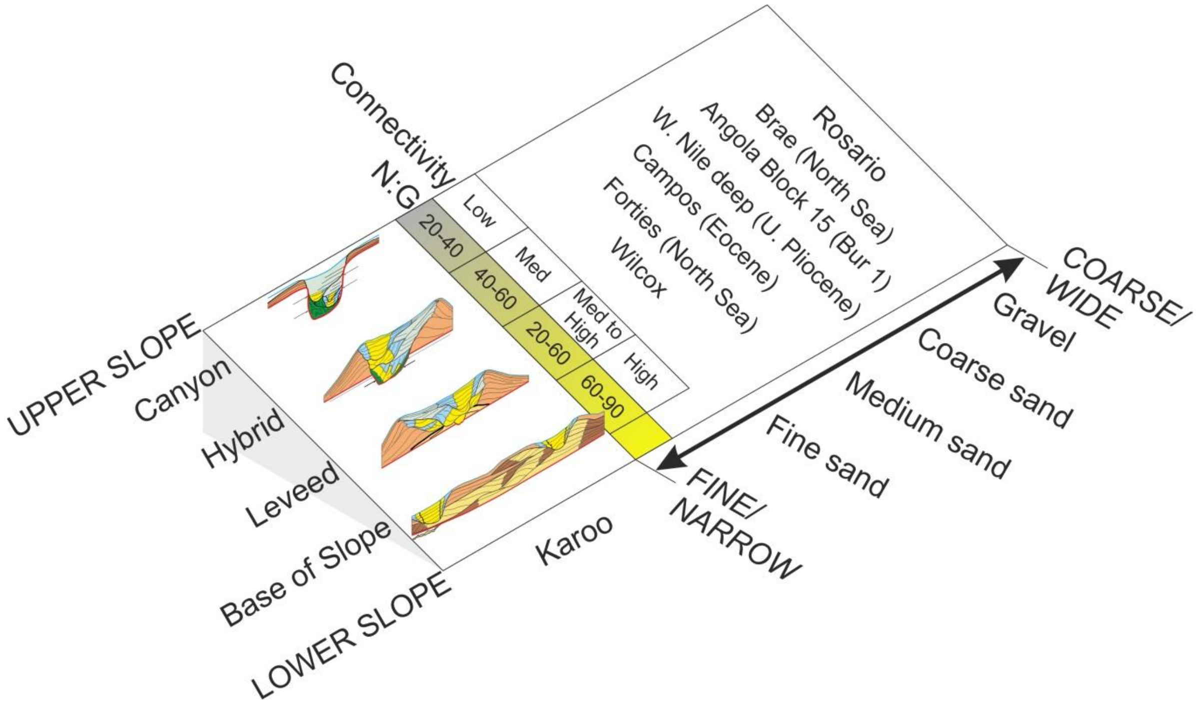


Figure 4: Concept diagram to illustrate how the project will capture comparative data on slope systems that differ from the Karoo base case. Here, we emphasise the wide grain size range in the Rosario as a key variable, against which we will assess architecture, connectivity and net: gross (% sand) trends. This project phase will fill in the rest of the diagram with quantified parameters.

Theme 2. Multiscale analysis of slope-channel related stratigraphic traps (WP 1, 2, 3, 4)

Stratigraphic traps have been successfully exploited at a wide range of scales, from basin margin- to channel-complex to intra-channel scale (Fig. 5, 6), but the key issue of de-risking stratigraphic traps in submarine slope successions remains. Up-dip stratigraphic traps near the basin margin / shelf-edge are attractive targets, but stratigraphic convergence of slope channels which feed into an updip canyon can be a leakage point. In THEME 2 we will investigate this using the 3D geometry and stratigraphic relationships of slope canyons and channels incised and routed around basin margin / shelf edge topography, versus relatively simple delta-fed systems. We will also characterise the canyon head facies and architecture, which is a generally unstudied component of slope systems, as highlighted by the Quaternary history of the Monterrey Canyon (Maier et al., 2018).

Farther down-dip, slope channel complexes may form attractive strat traps against the slope, where the relationships of external levees or erosional truncations to the slope are critical; the expression of these 'edges' at seismic scale will be investigated. Within slope channel systems, we will investigate lateral strat trap scenarios to understand, predict and de-risk the likely failure of strat traps, in particular related to thin-bed depositional environments within channel fills, e.g. connectivity of channel axis, channel margin and internal levee elements (Fig. 5, 6). To address these questions, we will document the range of architectures, from basin margin-scale stratigraphic traps and the external controls on them (WP 1), stratigraphic traps at the channel complex-scale (Fig. 8; WP 2), and stratigraphic traps within channels and channel complexes (WP 2). Testing the various scales of strat traps, in terms of seal integrity at pinchout and lateral facies changes will take place through facies simulation models (WP 3) and their expression at seismic-scale will be analysed using forward seismic models (WP 3).

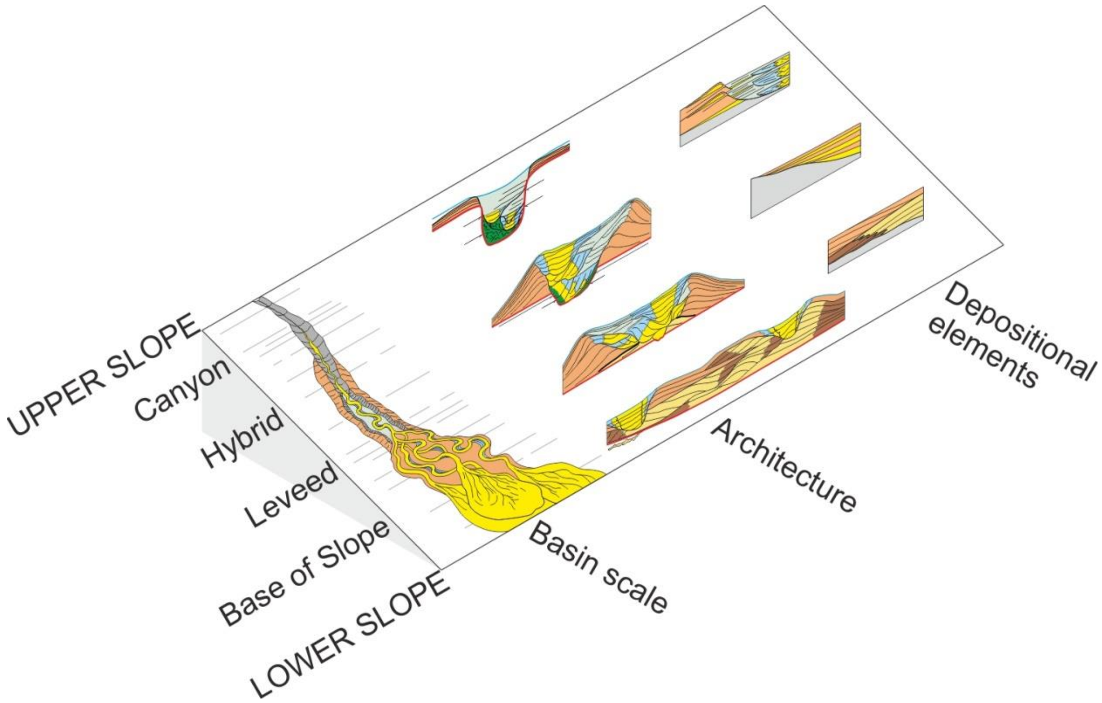


Figure 5: Stratigraphic traps across different scales of observation: the seismic to sub-seismic scale hierarchy approach being used to develop predictive understandings of deep-water stratigraphic traps in Slope Phase 5.

Details of the outcrop study areas (see Appendix 1 for details)

The four work packages will be addressed using three 'base systems' with calibration of specific features such as channel geometries and stacking patterns, levee architecture, preservation of high net:gross frontal lobes, etc. using a wider set of examples, including core and high resolution seismic datasets. The proposed base systems include the world class 1) Punta Baja and Rosario systems of Baja California, Mexico, 2) the Cenozoic Austral Basin succession exposed on the east coast of Tierra del Fuego, Argentina, 3) the Karoo Basin of South Africa. While being different in detail in order to test sensitivity against variables, these examples are in large basins, with seismic-scale exposures, thus being good analogues for exploration areas and for producing fields in West and East Africa, Egypt, the South China Sea, the Gulf of Mexico, Brazil and elsewhere.

Work packages

To address the above research questions the following work packages have been designed:

- **WP1. Slope-channel related stratigraphic traps**
- **WP2. Controls on slope channel architecture and hierarchy**
- **WP3. High resolution seismic and fluid flow modelling of facies and connectivity**
- **WP4. Embedding project results in sponsor workflows**

Work Package 1: Slope-channel related stratigraphic traps

How can we geologically de-risk stratigraphic traps in submarine slope successions? We will investigate using the 3D geometry and stratigraphic relationship of slope channels incised and routed around shallow marine carbonates versus delta-fed systems. Farther down-dip, in slope channel systems, we will investigate lateral strat trap scenarios to understand, predict and de-risk the likely failure of strat traps (Fig. 6). What is the range of 'edges' to slope channel complexes at sub-seismic scale? Does this vary as a function of grain size range and what are the implications for lateral sealing against levees, slope muds and older lobe remnants? To address these questions, we will document the range of architecture and connectivity sand-rich bases to external levees (remnants of older frontal lobes), to internal levees/terrace deposits, and to the role of syn- and post-depositional deformation (including injectites) to constrain strat trap integrity (Fig. 6).

This work package will examine the relationship of the Rosario Fm., with its long-lived entry point to the slope through a carbonate succession, within the Alisitos Fm. The up-dip pinch-outs are well exposed with 3-D control for several of the Rosario systems but have never been worked (Fig. 7, 8). They offer a world class example of up-dip pinchout with complex geometries and multi-component histories. Work will include mapping, sedimentary logging and tracing out complex geometries, with extensive use of UAV-based models.

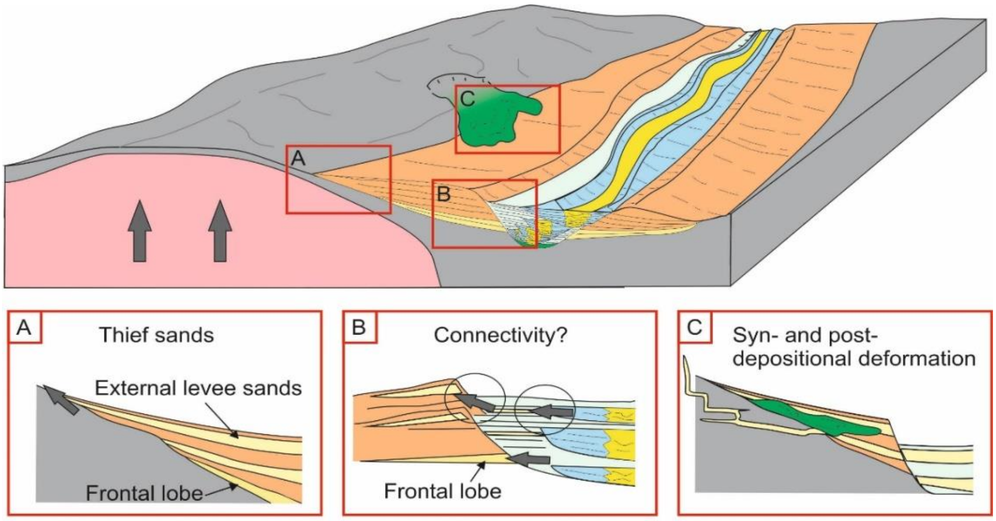


Figure 6: Schematic summary of some sedimentological/stratigraphic features that may contribute to failure of stratigraphic traps in slope settings.

