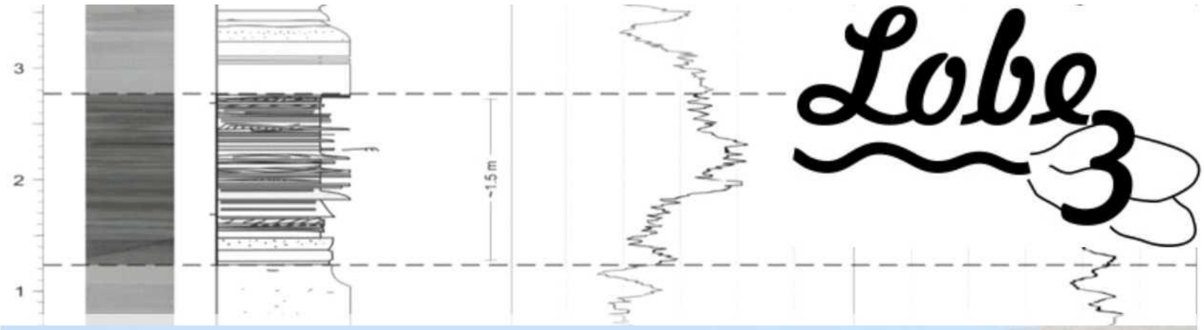
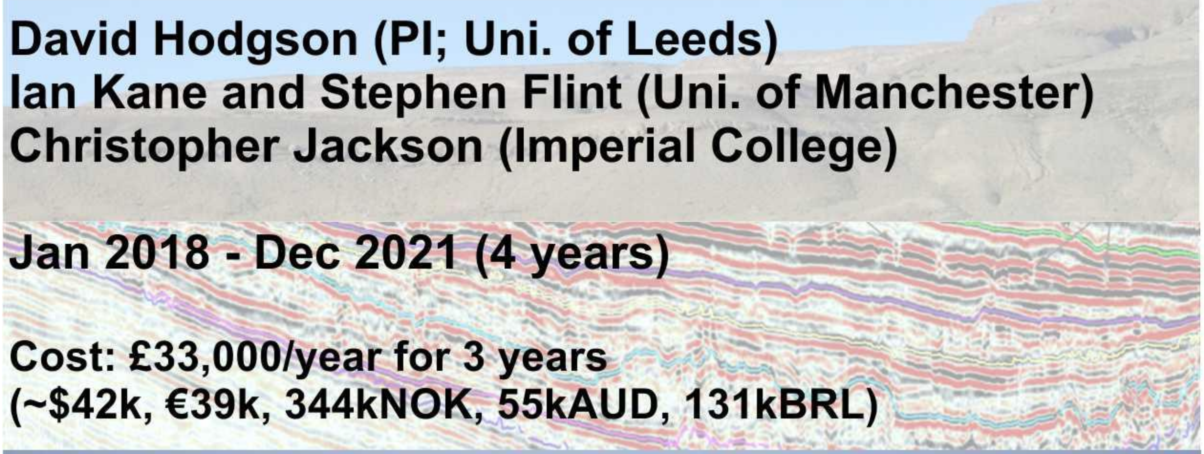
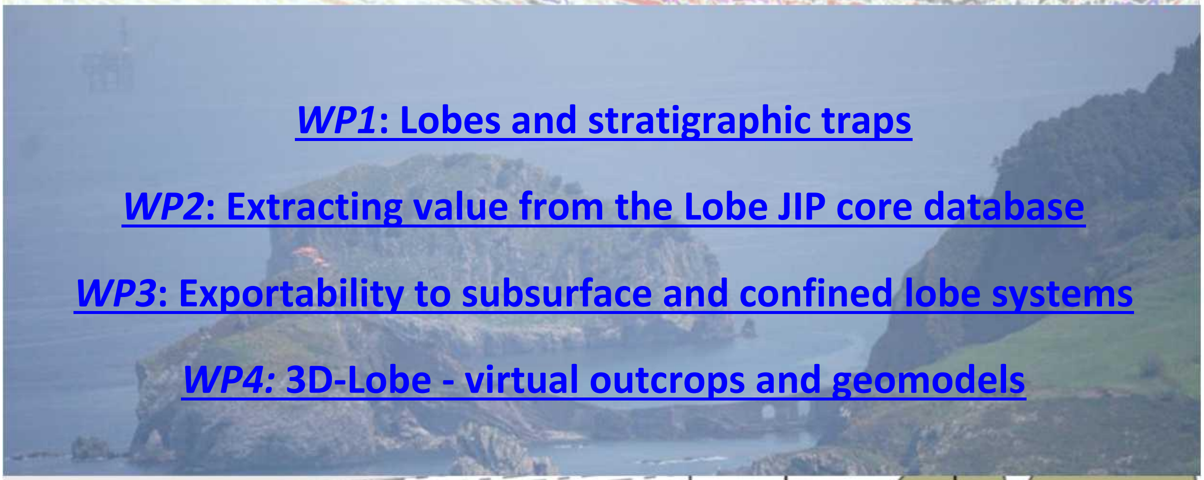




David Hodgson (PI; Uni. of Leeds)
Ian Kane and Stephen Flint (Uni. of Manchester)
Christopher Jackson (Imperial College)

Jan 2018 - Dec 2021 (4 years)

Cost: £33,000/year for 3 years
(~$42k, €39k, 344kNOK, 55kAUD, 131kBRL)

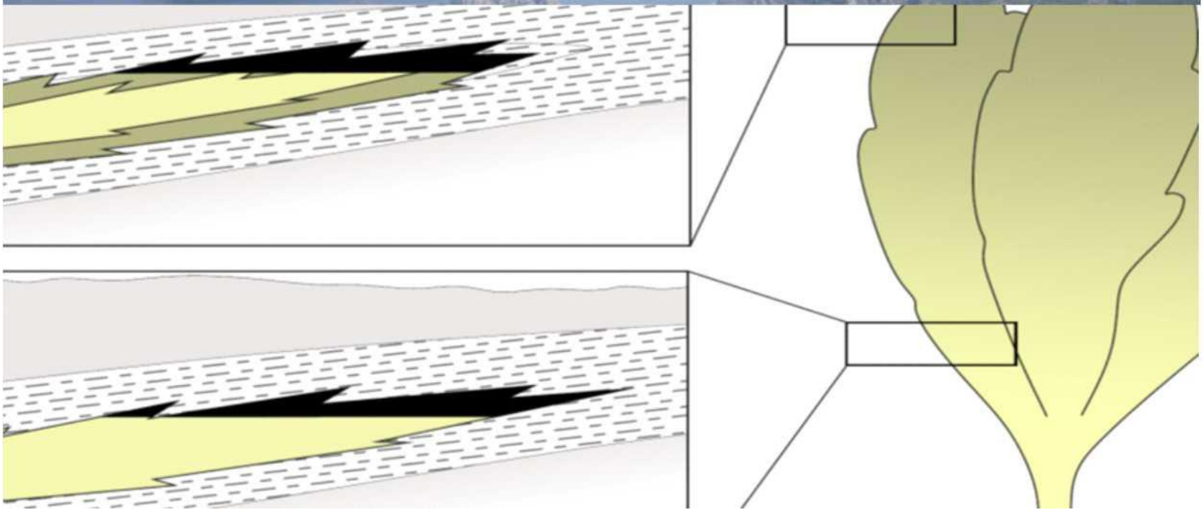


WP1: Lobes and stratigraphic traps

WP2: Extracting value from the Lobe JIP core database

WP3: Exportability to subsurface and confined lobe systems

WP4: 3D-Lobe - virtual outcrops and geomodels



Executive summary:

Lobe3 continues a long-standing and successful collaboration between Hodgson (PI) and Flint, and establishes a new collaboration with Kane and Jackson across three institutions. The central activity will be to extract additional value from the existing Karoo core database collected during Lobe2, and undertake further data collection in the Neuquén Basin (Argentina). In addition, the exportability of concepts and data will be tested in the Central North Sea, the Jaca Basin (Spain), and the Basque Basin (Spain) in order to:

i) reduce uncertainties in the geometry and distribution of base-of-slope to basin-floor **stratigraphic traps** associated with lobe systems (WP1)
ii) investigate impact of **salt diapirism** on submarine lobe deposit architecture (WP1)
iii) improve our ability to interpret **3D stacking patterns** of basin-floor systems from 1D well log data (WP2)
iv) quantify the **degree of confinement** of lobe systems (WP2)
v) test **exportability and applicability** of outcrop-derived concepts to data-rich post-rift subsurface systems and salt-influenced systems (WP3)
vi) **quantitatively compare** parameter between different systems (WP3)
vii) construct **geomodels and virtual outcrops** to support cost-efficient, non-field-based and blended training programmes, and archive Lobe JIP data in 3D (WP4)

Lobe3 will comprise four integrated Work Packages that will run concurrently, with Hodgson as PI, and the investigators forming a co-supervisory team for three associated PhD studentships with quarterly meetings to ensure commonality in approaches. The Lobe3 JIP will require a minimum of 5 sponsor companies to start.