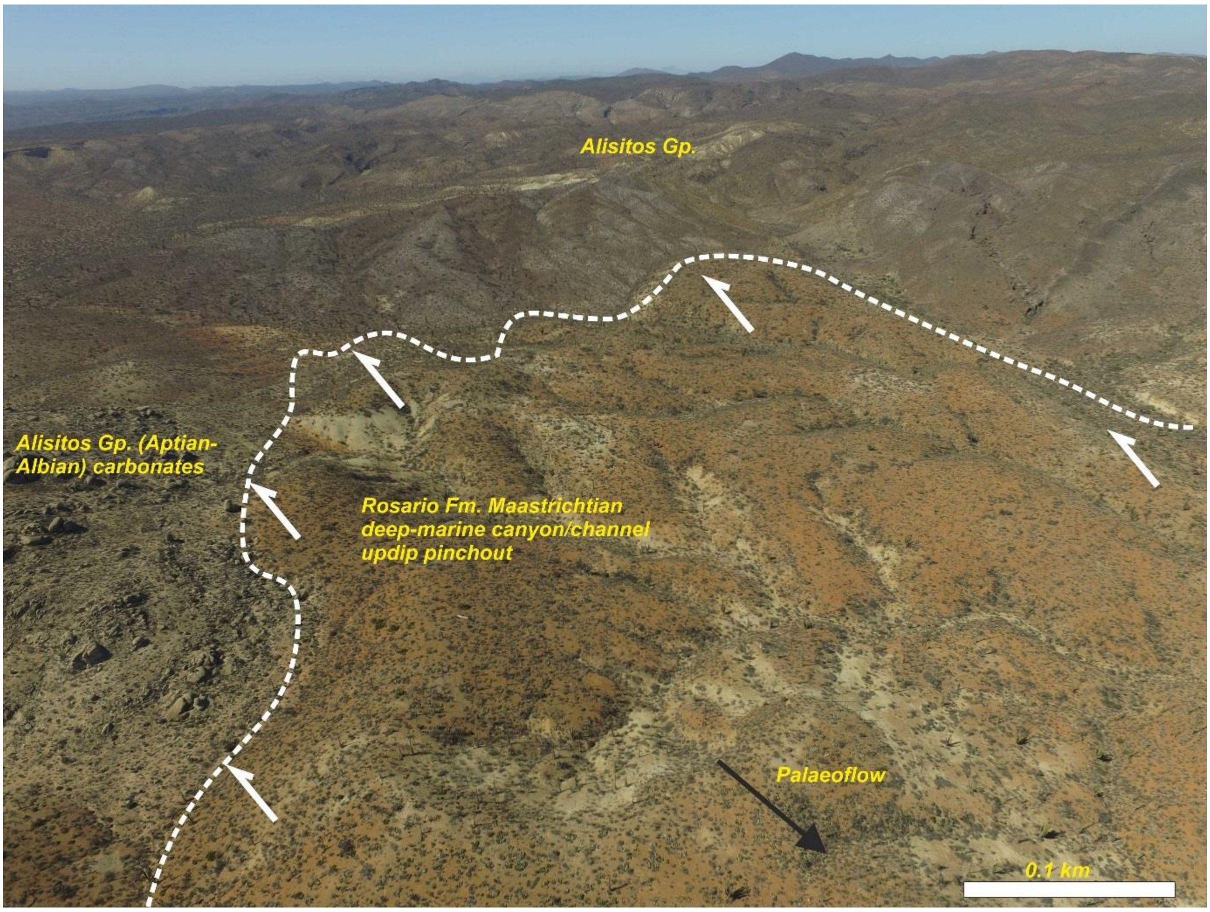


Figure 7: UAV photograph of the canyon head-fill, and updip pinchout, in the Rosario Fm. The canyon-fill incises the Alisitos Group carbonates.

Thick slope successions of channels, levees and mass transport complexes have been documented from the Rosario slope. The carbonates form a karstified surface, tilted basinward prior to being on-lapped by fluvial and potentially shallow-marine sediments (El Gallo Fm.). In turn, the El Gallo Fm. was eroded, and stripped off the carbonates apart from a few 'pockets' lining the complicated karstic topography. The succession was tilted basinward again, and incised and on-lapped by the Rosario Fm. slope channels and coastal deposits in multiple places along strike. Presently, above this 'hinge-point', the Rosario Fm. is represented by several tens of metres of conglomerate incised into the fluvial El Gallo Fm. and resting on top of the carbonates (Fig. 7, 8). At the margins of the carbonate, large blocks have been entrained into the slope conduits; these are often found as large (several metres across) sub-rounded blocks within slope channels up to 25 km down dip. The resulting succession shows a carbonate platform that had a complicated topographic expression, juxtaposed with fluvial and deep-marine sediments spanning a wide time interval, occurring as lenses and probably representing multiple episodes of reworking through time. The implication is that older systems are erosionally truncated and amalgamated with their younger counterparts in proximal areas, potentially leading to confusion with biostratigraphic analysis of onlapping turbidites. From a reservoir perspective, there is potential for all of the slope channel systems deeper in the basin to be tied to a common leakage point at the hinge zone.

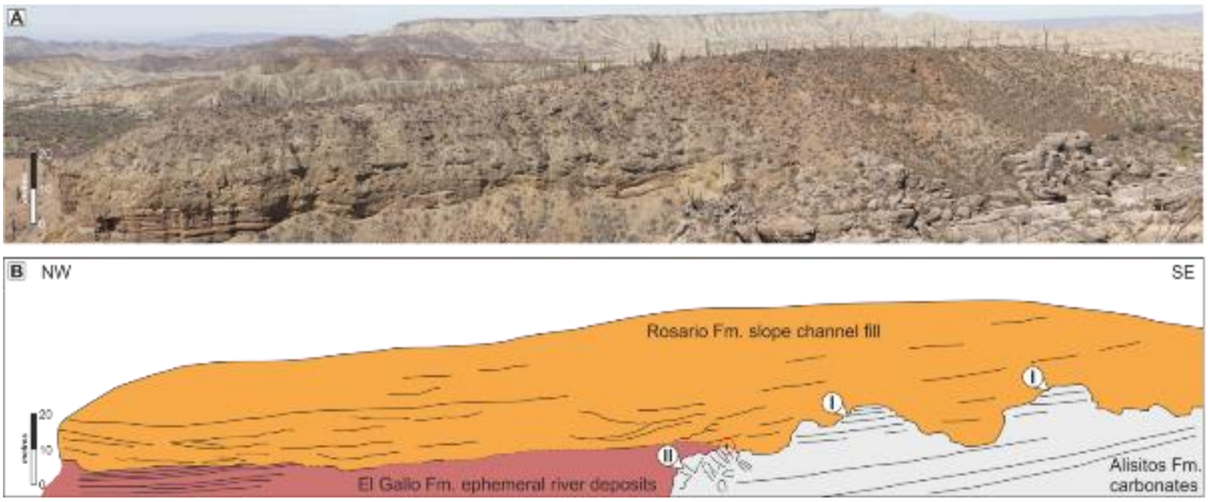


Figure 8: Los Pintas outcrop showing slope channels onlapping platform carbonates which acted as a long lived hinge point. The thin succession here expands to c. 1 km down slope.

Work Package 2: Controls on slope channel architecture

In this work package, we will critically test the predictive Karoo-based models and their stratigraphic hierarchy in the much wider grain size Rosario and Austral Basin systems. Does the fill style, and therefore net:gross range and connectivity of slope channel elements, maintain the predictable trend of simpler, more sandy-fills down dip and a down system decrease in confinement when the grain size range is wider (Fig. 4)? We will also use detrital zircon geochronology to constrain the timing and duration of the different Rosario canyon systems, to provide temporal analogue guidance.

Work Package 2A: Rosario slope canyon geometry, architecture, fill style and hierarchical elements

We will characterise the Mesa San Carlos, Punta Baja and Punta Canoas systems (Fig. 9, 10). The unstudied Punta Canoas system to the far south (Fig. 9, 11) includes a large-scale canyon with a range of fill styles, mappable for 10 km+ in dip section and fully exposed in strike section. The Rosario systems have much greater volumes of MTDs than the Karoo and we will develop criteria to reliably distinguish MTDs derived from the sand source area versus MTDs generated by instability and collapse from local topography. Do they have different geometries and different effects on sand body geometries?

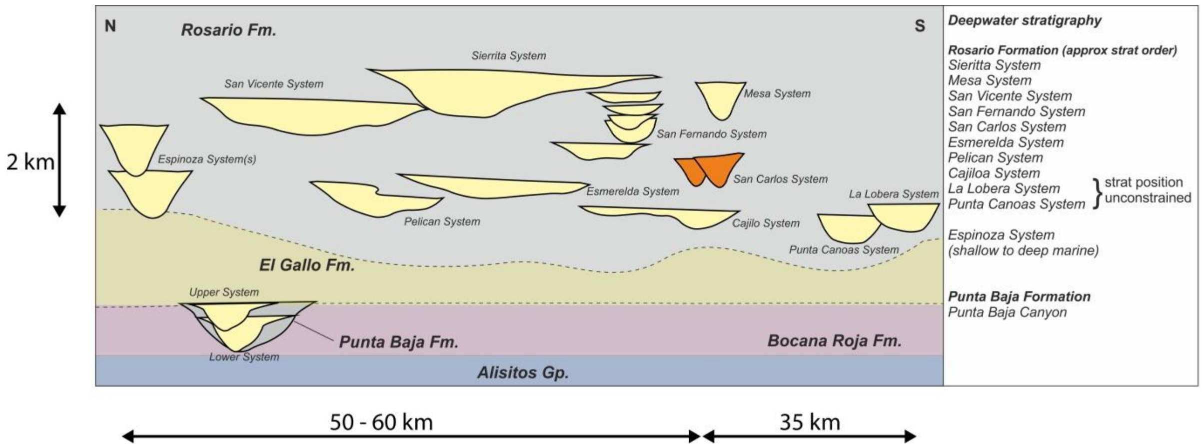


Figure 9: Slope canyon systems exposed for c. 100km strike width on the Baja California margin. Those worked in previous industry JIPs are shown in orange.

Initial reconnaissance fieldwork shows large differences in net:gross and architecture between these depositional systems. We will also work carefully on characterising the edges of channels and complexes at sub-seismic scale to test for variability as a function of grain size range. This work will assess the implications for lateral sealing and the development of stratigraphic traps against levees, slope muds and possibly older lobe remnants.

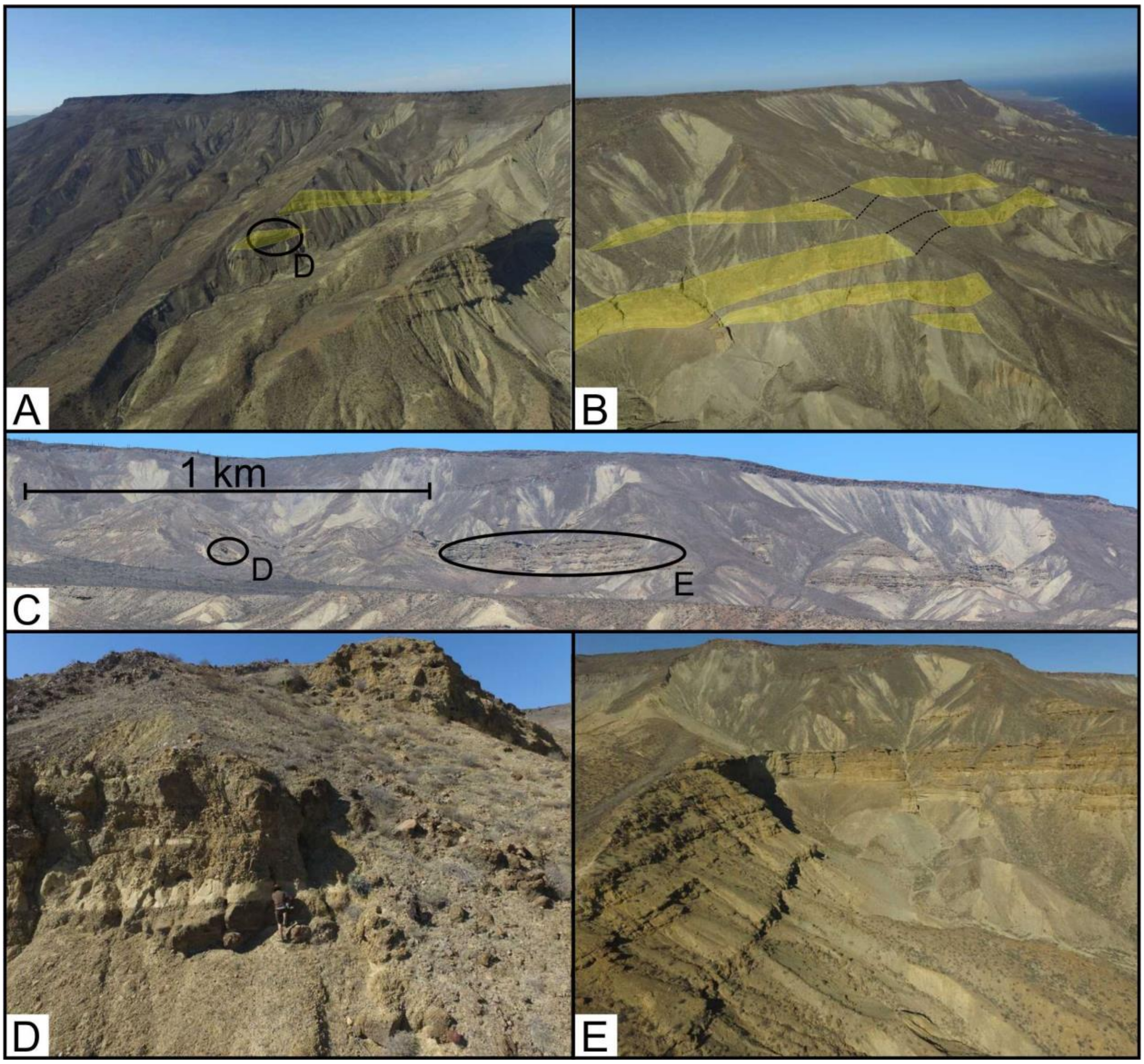


Figure *10: UAV photographs of the understudied Mesa San Carlos channel complex set, c. 120 m thick and 4 km wide. (A) and (B) are oblique views of the left and right hand central panel (C). Note the series of channel complexes, which tend to thin, or pinchout, into the cliff section, suggesting the outcrop is a several km long oblique dip section through a channel complex set. (D and E) Closer photos of channel complexes.*

The Punta Baja canyon system is the oldest canyon system in the area (Fig. 6), extensively exposed on the present day Punta Baja peninsula (Boehike and Abbot, 1986). Both margins are exposed and the fill is highly heterogeneous, including conglomeratic channel complexes, sandy channel margins and a range of within-container thin beds and MTCs (Fig. 11). Specific work will constrain the connectivity between the channel complex-fills and the internal-levee/terrace deposits, to help with recognition criteria and to aid prediction of recovery in analogous 'dim' seismic facies.

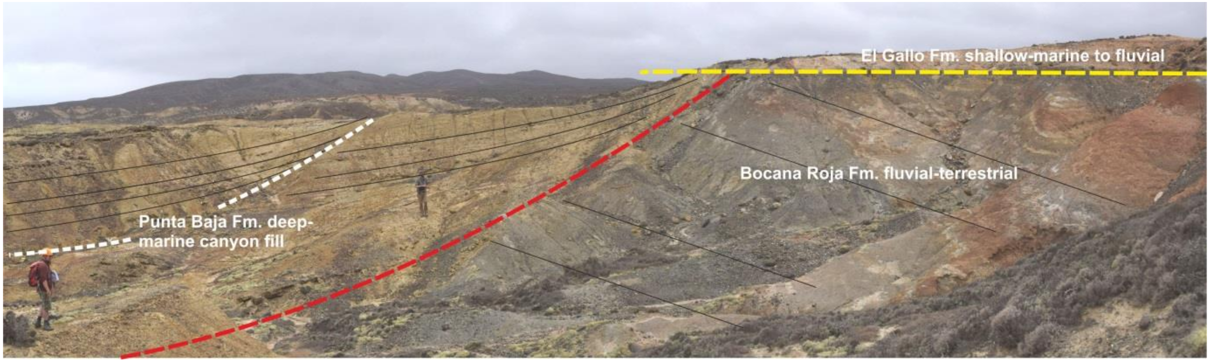


Figure 11: Eastern margin of the 300 m thick canyon-fill, cut into continental deposits. The fill is highly variable and dominated by pebble to cobble conglomerates in the west but major development of sandy thin beds in the east, giving a highly asymmetrical architecture – similar to several Karoo examples from farther down dip.

Work Package 2B: RateZr - Chronostratigraphy of the Rosario margin canyon systems

We know from modern systems that submarine canyons are not simple conduits for delivery of sediment to the slope and basin floor. Rather, sediment is stored and then flushed, sometimes in multiple episodes. Canyons can remain under-filled over multiple sea level cycles and may episodically backfill with a complex range of facies. Ground-breaking work by the University of Calgary on the Magallanes Basin slope systems of Chile (Daniels et al., 2018) and the Nanaimo Group, British Columbia, has proven the power of a new detrital zircon age dating method, using large numbers of grains to unravel sediment transfer history. U-Pb dating of detrital zircons from the Rosario systems will allow us to reconstruct the complex canyon activity history along the margin and better understand lag times and the degree of continuity of sediment supply. It will also enable correlations, both down-dip and along-strike, where outcrops cannot be traced across widely spaced mesas.

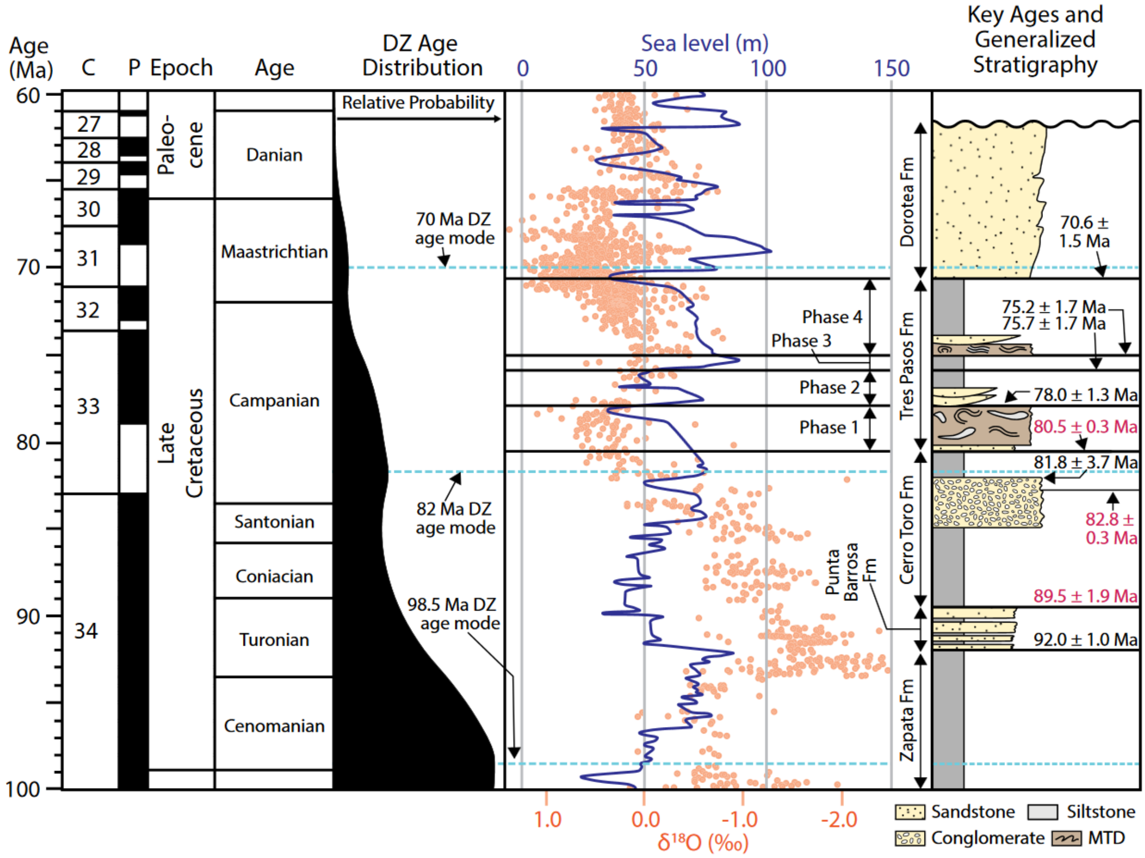
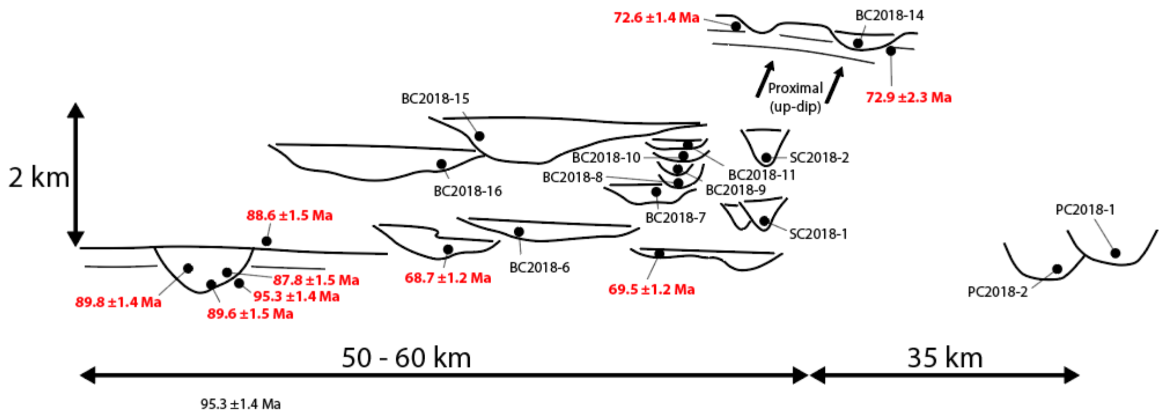


Figure 12: Zircon age dates displayed against magnetic polarity history and sea level curve derived from oxygen isotope data cloud (pink dots) for the Magallanes Basin deep-water succession – which spans the same middle Cretaceous to Palaeocene time period as the Rosario (Daniels et al., 2018).

This work package will involve integrated logging and sampling by the project team, tied to facies and stratigraphic hierarchy. Figure 12 shows the results from the recent Chile studies. The concept is that if the provenance area is dominated by first cycle zircons from a magmatic source and that source remains active during the basin filling, then the youngest coherent statistically valid population of zircons in a sample should reflect the age of crystallisation and, in a simple source-to-sink situation, will be close to the depositional age of the host sediments. Continued magmatic activity should ensure that the youngest zircon population gets progressively younger up section. This differs from classic age inversion seen in the unroofing of an ancient, inactive magmatic source. Previous regional studies of the Rosario confirm arc activity through the Cretaceous and early Cenozoic (Busby et al., 1998).