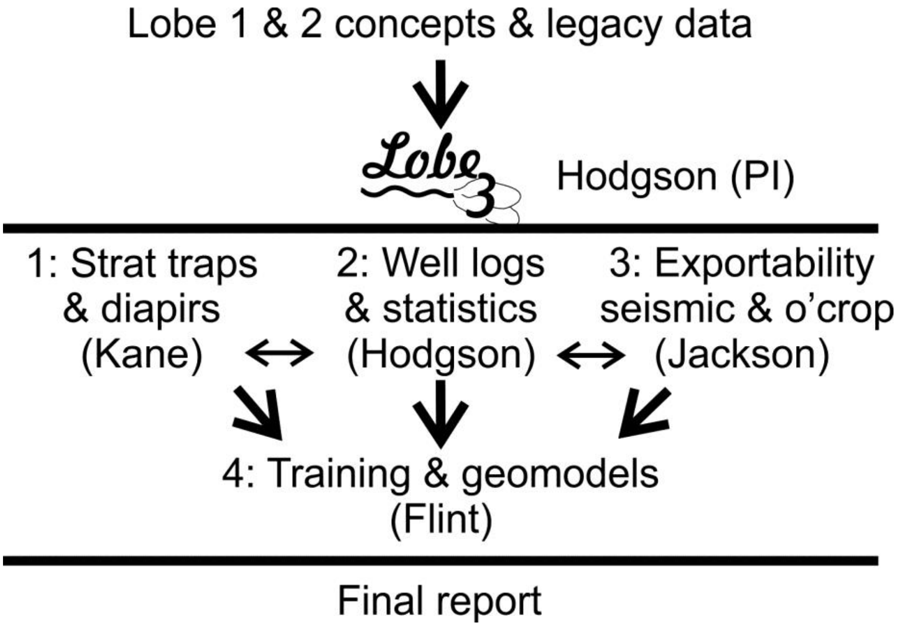


Figure 1: Structure of Lobe3 work programme as four Work Packages.

Lobe2 (2012-2016) highlights:

- **Seven fully cored research boreholes** with a full suite of well logs have allowed reliable direct calibration of core with borehole image log datasets, and comparison to adjacent outcrop 3-D geometry and architecture.
- Sedimentological and stratigraphic recognition criteria for **intraslope or perched lobes and lobe complexes** (Spychala et al. 2015).
- Recognition criteria to distinguish between basin-floor channel fills and **scour-fills**.
- Recognition and analysis of the suite of components that characterise **channel-lobe transition zones**, such as sediment waves, scour-fills, and base-of-slope lobes, to aid identification of the stratigraphic expression (Hofstra et al. 2015).
- A matrix of **key characteristics of lobes and lobe complexes** in different palaeogeographic positions to aid subsurface interpretation.
- Documented analysis of the effect of subtle (<1 degree) slopes on flow behaviour and stacking patterns in the construction of **thick aggradational lobe fringes** (Spychala 2017a).
- An assessment of the **stratigraphic relationship between sand-rich channel-fills, and underlying lobe deposits**, and how this can be used to infer avulsion dynamics, and the impact on reservoir quality and sandbody connectivity.
- For the first time, an assessment and process explanation for the differences in sedimentology between **frontal and lateral lobe fringes** (Spychala et al. 2017b).
- **Quantification of lobe thickness and facies proportions** by EoD.
- Reliable observation-based criteria have been established in core and well logs to distinguish between superficially similar **thin bed types**, including lateral, frontal, and aggradational lobe fringes.
- The integrated outcrop, core and well log results and interpretations from LOBE2 represent a unique dataset and housed in a new Statoil-funded core store for **training future generations** of geoscientists and petroleum engineers.

Figure 2: New Lobe2 and Slope4 core store, Inverdoorn, South Africa

Lobe3 programme summary:

***WP0:* Advances in submarine lobe sedimentology and stratigraphy** *(Lead: David Hodgson)*: The last decade, since the Lobe JIP began, has seen a huge increase in the number of studies of exhumed, modern, and ancient subsurface basin-floor systems. A comprehensive review of submarine lobe deposits is timely. We will compare facies proportions and distributions, dimensions, and stacking patterns across systems to identify commonalities and differences.

***WP1*: Lobes and stratigraphic traps** (*Lead: Ian Kane*): Stratigraphic traps form at pinchouts of lobes, and are plays in mature (e.g. North Sea) and frontier (e.g. Palaeogene GoM) hydrocarbon basins. Using outcrop and subsurface analogues, we can reduce the risks associated with targeting basin-floor and base-of-slope stratigraphic traps. Subsurface datasets lack the resolution to constrain the rates and styles of lateral facies changes, or the architectural relationships that impact reservoir quality at sand pinchouts. Outcrop analogues can help to constrain this. The interplay between structurally induced seabed relief and sediment gravity current flow processes are key to predicting, for example, the rate of thinning and changes in lithofacies (and hence reservoir quality) towards pinchout.

1.1 Investigation of the relationship between **salt diapirism and lobe deposition** will result allow us to build architectural panels from outcrop (Bakio, N Spain) and subsurface (Central North Sea) datasets; we will construct numerical models of growth (and collapse) with different sedimentation rates.