Geochronology studies sometimes fail due to highly complex provenance area changes through time and issues with lead loss in zircons, both situations producing equivocal data with overlapping error bars. In order to de-risk this work package our reconnaissance fieldwork included collection of samples from several of the regional canyon systems and fast-tracking of analyses to test that the

Rosario system would yield convincing and straightforward age dates, as expected from the relatively simple source-to-sink configuration. Figure 13 shows the early results, which encouragingly show distinct youngest ages for different lithostratigraphic formations, but also distinctive older zircon populations, which will help will provenance analysis.



BC2018-1 (**89.6 ±1.5 Ma**)	Punta Baja Fm. basal channel complex	SC2018-1	Rosario Fm., basal San Carlos channel system
BC2018-2 (**95.3 ±1.4 Ma**)	Bocana Roja Formation adjacent to canyon	SC2018-2	Rosario Fm., Mesa channel system
BC2018-3 (**87.8 ±1.5 Ma**)	Punta Baja Fm. base of internal levee section	BC2018-12 (**72.6 ±1.4 Ma**)	El Gallo Fm(?), Los Pintas, updip
BC2018-4 (**68.7 ±1.2 Ma**)	Rosario Fm., Pelican channel system	BC2018-13 (**72.9 ±2.3 Ma**)	Bocana Roja Fm., Pepper Farm, updip
BC2018-5 (**69.5 ±1.2 Ma**)	Rosario Fm., Cajiloa channel system	BC2018-14	Rosario Fm., Rosario cyn head (AIDS)
BC2018-6	Rosario Fm., Esmeralda channel system	BC2018-15	Rosario Fm., Sierrita channel system (Paleogene)
BC2018-7	Rosario Fm., San Fernando channel system (CCS-1)	BC2018-16	Rosario Fm., San Vicente channel system
BC2018-8	Rosario Fm., San Fernando channel system (CCS-2)	BC2018-20 (**88.6 ±1.5 Ma**)	El Gallo Fm., at contact with Bocana Roja, Punta Baja
BC2018-9	Rosario Fm., San Fernando channel system (CCS-3)	PB2018-1 (**89.8 ±1.4 Ma**)	Punta Baja Fm., ash near base/mid of upper channel complex
BC2018-10	Rosario Fm., San Fernando channel system (CCS-4)	PC2018-1	Rosario Fm., La Lobera channel system base
BC2018-11	Rosario Fm., San Fernando channel system (CCS-5)	PC2018-2	Rosario Fm., Punta Canoas channel system base

Figure 13: Initial (unpublished) zircon age dates (in red) from reconnaissance fieldwork for some of the canyon- and channel-fills, also showing samples yet to be analysed. These data are in accord with the limited regional dates and show promise in being able to reconstruct the relative timing of activity in the deep-water canyons along the exhumed Baja California margin.

Work Package 2C: Comparison with Karoo canyon and slope valley-fills to capture model variability

We will undertake comparative analysis of the Rosario systems with those of the Karoo, such as the CD Ridge and additional complexes further down dip in Units D and E. This will critically test the importance or otherwise of a much wider grain size range on the resulting stratigraphy (Fig. 4). We will also be able to characterise the mass transport deposits that are more common in Rosario systems compared to the Karoo (Fig. 14) and to see what differences these produce in terms of facies organisation and net:gross across the channel hierarchy. The role of MTDs as potential seals will also be addressed.

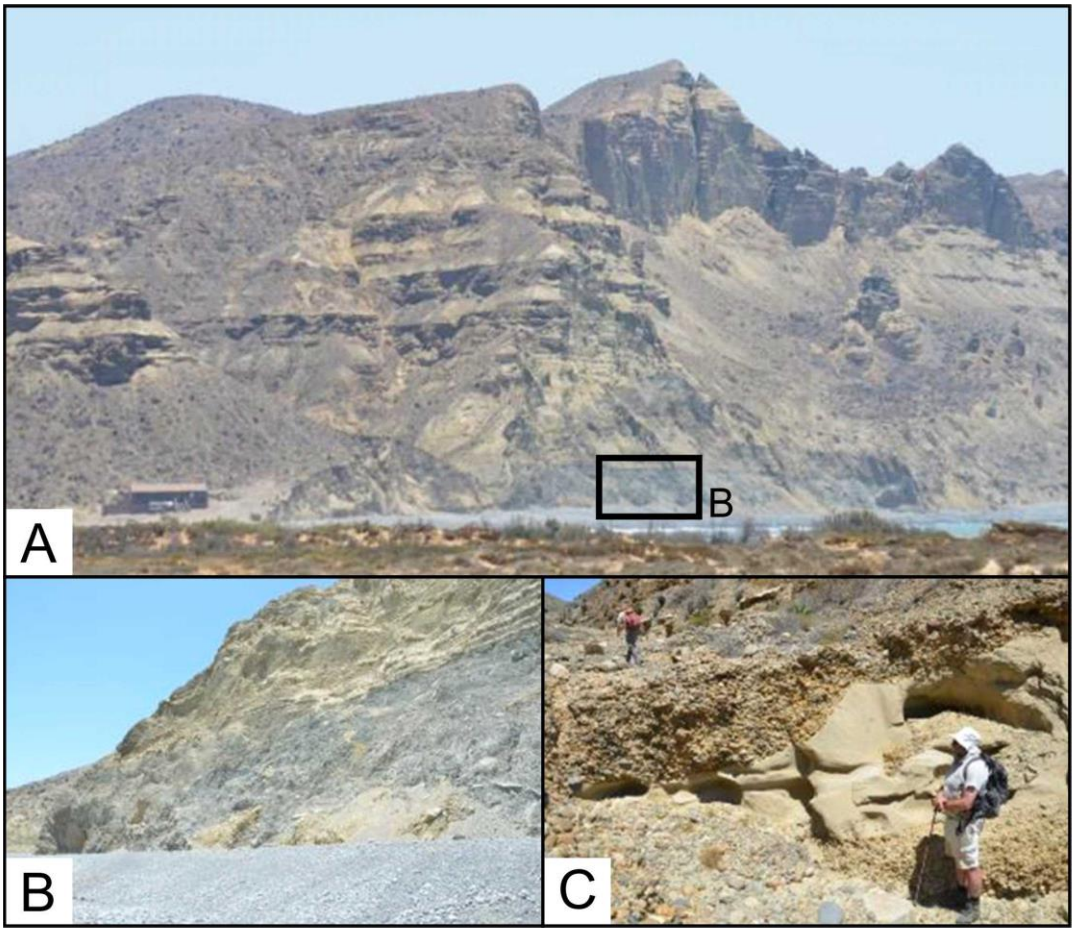


Figure 14: (a) Overview of one system of the Rosario Fm. at the coast. Black box marks position of (b), basal 12 m thick MTC overlain by bedded sandstones; (c) Facies within one phase of the canyon fill, showing extreme and abrupt grain size changes over short distances, hence likely complex permeability structure.

Work Package 2D: Hyperpycnal delta-fed slope channel systems, Austral basin, Tierra del Fuego

This work will provide a test of the geometrical and hierarchy models against a wider grain size but also with a system interpreted to be dominated by hyperpycnal flows related to extreme river flood events (Ponce and Carmona, 2011). We will assess objectively the evidence for hyperpycnal flows, but in either case it adds new depositional styles to the project, allowing us to understand what differences a different range of processes have on architecture. Individual channels are up to 500 m in width and 40 m in depth. The basal fills consist mainly of sandy conglomerates and pebbly sandstones, with subordinate large (up to 1 m) intraformational boulders and slump deposits (Fig. 15). The upper part of the channel fill is completely aggradational and consists of graded tabular beds, which onlap the erosive channel margins.

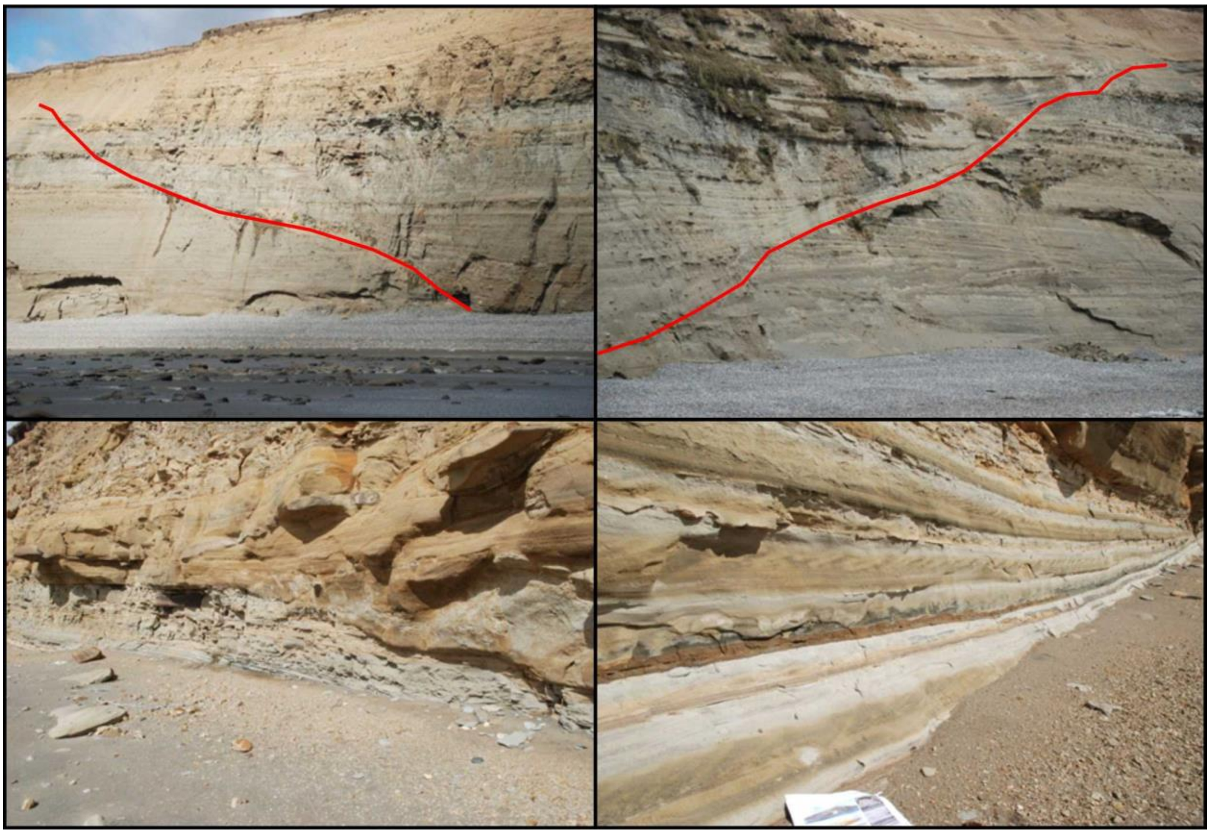


Figure 15: Exposures of slope channel complexes that allow characterization at multiple scales. Channels are up to 500 m wide and 40 m deep. Grain size reaches pebbles and these deposits have been interpreted previously as related to river flood-derived hyperpycnal flows, thus providing additional variation against which to test the Karoo-based predictive models.

Work Package 2E: Knick points in canyons, supercritical and transcritical flows and bedforms and resultant reservoir architecture

The complex slope morphology, wide grain size range, and active tectonic setting of the Rosario systems are likely to have resulted in greater flow complexity, including erosional and depositional bedform development under supercritical flows (e.g. Hage et al., 2018). These conditions may be linked to the presence and migration of knickpoints and their spatial and temporal migration within the canyon. We will test preservation of knickpoints in canyons using down dip sections through canyon-fills. The upstream migration of knickpoints, and associated bedforms, has been shown to be normal in canyons (Fig. 16), so can we identify their record in the rocks? In the last few years more robust recognition criteria have been developed to recognise the products of supercritical flows at outcrop (Ono and Plink-Bjørklund, 2018), supported by flume tank studies. Initial investigations suggest that both conglomeratic and sand-rich parts of the Rosario canyons were dominated by supercritical flow (Fig. 17).

Several questions will be addressed here: What is the role/importance of supercritical and transcritical (flows with both supercritical and subcritical components) flows in building deep-water reservoir elements? Can we support flume experiment evidence that systems dominated by supercritical behaviour are less well organised, with more frequent channel avulsion, hence different element geometries and connectivity? Are supercritical processes and products preferentially developed or preserved at specific time intervals (e.g. early vs late lowstand)?

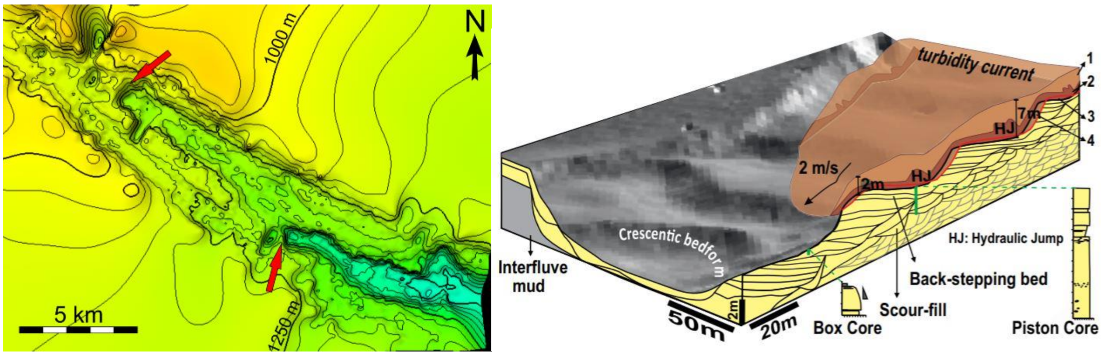


Figure 16: Left: Two phases of knickpoint (red arrows) migration identified through mapping the base of a canyon fill, Canterbury Basin margin, New Zealand (Wakka survey). Right: Summary schematic of crescentic bedforms formed by supercritical turbidity currents and their depositional architecture, based on observations from the Squamish River, British Columbia, Canada (Hage et al., 2018).

Figure 17: Punta Baja canyon fill deposits. A) Extensive intra-canyon turbidites (note incision from top left to bottom right). B) Thicker beds are formed from amalgamated upstream-migrating bedforms inferred to represent supercritical flow conditions; palaeoflow is well constrained from sole structures (flutes, tools, canyon wall incision orientation) and ripple-cross lamination.

Work Package 3: High resolution seismic and fluid flow modelling of facies and connectivity

In this work package, we will (a) test and extend the Karoo-based criteria for reliable recognition of different thin bed types in core, image logs and routine wireline logs, and better understand the likely contribution of thin bed STOIIP to recovery, (b) investigate the effects of facies-controlled permeability extremes on fluid flow in slope valleys and canyons, (c) investigate the hydraulic characteristics of different pinch-out types to understand stratigraphic trap integrity and (d) create seismic forward models to understand 'visibility' of stratigraphic trap geometries.

Work Package 3A: Thin beds – architecture, criteria for recognition of environment and connectivity

SLOPE phases 3 and 4 established reliable criteria to distinguish a range of thin-bedded slope environments: external levee, internal levee/terrace deposits, channel margin and frontal/lateral lobe fringe thin beds, thus aiding interpretation of net:gross and connectivity (Fig. 18). This work package will extend these recognition criteria to thin bed environments in other systems, in order to calibrate for different grain size ranges and process regimes. This will leverage the rich database of over 2 km of Karoo core that has not been fully exploited for understanding thin bed pay. We will also integrate key results from recent work in other deep-water basins such as the highly confined Annot and Jaca systems, plus core and wireline log datasets from Ainsa.

Thin-bed comparator table for sub-environment identification

Characteristics	Proximal External Levee	Distal External Levee	Channel margin	Lobe fringe
Average Bed thickness	5-20 cm	1-7cm	1-20cm thick	2-10cm thick
Average grain size – sand versus silt content	10-20% silt	40-45% silt	40-50% silt	60-80% silt
Large scale bedforms	✓	✗	✓	✗
Current Ripple laminae?	✓	✓	✓	✓
Climbing ripple laminae?	✓	✗	✗	✗
Stoss-side preserved ripple laminae?	✓	✓	✗	✗
Dm-scale cross laminae?	✓	✗	✓	✗
Multidirectional current laminae?	✗	✗	✗	✗
Dip changes above erosion surfaces?	✗	✗	✓	✗
%5Poorly sorted upper division?	✗	✗	✗	✓
Mud drapes?	✓	✓✓	✗	✗
Bioturbated?	✓ (1/2)	✓ (1/2)	✗	✗
Erosion surfaces – how common?	✓	✗	✓✓	✗
Are fining upwards sequences present?	✗	✓	✓	✓
Water escape structures?	✗	✗	✓	✗
Loaded bases?	✗	✓	✓	✗
Slumps and slides?	✗	✗	✓	✗

Figure 18: Recognition criteria for distinguishing superficially similar thin bed types and their depositional environments from core, image and wireline log data from behind-outcrop research wells, tied to Karoo outcrop geometries and architecture in SLOPE Phase 3. We will critically test and extend this work to the different types of deep-water systems being worked in Phase 5.

These will be augmented by detailed 2D architectural panels from the Karoo, Rosario, and Austral, in order to provide a full breadth of recognition criteria across different system types.

Additional targeted work will continue in the Karoo slope succession to characterise slope valley lateral seals and connectivity ranges with levees and older frontal lobes. This approach will rigorously test and extend the Karoo-based model into a globally calibrated model for deep-water exploration and development, and will improve prediction of recoverables in slope valley fills.

Work Package 3B: Modelling the effects of permeability extremes on fluid flow

Reconnaissance fieldwork in the Rosario shows very large grain size variability over short distances, both vertically and laterally (Fig. 14). It is therefore likely that facies-controlled permeability variability is extreme and will be investigated through the building of local reservoir models, embedding realistic oilfield facies-related permeabilities and simulating fluid flow to understand potential sweep efficiency and the effect of highly permeable thief zones. We will extend our Karoo work on thin-bed pay in slope channels and valleys, adding datasets from the Rosario and Austral outcrops and test for any generic differences. The S-Bed software will be used to build appropriate facies models.

Work Package 3C: Hydraulic characteristics and strat trap pinchout integrity

One way to partly quantify potential strat trap leakage is to build detailed models of the facies close to and at pinchouts, onlaps and bypass surfaces draped by mud (Fig. 5). We plan to use the S-Bed software to build small models, assign realistic subsurface permeabilities and undertake fluid flow modelling to address this important issue. There is the opportunity to compare results on stepped vs simple slopes and with different geometries of channel complexes in different settings, in order to investigate which slope styles are more conducive for development of stratigraphic traps.

Work Package 3D: Forward seismic modelling of pinchouts

A key challenge in the interpretation of pinch outs in seismic datasets is the determination of the true pinch out edge. Typically this is the seismic detectability limit, where the amplitude of the response falls below the background noise level. By creating seismic forward models of outcrops exhibiting a range of pinch out styles, it may be possible to relate attributes such as the rate of change of reflection amplitude approaching the detectability limit, or the width of the tuning zone, to the rate of bed thinning and extent of sand (Bakke et al., 2013). We will undertake forward seismic modelling using a range of source frequencies and realistic rock properties from well-known producing basins to investigate how well the key building blocks of slope reservoirs can be constrained from seismic data alone (Fig. 19). We will investigate how net:gross estimates vary as a function of seismic resolution compared to the known net:gross of the outcrop. Initial models were built in Slope Phase 3 for the CD Ridge unit in the Laingsburg depocentre of the Karoo Basin.

The range of models will be delivered to sponsors for direct comparison with their own subsurface examples but with the sub-seismic details of architecture, connectivity and hierarchy will be provided. To leverage the latest digital integration processes, we plan to create a digital atlas that links modelled seismic geometries to both seismic and sub-seismic scale drone flypast imagery, such that the sponsors can visually appreciate the facies types, likely net:gross and sub-seismic geology. This will allow ‘zoom-in’ to understand the sub-seismic geological detail that controls fluid flow. The datasets will be useful in training schools, as has been demonstrated in the Karoo.

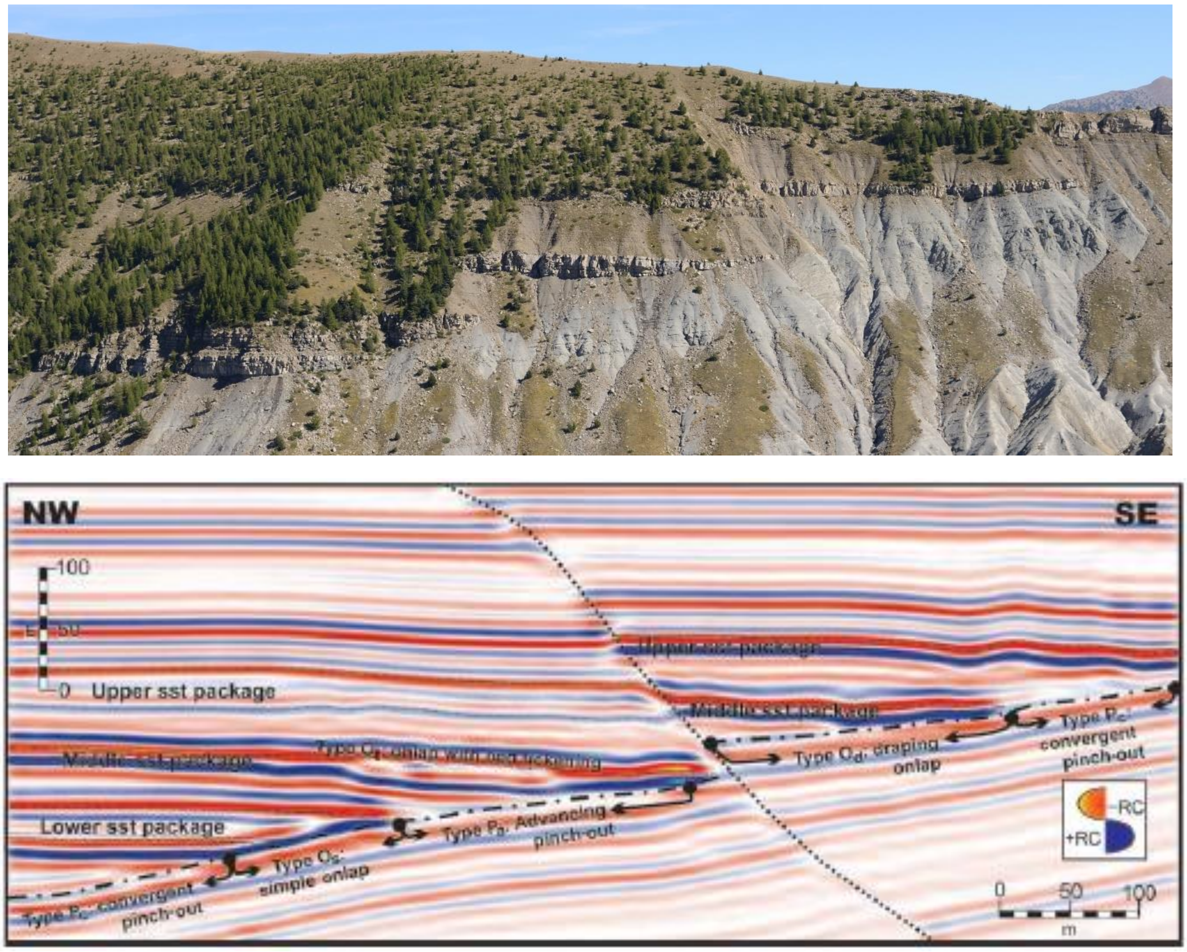


Figure 19: The Chalufy deep-water onlaps, Annot Basin, French Alps, with high-resolution (50 Hz) forward seismic model from Bakke et al. (2013). The 50 Hz frequency gives a vertical resolution of ~12-m. Heterolithic units are low amplitude compared to the sandstone units.