1.2 **Facies and seismic forward models** of the terminations of lobe complexes, with rates and styles of facies change constraining the 3D architecture of stratigraphic traps. This will use sandbody pinchouts from well-constrained basins, such as the Neuquén and Jaca Basins, where the architecture of dip sections crop out.

***WP2*: Extracting value from the Lobe JIP core database** (*Lead: David Hodgson*): The Lobe JIP heritage database comprises 14 research boreholes, and several kilometres of core, and is the world's best-integrated dataset of its type. The core and well logs were calibrated in Lobe2, with an atlas of element types compiled. However, a huge amount of potential remains in this database. This will be extracted and applied quantitatively to subsurface systems where the geometry of sandbodies, and the distribution of reservoir quality sand and heterogeneities in basin-floor systems are poorly constrained.

2.1 Detailed well-log analysis to characterise facies and different lobe elements identified in core, and to develop **electrofacies methodologies**, with a focus on thin-bedded successions. We will also investigate the use of machine-learning techniques to automatically pick elements based on well log character and shape.

2.2 Novel integration of the lobe dimension database to **numerically model lobe stacking patterns** in synthetic basins with different geometries and degrees of confinement. This will require stacking pattern and facies distribution data from confined lobe systems (e.g. Jaca Basin, Neuquén Basin) to condition the models.

***WP3*: Exportability to subsurface and confined lobe systems** (Lead: Christopher Jackson)

Lobe systems are documented from many different basin types. The Karoo and Neuquén lobe deposits share characteristics with many other systems in terms of dimensions, facies distributions, and stacking patterns. However, the exportability of concepts and models to systems with wider grain-size ranges, and more (active or static) seabed topography remains poorly constrained. A common subsurface setting is post-rift systems that can form volumetrically important reservoirs in several basins (e.g. Outer Moray Firth, Agat).

3.1 **Quantitative comparison across systems** will permit the utility and applicability of predictive models arising from largely outcrop-based research programs to be critically and quantitatively tested against other systems.

3.2 Publically available **subsurface datasets**, for example from NW Shelf of Australia, will allow testing of outcrop-derived predictive models. As an example, in this location, an early post-rift, Upper Jurassic deep-water succession, the Angel Fm., is penetrated by numerous wells and imaged by newly released 3D seismic reflection data in a tectonic setting that complements ongoing work in the Neuquén Basin, Argentina.

***WP4:* 3D-Lobe - virtual outcrops and geomodels** (Lead: Steve Flint):

Recent technological advances permit the construction of geomodels and virtual outcrops. Digital outcrop models of key Lobe JIP locations will support cost-efficient, non-field-based and blended training programmes (Fig. 2), and all Lobe data digitally archived

4.1 **Virtual outcrops** using UAV and photogrammetry (Fig. 3) to build geomodels of key outcrops tied to research boreholes. These can complement outcrop-based learning, allowing integration with in-house training modules, e.g., tied to seismic interpretation workshops, or in advance of targeted outcrop-based learning.

4.2 **3D Lobe**, housing the existing Lobe database in ArcGIS, GoogleEarth and Petrel, together with isopach maps, correlation panels etc., to provide easy company-wide access to all the available Lobe JIP data. This approach was a successful outcome from Slope 4 JIP.

Figure 3: UAV-based photograph of Unit A near the town of Laingsburg. The stratigraphic thickness of succession of stack lobe complexes in this view is ~130m.

Summary of Lobe3 deliverables

WP1 - Lobes and stratigraphic traps

- Architectural panels from the outcrop and subsurface cases with measured sections showing the rate of facies change, bed thinning and the effects of active topographic development on lobe growth, facies and stacking patterns, and resultant reservoir and reservoir quality distribution.

- Computational geometrical models for case studies to examine architectural response to variable boundary conditions, e.g., structural growth, sediment supply; these will result in more generically applicable models.

- Detailed quantified architecture and facies panels from the outcrop and subsurface cases with measured sections showing the rate of facies change,% sandstone, bed thinning and the effects of active topographic development on lobe growth, facies and stacking patterns, and resultant reservoir and reservoir quality distribution.

- Seismic forward models tied to facies patterns observed in outcrop and compared directly to the salt-affected cases from strike and dip sections.

WP2 - Maximising value and application of the Lobe well database

- Refined down-hole recognition criteria in core and wireline log datasets for lobe elements, lobes and lobe complexes in different positions (axis to fringe).

- Statistical analysis of thickness trends in lobe tied to outcrop constrained hierarchy.

- Numerical modelling of lobe and lobe complex stacking patterns from 1D data to support interpretation of the degree (and style) of system confinement.

WP3 – Subsurface analysis of lobes

- Raw quantitative data compiled from existing databases, new data collected in other Work Packages, and the published literature, to construct parameter space plots for different aspects of lobe systems, such as rate of thinning, tied to different configurations. Sponsor companies will be able to readily plot their own data to identify suitable analogues and help to reduce uncertainty.