Work Package 4: Embedding the project results in sponsor knowledge bases and workflows

Work Package 4A: Annual field-based progress workshop and data delivery

As with previous phases of the project, we will invite representatives of the sponsor companies to an annual workshop (Fig. 20), which will include a formal steering committee meeting to discuss progress against objectives and timeline.

Work Package 4B: Embedding the project results

The PIs will hold workshops in sponsor companies at the 18 month halfway point and at project end, to work with colleagues to ensure that the project results are comprehensively understood and applied to sponsor assets, to guarantee added value (Fig. 20).

Work Package 4C: Overall Project Deliverables

Each work package has specific deliverables stated above but this work package for the P.I.s will ensure integration of the results into key predictive understandings and approaches to the two overarching themes of **Global exportability of slope system architecture** and **Multiscale analysis of slope channel related stratigraphic traps**:

I. An integrated, semi-quantitative predictive model for the range of stratigraphic traps in deep-water slope systems and geological risk analysis of factors controlling their integrity (**Theme 2: Work Package 1, 3A, 3C, 3D**)

II. Documentation and understanding how different shelf edge delivery systems control the nature of slope turbidites, the architecture of canyon-fills, and across-strike variability (**Themes 1 and 2**: **Work Packages 1, 2A, 2B, 2D, 2E**); In the Rosario this work will include mapping and characterising the seismic-scale 'wedges' from shelf-edge canyons into expanded successions basinward.

III. Extension of the Karoo-based architectural hierarchy scheme for slope channel deposits in very different grain size systems with a range of delivery styles (shelf edge delta, possible hyperpycnal river; karstified carbonate) (**Theme 1: Work Packages 2A, 2B, 2C, 2D, 2E, 3A**).

IV. The likely effect of facies controlled permeability extremes will be investigated through small scale fluid flow modelling using realistic rock properties from subsurface datasets (**Themes 1 and 2: Work Package 3B**);

V. A range of forward seismic models using outcrop geometries and realistic rock properties from exploration plays to test the levels of uncertainty in net:gross and connectivity prediction at common seismic resolutions, with specific reference to stratigraphic trap pinchout geometries (**Theme 1: Work Package 3D**); This will be linked into a digital atlas that links modelled seismic geometries to both seismic and sub-seismic scale drone flypast imagery, such that the sponsors can visually appreciate the facies types, likely net:gross and sub-seismic geology.

VI. Geochronology of the Rosario study systems, based on a combination of biostratigraphy and U-PB dating of detrital zircons to establish the history of sediment supply, canyon storage and flushing, and the role of tectonics in driving relative sea-level changes and shoreline displacement (**Theme 1: Work Package 2B**).

The final product will allow sponsors to interrogate the datasets, from frontier exploration scale, low resolution seismic scale, down to the individual reservoir element and its core/well log expression, in a consistent sequence stratigraphic hierarchy. The overall aim is to provide a range of more deterministic models for slope systems at all scales, reducing the need for statistical approaches, due to globally calibrated parameters. Time and budget are allocated for the PIs to visit sponsors for short handover workshops to ensure that project deliverables are embedded into subsurface workflows (Fig. 20).

Project Management and Team

As with SLOPE Phase 4, we will continue the co-location of the project between the Universities of Manchester and Leeds. This arrangement worked very effectively in Phase 4, with monthly project meetings alternating between the two sites. The PhD students build valuable professional relationships in both Schools and the project gains useful peer review/assist from colleagues in both Universities.

The project will be coordinated by Professor Stephen Flint, Professor David Hodgson and Dr Ian Kane, who joined the Faculty at Manchester in 2015 from Statoil. Ian has published extensively on the Rosario deep-water succession. In his 5 years at Statoil Ian was a user of the earlier SLOPE project phases, amongst other JIPs, and brings an industry perspective to the project. The zircon geochronology work package will be led by Dr Stephen Hubbard (University of Calgary), a recognised expert in this area. The experienced project team will include Dr Rufus Brunt (Manchester), who has been in the SLOPE project since Phase 2 and also has extensive experience in the Annot Basin and Dr Adam McArthur (Leeds) who has worked the Rosario and brings expertise in linking sedimentology, biostratigraphy and palynofacies analysis. Long term continuity with the Karoo project is enhanced by the continued involvement of Dr Miquel Poyatos-Moré (Slope Phase 4 post-doc), now at the University of Oslo.

In terms of work allocation within the overall integrated team, the Post-Doc will be responsible for Work Packages 1 and 2, although fieldwork will be carried out by a team including all the above members. One of the PhD students will focus on Theme 1 recognition criteria for thin bed types and comparison with the Karoo and other core and well log datasets and with flow modelling, cores and well logs (Work Package 3). The other PhD student will focus on the architecture and lateral facies changes in thin beds associated with strat traps and will include seismic forward modelling.

Timing

The planned project start is spring 2019 (Fig. 20). The project will run for 3 years with the customary annual sponsors' field workshops, including South Africa, Argentina and Mexico, supplemented by reporting visits to sponsors at the 18 month and 36 month points. In addition, project progress presentations are planned to be held privately at the AAPG annual conventions.

Budget

With 8 of the 15 current sponsors continuing to fund the project the cost is £33,000 per year for 3 years and this is considered the minimum number of sponsors to achieve the project objectives. With any additional sponsors we will keep the ticket price the same but add more team members / staff time and additional PhD students. With extra sponsors, a planned new component to SLOPE will be the development of machine learning approaches to identification of facies, architectural elements and stacking patterns within the stratigraphic hierarchy. This work will be developed on the 2 km+ of core and image logs in the well understood Karoo systems and extended to work on selected cores from Ainsa. Additional objectives will include further work with S-Bed models of strat trap pinchout styles and a wider range of seismic forward models integrated with UAV surveys.

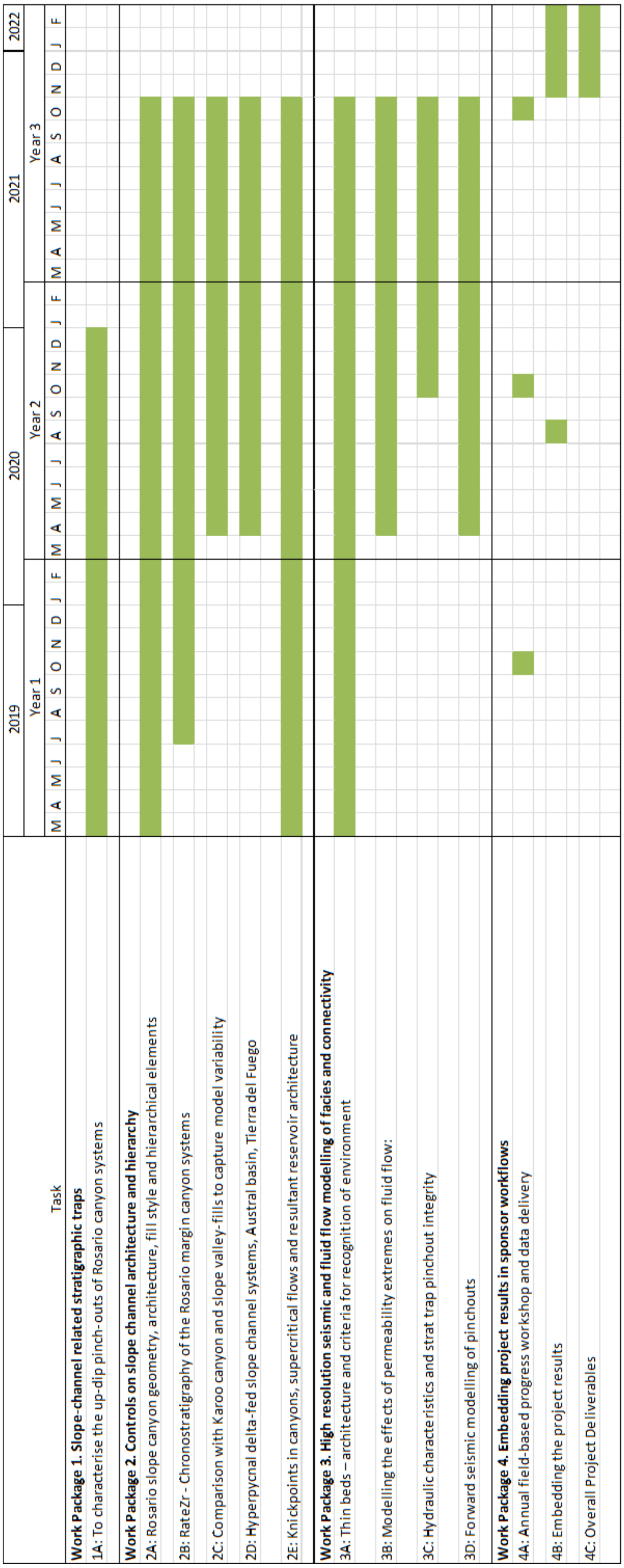


Figure 20: Proposed phasing of the different work packages and annual sponsor field workshops. NB: The time frame is displaced by 9 months, with project start now in November 2019.

Report preparation

This will be undertaken during the last 6 months of the project period, by the whole study team. The report format will be, as usual, an interactive CD-based searchable HTML document with accompanying GIS and spreadsheet databases. In addition, there will be a series of short videos shot from UAVs to highlight spatial relationships and geometries. Sponsors will also receive electronic copies of the PhD theses. The P.I.s will hold workshops in sponsor companies at project end, to work with colleagues to ensure that the project results are comprehensively understood and applied to sponsor assets, to guarantee added value.

Costs

GBP 33K per year for 3 years

For new sponsors, there is a buy-back fee of 1 year of the previous phase (GBP 30,000, which releases the final reports for SLOPE Phases 1-4 (15 years of work).

References

Bakke, K., Kane, I., Martinsen, O., Petersen, S., Johansen, T., Hustoft, S., Hadler Jacobsen, F., Groth, A., 2013, Seismic modelling in the analysis of deep-water sandstone termination styles. AAPG Bulletin, 97, 1395–1419

Boehike, J.E., Abbott, P.L., 1986, Punta Baja Formation, a Campanian submarine canyon fill, Baja California, Mexico. In: Cretaceous Stratigraphy of Western North America, (Ed. Abbott, P.L.) Speical Publication 46, SEPM, 91-101.

Bouma, A.H., Wickens, H.D., 1994, Tanqua Karoo,ancient analog for fine-grained submarine fans, in Weimer, P., Bouma, A.H., Perkins, B.F. eds., Submarine fans and turbidite systems: sequence stratigraphy, reservoir architecture, and production characteristics. SEPM Gulf Coasts Section 15th Annual Research Conference, p. 23–34.

Brooks, H.L., Hodgson, D., Brunt, R., Peakall, J., Flint, S., 2018. Exhumed lateral margins and increasing flow confinement of a submarine landslide complex, Sedimentology, 65, 1067-1096.

Busby, C., Smith, D., Morris, W., Fackler-Adams, B., 1998, Evolutionary model for convergent margins facing large ocean basins: Mesozoic Baja California, Mexico. Geology, 26, 227-230.

Daniels, B.G., Auchter, N.C., Hubbard, S.M., Romans, B.W., Matthews, W.A., Stright, L., 2018, Timing of deep-water slope evolution constrained by lange-n detrital and volcanic ash zircon geochronology, Cretaceous Magallanes Basin, Chile. GSA Bulletin, 130, 438-454.

Di Celma, C., Brunt, R., Hodgson, D., Flint, S., Kavanagh, J., 2011. Spatial and temporal evolution of a Permian submarine slope channel-levee system, Karoo basin, South Africa. Journal of Sedimentary Research, 81, 579-599.

Dykstra, M., Kneller, B., 2007. Canyon San Fernando: A Deep-Marine Channel-Levee Complex Exhibiting Evolution from Submarine Canyon-Confined to Unconfined, in: Nilson, T., Shew, R., Steffens, G., Studlick, J. (Eds.), AAPG Atlas of Deepwater Outcrops, Tulsa, p. 226–229.

Gastil, R.G., Philips, R.C. and Allison, E.C., 1975. Reconnaissance geology of the state of Baja California. GSA Memoir, 140, 170 p.

Gomis, L., Poyatos-Moré, M., Flint, S., Hodgson, D., Brunt, R., Wickens, H. DeV. 2017. Anatomy of a mixed-influence shelf-edge delta, Karoo Basin, South Africa. In: Hampson, G., Reynolds, A., Kostic, B. and Wells, M., eds., Sedimentology of Paralic Reservoirs: Recent Advances; Geol Soc Spec. Publ. 444, 393-418.

Gomis-Cartesio, L., Poyatos-Moré, M., Hodgson, D., and Flint S., 2018. Shelf-margin clinothem progradation, degradation and readjustment: Tanqua Depocentre, Karoo Basin (South Africa), Sedimentology, 65, 809-841.

Grecula, M., Flint, S., Wickens, H. DeV., Potts, G.J. 2003. Partial Ponding of Turbidite Systems in a Basin with Subtle Growth-fold Topography: Laingsburg-Karoo, South Africa. Journal of Sedimentary Research, 73, 603-620.

Grecula, M., Flint, S., Wickens, H. DeV., Johnson, S. 2003. Upward-thickening patterns and lateral continuity of Permian sand-rich turbidite channel-fills, Laingsburg Karoo, South Africa. Sedimentology, 50, 831-853.

Hage, S., Cartigny, M.J., Clare, M.A., Sumner, E.J., Vendettuoli, D., Hughes Clarke, J.E., Hubbard, S.M., Talling, P.J., Lintern, D.G., Stacey, C.D. and Englert, R.G., 2018. How to recognize crescentic bedforms formed by supercritical turbidity currents in the geologic record: Insights from active submarine channels. Geology, 46, 563-566.

Hodgson D.M., Flint S., Drinkwater N.J., Johannesson E.P., Luthi, S. 2006. Palaeogeographic and stratigraphic evolution of submarine fan systems in the Tanqua depocentre South Africa, Journal of Sedimentary Research, 76, 19-39.

Hodgson, D.M., Di Celma, C., Brunt, R., Flint, S., 2011. Submarine Slope Degradation and Aggradation and the Stratigraphic Evolution of Channel-Levee Systems. Journal of the Geological Society of London, 168, 625-628.

Hodgson, D.M., Kane, I, Flint, S., Brunt, R.L., 2016. Progressive submarine slope confinement and the progradation of basin-floor fans. Journal of Sedimentary Research, 86, 73-86.

Hofstra, M., Peakall, J., Hodgson, D.M., Stevenson, S., 2018, Architecture and morphodynamics of subcritical sediment waves in an ancient channel–lobe transition zone. Sedimentology, 65 (in press).

Johnson, S.D., Flint, S., Hinds, D., Wickens, H. DeV. 2001. Anatomy of basin floor to slope turbidite systems, Tanqua Karoo, South Africa: Sedimentology, sequence stratigraphy and implications for subsurface prediction. Sedimentology, 48, 987-1023.

Jones, G., Hodgson, D., Flint, S. 2015. Lateral variability in clinoform trajectory, process regime, and sediment dispersal patterns beyond the shelf-edge rollover in exhumed basin margin-scale clinothems. Basin Research, 27, 657-680.

Kane, I., Hodgson, D., 2011. Sedimentological criteria to differentiate submarine channel levee subenvironments: Exhumed examples from the Rosario Fm. (Upper Cretaceous) of Baja California, Mexico, and the Fort Brown Fm. (Permian), Karoo Basin, S. Africa. Marine and Petroleum Geology, 28, 807–823.

Kane, I.A., Kneller, B.C., Dykstra, M., Kassem, A., McCaffrey, W.D., 2007. Anatomy of a submarine channel-levee: an example from Upper Cretaceous slope sediments, Rosario Formation, Baja California, Mexico. Marine and Petroleum Geology 24, 540-563.

Kane, I.A., Dykstra, M., Kneller, B.C., Tremblay, S., McCaffrey, W.D., 2009. Architecture of a coarse grained channel-levee system: the Rosario Formation, Baja California, Mexico. Sedimentology 56, 2207-2234.

Kane, I.A., McCaffrey, W.D., Peakall, J.,2010.On the origin of paleocurrent complexity in deep marine channel-levees. Journal of Sedimentary Research 80, 54-66.

Maier, K.L., Johnson, S.Y., Hart, P., 2018. Controls on submarine canyon head evolution: Monterey Canyon, offshore central California. Marine Geology, 404, 24-40.

Morris, E.A., Hodgson, D.M., Flint, S., Brunt, R.L., Luthi, S.M., Kolenberg, Y. 2016. Integrating outcrop and subsurface data to assess the temporal evolution of a submarine channel-levee system. AAPG Bulletin, 100, 1663-1691.

Morris, W.R., 1992. The depositional framework, palaeogeography and tectonic evolution of the Late Cretaceous through Paleocene Peninsular Range forearc basin in the Rosario Embayment, Baja California, Mexico. Ph.D. Thesis, University of California, Santa Barbara, 240p.

Morris, W., Busby-Spera, C.J., 1988. Sedimentologic Evolution of a Submarine Canyon in a Forearc Basin, Upper Cretaceous Rosario Formation, San Carlos, Mexico. AAPG Bulletin, 72, 717–737.

Morris, W., Busby-Spera, C.J., 1990. A submarine-fan valley-levee complex in the Upper Cretaceous Rosario Formation: Implication for turbidite facies models. GSA Bulletin 102, 900–914.

Ono, K., Plink-Bjorklund, P., 2018. Froude supercritical flow bedforms in deepwater slope channels? Field examples in conglomerates, sandstones and fine-grained deposits. Sedimentology, 65, 639-669.

Ponce, J.J., Carmona, N.B., 2011. Miocene deep-marine hyperpycnal channel-levee complexes, Tierra del Fuego, Argentina: Facies associations and architectural elements; in Slatt, R.M. and Zavala, C., eds., Sediment transport from shelf to deep water: revisiting the delivery mechanism. AAPG Studies in Geology, 61, 75-95.

Poyatos-Moré, M., Jones, G., Brunt, R., Hodgson, D., Flint, S. 2016. Mudstone-dominated basin margin progradation: processes and implications. Journal of Sedimentary Research, 86, 863-878.

Prelat, A., Hodgson, D., Flint, S. 2009. Evolution, architecture and hierarchy of distributary deep-water deposits: a high-resolution outcrop investigation from the Permian Karoo Basin, South Africa. Sedimentology, 56, 2132–2154.

Pringle, J., Brunt, R., Hodgson, D., Flint, S. 2010. Capturing stratigraphic and sedimentological complexity in 3D digital outcrop models of submarine channel complexes, Laingsburg Formation, Karoo basin, South Africa. Petroleum Geoscience, 16, 307-330.

Sixsmith, P.J., Flint, S., Wickens, H. DeV, Johnson, S.D. 2004. Anatomy and stratigraphic development of a basin floor turbidite system in the Laingsburg Formation, main Karoo basin, South Africa. Journal of Sedimentary Research, 74, 239-254.

Spychala, Y.T., Hodgson, D.M., Prélat, A., Kane, I., Flint, S., Mountney, N.P., 2017. Frontal vs. lateral lobe fringe: Comparing sedimentary facies, architecture and flow processes. Journal of Sedimentary Research, 87, 75-96.

Van der Merwe, W., Hodgson, D., Flint, S. 2009. Widespread syn-sedimentary deformation on a muddy deep-water basin-floor: the Vischkuil Formation (Permian), Karoo Basin, South Africa. Basin Research, 21, 389-406.

Van der Merwe, W., Flint, S., Hodgson, D. 2010. Sequence stratigraphy of an argillaceous, deep-water basin plain succession: Vischkuil Formation (Permian), Karoo Basin, South Africa. Marine and Petroleum Geology, 27, 321-333.

Wickens, H.D., 1994. Basin floor fan building turbidites of the southwestern Karoo Basin, Permian Ecca Group, South Africa. Unpublished Ph.D. thesis, University of Port Elizabeth, 233 p.

Wild, R., Flint, S., Hodgson, D. 2009. Stratigraphic Evolution of the Upper Slope and Shelf Edge in the Karoo Basin, South Africa. Basin Research, 21, 502-527.

Appendix 1 – Outcrop study areas

The Rosario and Punta Baja systems of Baja California are the youngest unit of a belt of Upper Cretaceous sedimentary rocks that crop out discontinuously along the Pacific coastal margin of southern California and northern Baja California (Gastil et al., 1975) (Fig. 21). The formation consists of non-marine, shallow-marine, and deep-marine sediments predominantly sourced from volcanic and plutonic rocks of the Upper Jurassic to Early Cretaceous former arc complex to the east (Gastil et al., 1975), but also includes sedimentary and metasedimentary rocks (Morris & Busby-Spera, 1990), which were deposited in the Peninsular Ranges fore-arc-to the west (Busby et al., 1998). There are multiple slope conduits exposed along strike within the Rosario Formation. The Punta Baja system is an underlying deep-marine slope canyon filled with mass transport, conglomeratic and sand-rich channels, with associated sand-rich margins and internal levees.

Previous studies on the Rosario and Punta Baja systems

Most attention has been placed on a single system; the San Fernando System, with lesser work on the Mesa San Carlos System. Following the pioneering work of Morris and Busby-Spera (1988; 1990), two Industry JIPs on the Rosario have focussed on two of the eleven slope canyon systems (Dykstra and Kneller, 2007; Kane et al., 2007; 2009; 2010) but have not documented the longitudinal changes in architecture, or up-dip pinchouts. The great majority of the work has been on the well-documented San Fernando system (Fig. 9; 21), with multiple publications from the Aberdeen group over the last decade. Initial work on the Mesa San Carlos system includes two Masters theses from the University of Montana in 2008. These JIPs were funded by several of the SLOPE project companies. It makes no sense to repeat any earlier work on the Rosario. Therefore, reconnaissance fieldwork was undertaken in June 2018 to assess the potential of other Rosario canyon systems, some of which have never been worked, beyond the pioneering regional mapping of Morris (1992). Figure 9 shows both the geographical and stratigraphic extent of the previous studies in the regional context of the Rosario and shows clearly how much of the margin has not been worked. Our fieldwork also confirmed that (a) the different systems show a wide range of architectural styles and net:gross ranges compared to the San Fernando system and (b) exposure and access considerations will allow us to successfully address all the project objectives. We noted the excellent exposures of the older Punta Baja Fm., which is a canyon and infilling channel system, incised into and overlain by fluvial to shallow marine rocks. The system offers excellent 3D control of the interfingering relationship between coarse-grained thalwegs, sandy channel margins, to overbank deposits, thus an opportunity to investigate connectivity and stratigraphic trapping in proximal channel settings.