- Refined down-hole recognition criteria in core and well-log datasets for lobe elements, lobes and lobe complexes, thereby complimenting outcrop-derived deliverables from WP2.

- A suite of stratigraphic and architectural panels for lobe systems in late syn-rift to early post-rift deep-water successions

- An atlas-style compilation illustrating the seismic, core and well-log expression of deep-water depositional elements

WP4 - 3D-Lobe - virtual outcrops and geomodels

- Support to WP1 and WP2 by extending the analysis of pinch-out styles for lobes in different settings into 3D and near-3D to better understand local variability

- Support to WP3 by comparing seismic scale geometries with equivalent outcrop geometries, while embedding the sub-seismic detail within the models.

- Training images of different lobe types for use in MPS geological modelling

WP1 - Lobes and stratigraphic traps (Lead investigator: Ian Kane):

Rationale: Stratigraphic traps form at pinchouts of lobes and lobe complexes in mature (e.g. North Sea) and frontier (e.g. Wilcox Group, GoM) hydrocarbon basins. Using outcrop and subsurface analogues, we can reduce the risks associated with targeting basin-floor and base-of-slope stratigraphic and combination traps. Subsurface datasets typically lack the resolution to constrain lateral facies and architectural relationships affecting reservoir pinchouts; outcrops can be used to constrain this. The interplay between structurally induced seabed relief and sediment gravity current processes are key to predicting, for example, the rate of thinning and change in lithofacies (and hence reservoir quality) towards pinchout. Two cases will be examined in detail: 1) Salt-affected lobes, and 2) Partially-confined lobes in a post-rift setting.

1.1 Salt-affected lobes: Investigating the relationship between salt diapirism and lobe deposition will result in quantified architectural panels from both outcrop (Bakio, N Spain, Fig. 4, https://youtu.be/DPYRDwN6IVc) and subsurface (Central North Sea) case studies; computational numerical models of growth (and collapse) with different sedimentation rates. These can contribute towards a better understanding of stratigraphic trapping potential and realistic column height estimation (Fig. 5).

Figure 4: Turbidite lobes and debrites onlapping salt-related topography; note the convergence of beds towards the palaeotopography of the salt diapir. This area has been the focus of structural and broad stratigraphic studies, but no detailed sedimentological and architectural work has been completed previously.

Many of the challenges associated with deep-water exploration are exemplified by basins affected by salt diapirism, where complex and evolving topography affects the behaviour of incoming sediment-gravity-flows, and accordingly the architecture of sedimentary systems around them. The prolific hydrocarbon province of the Central Graben, North Sea, is an area where sediment-gravity-flow deposition was strongly influenced by salt diapirism. The key aim of this work package is to determine the evolution of lobe sedimentary sequences deposited above and adjacent to active salt diapirs, with the aim of discerning 'halokinetic sequences' (i.e., sedimentary units directly affected by salt movement) from 'autocyclic sequences' (i.e., lobes or other architectural elements reflecting autocyclic evolution of a sedimentary system). Detailed architectural panels with quantified facies data will be used to provide insight into stratigraphic trapping potential, and the influence that onlap facies may have on, for example, column height estimation in the subsurface.

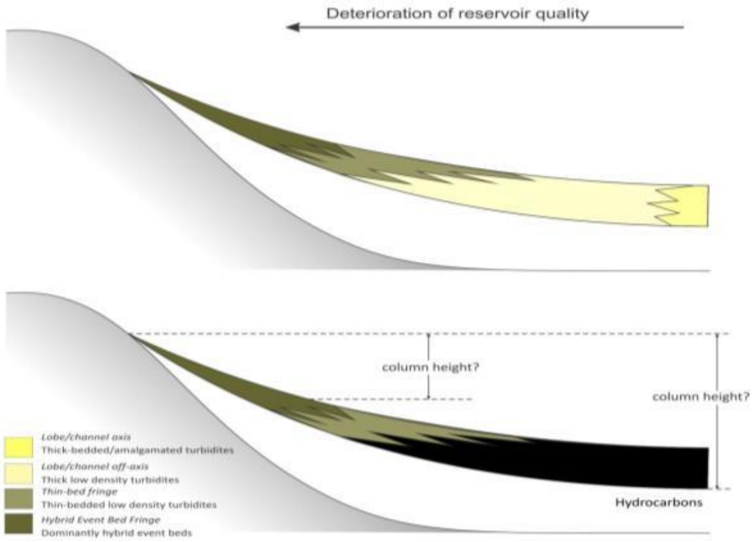


Figure 5: Reservoir quality typically decreases towards pinchout. The rate of decay and the height the reservoir extends up palaeotopography are a primary product of sediment gravity flow character; conservative column height estimations may mean that good reservoir may be entirely missed by appraisal wells.