The Punta Baja system has received little attention but offers excellent exposure of interfingering channel-margin-levees. Some basic mapping and facies analysis work has taken place (Boehike and Abbott, 1986; Morris, 1992) but there are no modern studies on this system, barring our own reconnaissance work (McArthur et al. in press).

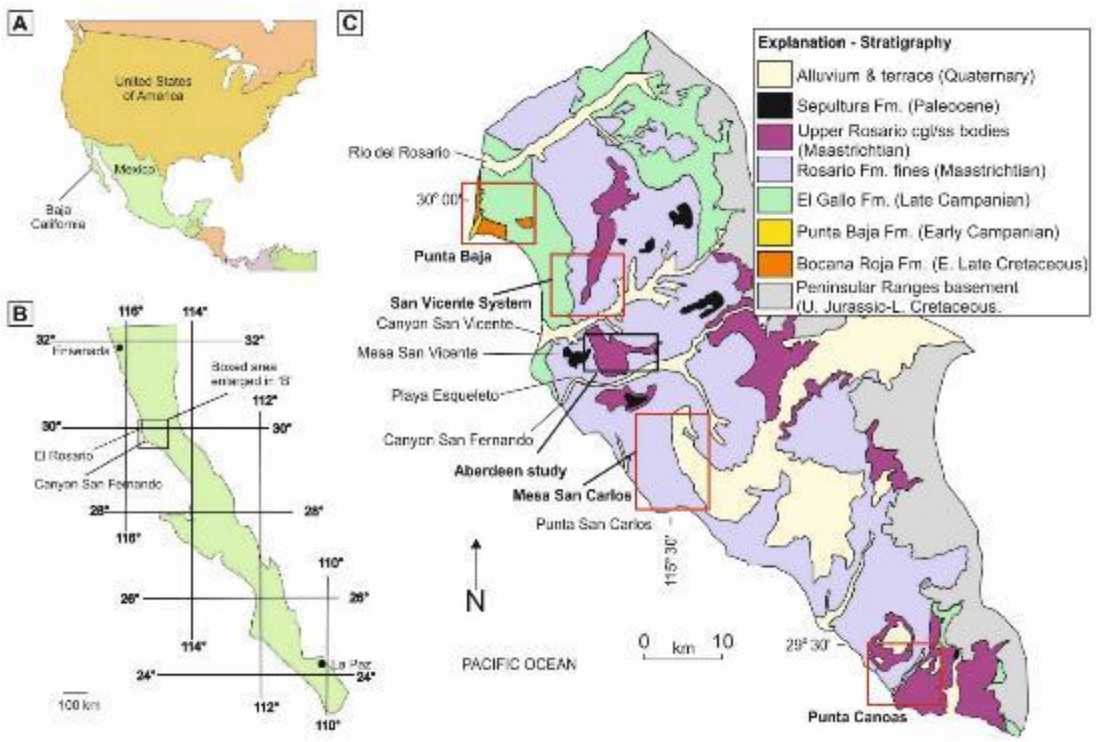


Figure 21: Location of the Rosario Formation, near to the town of El Rosario, Baja California. Proposed (red boxes) and previous (black boxes) study areas are highlighted.

The Austral Basin, exposed on the east coast of Tierra del Fuego, hosts up to 8000 m of rift (Triassic to Middle-Upper Jurassic), post rift (Upper Jurassic to Lower Cretaceous) and foreland (Upper Cretaceous to Cenozoic) deposits (Fig. 22). During this latter stage, sediment was sourced from uplifted areas in Central Patagonia and the Río Chico High located towards the northwest. Clastic wedges prograded towards the basin centre leading to a south-easterly migration of the depocentre.

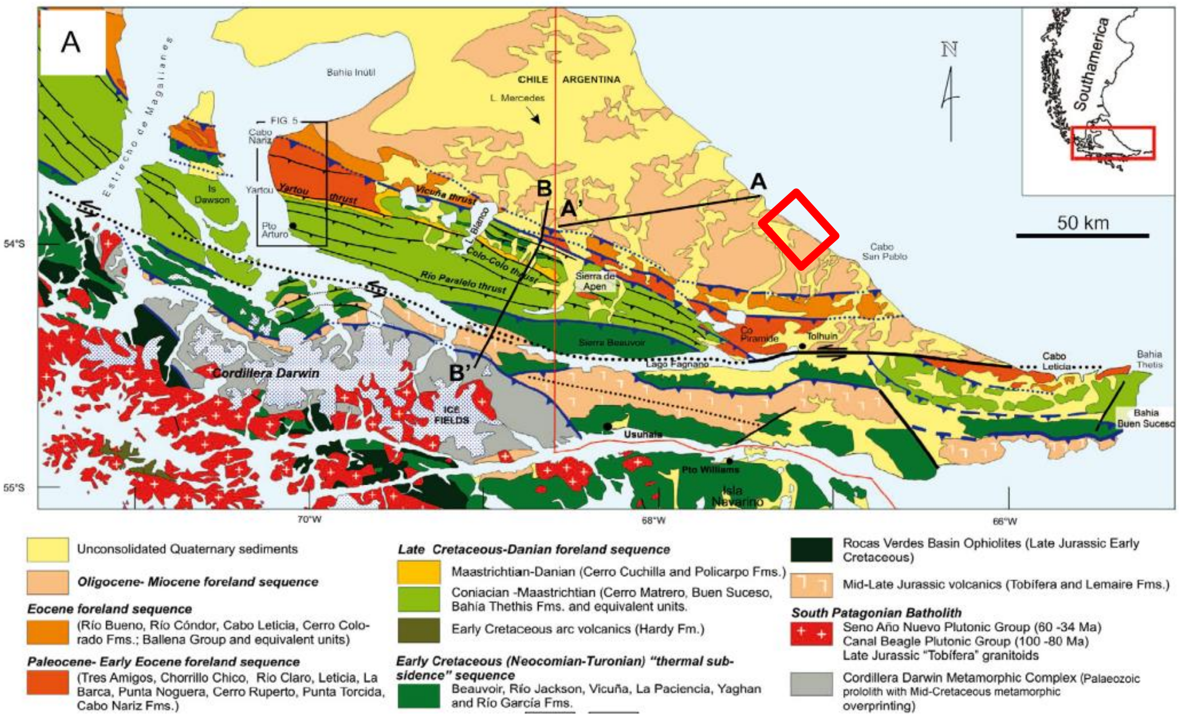


Figure 22: Location of the study area on the east coast of Tierra del Fuego, south of Rio Grande. Coastal cliff sections of the study sections have been visited 3 times by the P.I.s

In the Miocene Cabo Viamonte beds, deep-marine channel-levee complexes (CLC) were recognized at the toe of depositional slope breaks in sigmoidal clinoforms (Ponce and Carmona, 2011). The channel deposits show complex internal geometries characterized by multiple, large-scale, lenticular cut-and-fill structures. Individual depositional units bear abundant fossil leaves and show recurrent lateral transition of current sedimentary structures that reflect fluctuations in flow velocity. These features have been used by previous workers (Ponce and Carmona, 2011) to interpret deposition from hyperpycnal flows. We will critically assess this hyperpycnite interpretation and test the hierarchy model from the Karoo.

One of the key requirements for deep-water exploration in frontier and mature hydrocarbon basins is accurate predictive models for stratigraphic trap development and integrity in a range of slope settings, alongside the understanding of source-to-sink configuration, and the chronostratigraphic framework in which to estimate sediment supply volumes and routing. In field development, key requirements are sub-seismic prediction of geometry, architecture and connectivity and how these control facies-related permeability distribution. A quantitative understanding of the contribution of thin-bedded pay remains a critical risk in accurately estimating STOIIP and recovery.

The Karoo Basin of South Africa (Fig. 23) is one of the best known and most intensively studied deep-water outcrop analogue systems in the world. Early work in the late '80s and 1990s by Wickens (1994), Bouma and Wickens (1994) and the University of Liverpool (Johnson et al., 2001; Grecula et al., 2003a; b; Sixsmith, 2004), the area became the focus of a series of large Strat Group research projects from 2001 onwards (Fig. 1, 2), led by P.I.s Flint and Hodgson. The NOMAD project was a European Union 5th Framework project (2001-2004) that partnered the Universities of Liverpool, TU Delft and Stellenbosch with Statoil and Schlumberger Research in extensive fieldwork and completing a series of cored and image logged research boreholes. In 2004, the SLOPE project was initiated as a multi-company JIP, which has completed four 3-year phases (SLOPE 1, 2, 3 and 4). In addition, the LOBE project, largely based in the Karoo has completed two 3-years phases (LOBE 1 and 2) and LOBE 3 has recently started. Ten Karoo PhDs have been completed to date within SLOPE and LOBE and hundreds of industry colleagues have undertaken field schools and workshops in the Tanqua and Laingsburg study areas.

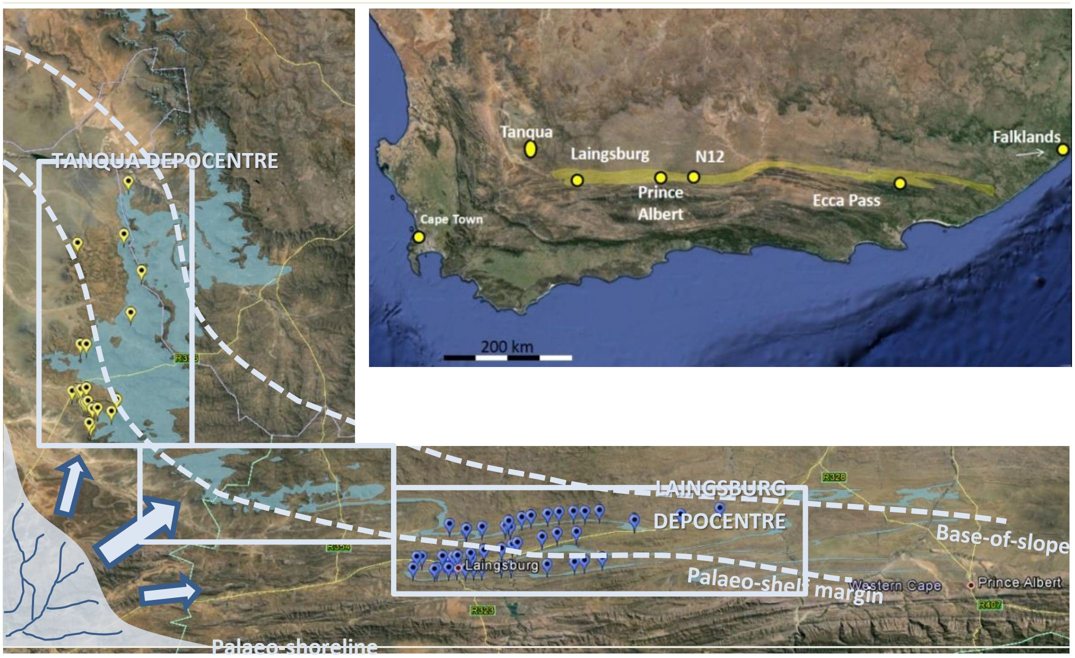


Figure 23: Location of the Tanqua and Laingsburg depocentres in the SW Karoo Basin, South Africa. The Permian deep-water system is interpreted to have been delta-fed from the southwest.

In SLOPE phase 5, the Karoo will serve as the reference database, against which to test the effects of changing a series of different parameters, as discussed above. We envision limited additional fieldwork in the Karoo to revisit specific issues that arise from the new studies in the Rosario and Austral systems, where (for example) levee geometries or channel margin thin bed lengths need to be compared.