Three principal strands will form the basis of this investigation: 1) an outcrop case study of the Bakio salt diapir in the Basque Country, Spain (Fig. 4); 2) a subsurface case study from the Central Graben, Northern North Sea (e.g. Banff, Machar diapirs, and others); 3) geometric modelling of deep-water sedimentary packages adjacent to static and dynamic topography to discern the relative influence of structural and sedimentological controls on stacking patterns and architecture.

Research questions:

How are facies and reservoir quality distribution affected by structural growth?

How does rate of salt/structural growth affect lobe stacking patterns compared to fully-unconfined lobes such as the Skoorsteenberg Fm. (Tanqua Karoo), or largely confined lobes in relatively static basins, such as the Grès d'Annot (France)?

What are the implications for effective stratigraphic trap development and assessment of column height in subsurface datasets?

Deliverables:

1) Architectural panels from the outcrop and subsurface cases with measured sections showing the rate of facies change, bed thinning and the effects of active topographic development on lobe growth, facies and stacking patterns, and resultant reservoir and reservoir quality distribution.

2) Construction of computational geometrical models for the case studies to examine architectural response to variable boundary conditions, e.g., structural growth, sediment supply; these will result in more generically applicable models.

1.2 Quantitative stratigraphic traps analysis: Several examples of basin-floor sandbody pinchouts are well established from the Tanqua and Laingsburg databases. However, the slope gradients that confine these systems are rarely greater than 1 degree (Fig. 6). This means that their waste zones are normally wide, making them unsuitable as analogues for many stratigraphic trap configurations. Therefore, we will utilise superbly exposed lobe and lobe complexes pinchout successions identified by Lobe2 PhD student, Aurelia Privat in the Los Molles Formation, Neuquén Basin, Argentina, to develop facies and architectural panels (Fig. 7). Of particular interest is the number of dip sections through post-rift onlaps, which remain undocumented in exhumed examples. These panels will be used to seismic forward model terminations of lobe complexes, with rates and styles of facies change (% sandstone, amalgamation ratio etc.; Fig. 8) to constrain the 3D architecture of stratigraphic traps. This will improve the assessment of stratigraphic traps in lobe complexes in conventional seismic data. In addition, the close association of stratigraphic traps and injectite complexes (Cobain et al. 2017) and will be explored in other basins, and included as a variable in forward seismic models.

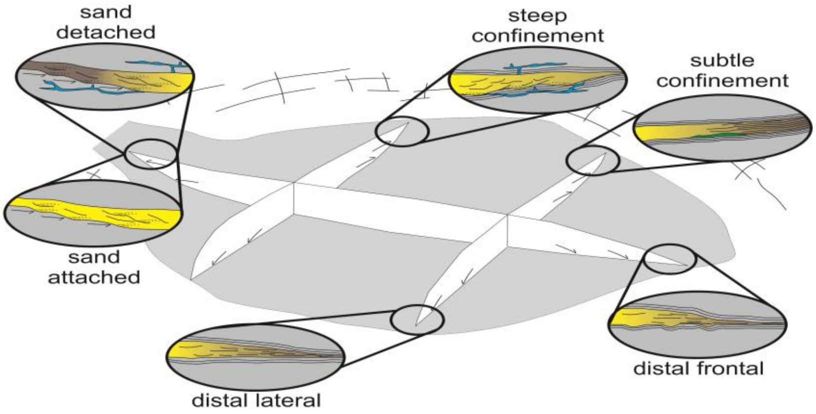


Figure 6: Different pinchout configurations of lobe complexes in base-of-slope to basin-floor configurations.

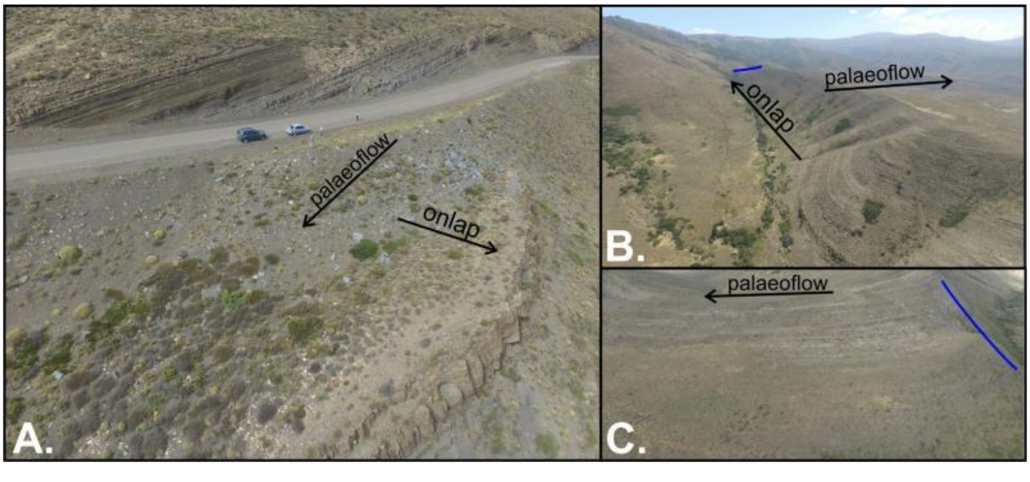


Figure 7: Deep-marine strata onlap several intrabasinal slopes in the post-rift Los Molles Formation, Neuquén Basin, Argentina. The orientation of palaeoflow and inherited structures means that dip sections through onlaps are common (A). Blue line in (B) and (C) references the same location.

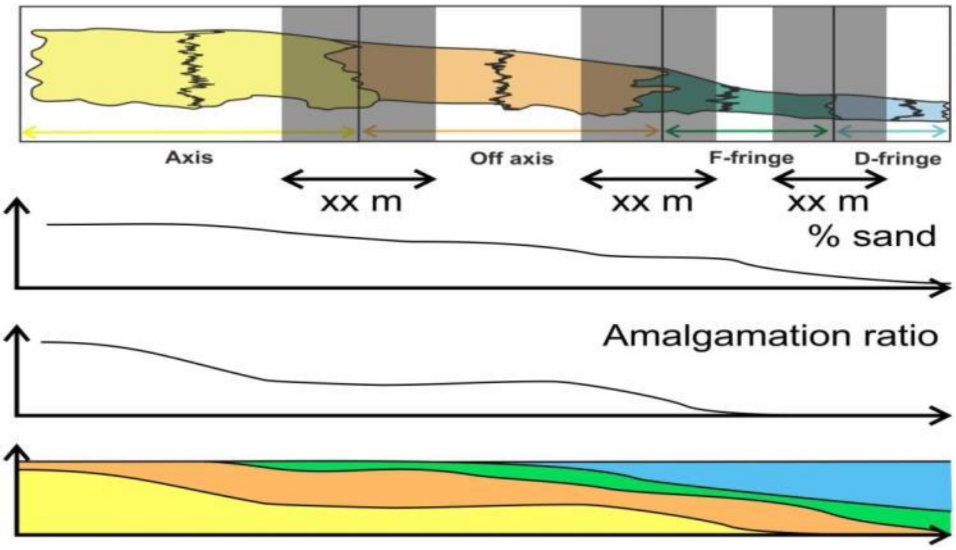


Figure 8: Cartoon to illustrate the key data from exhumed analogues of deep-water stratigraphic traps: width of transition zones, amalgamation ratio, percentage sandstone, nature of base and top contacts, and facies proportions. These data can be used to improve geological models, and produce synthetic seismic models.

Research questions:

How are facies and reservoir quality distributed in a gently subsiding post-rift setting?

What are the implications for effective stratigraphic trap development of varying sediment gravity flow deposits and their run-out distances?

Deliverables:

1) Detailed quantified architecture and facies panels from the outcrop and subsurface cases with measured sections showing the rate of facies change, bed thinning and the effects of active topographic development on lobe growth, facies and stacking patterns, and resultant reservoir quality distribution.

2) Seismic forward models tied to facies patterns observed in outcrop and compared to the salt-affected cases and unconfined cases.

WP2 - Maximising value and application of the entire Lobe core and well log database (Lead: David Hodgson):

Rationale: The Lobe JIP databases comprise eight research boreholes, and with the heritage NOMAD database, this totals ~3.5 km of core and well logs. These data have been calibrated and provisional analysis undertaken as part of the Lobe2 deliverables. However, there remains a huge amount of potential in this database. This knowledge can be extracted and applied to subsurface systems where the geometry and reservoir quality of basin-floor systems are more poorly constrained (2.1), and use to condition numerical models (2.2).

2.1 Detailed well-log analysis: We will establish the best practice workflow in electrofacies analysis of lobe complexes. Detailed well-log and petrophysical analysis will allow the characterisation of different depositional environments, and different thin-bedded turbidite settings. Furthermore, we can investigate the most appropriate scale of electrofacies analysis, from individual facies, through elements to complexes in core and well logs. We will investigate the development of machine-learning technology to pick elements based on well log character and shape. This is a rapidly growing area of research, and these data provide a suitably well grounded, and large database to investigate this exciting new approach.

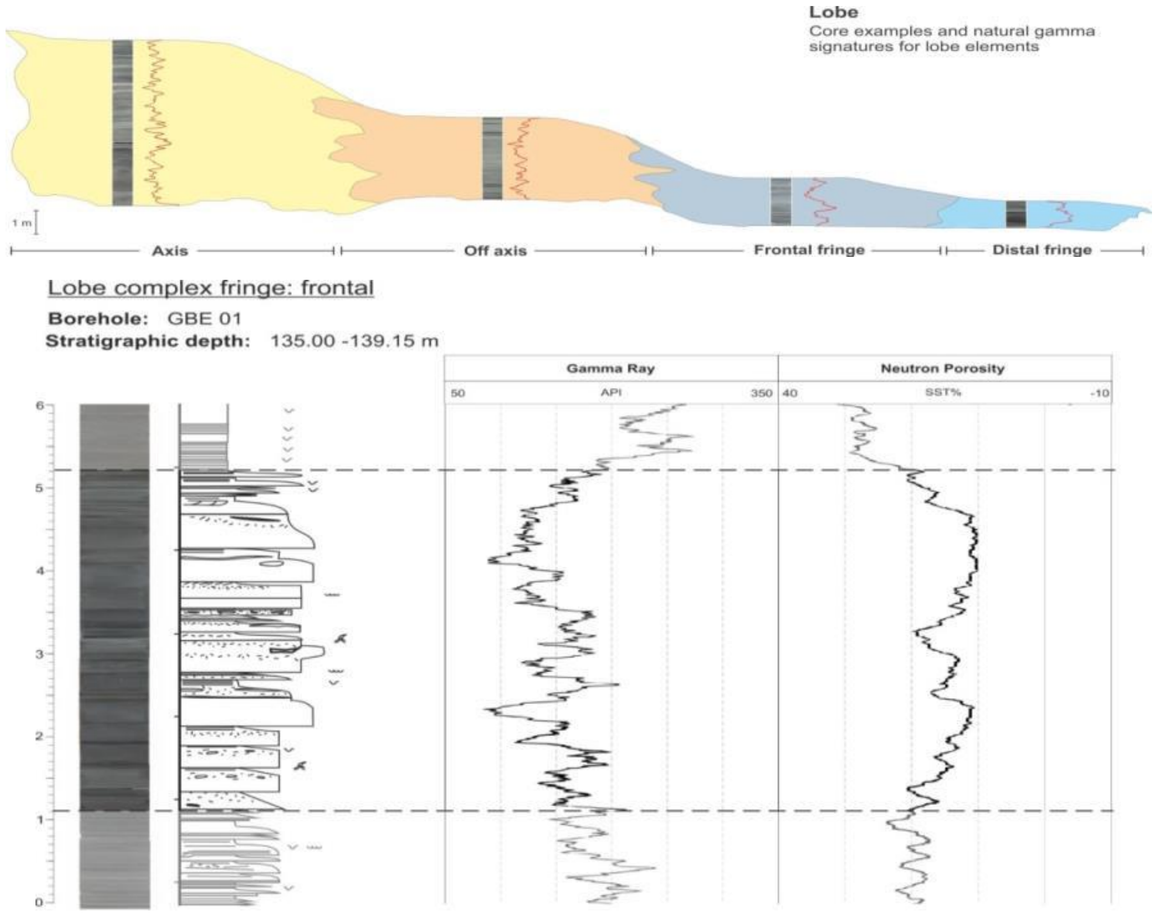
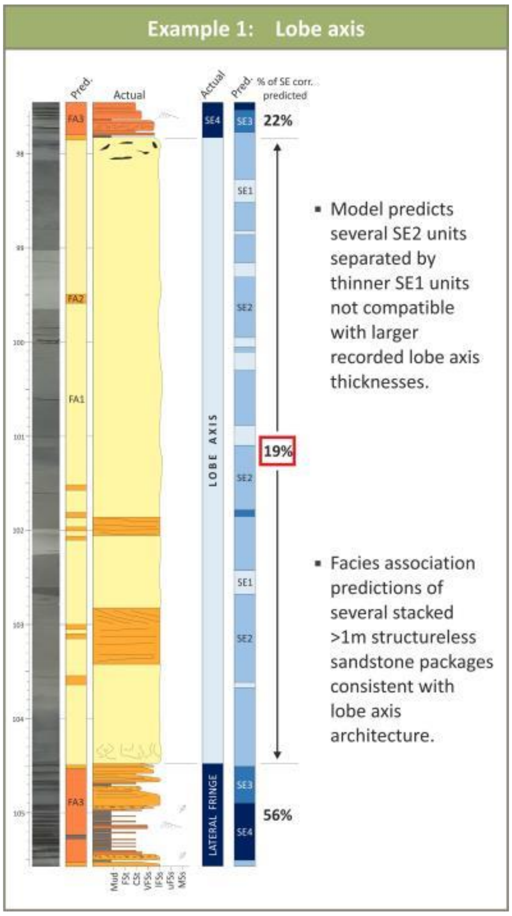


Figure 9: Examples of the integration of core and well log data from the Lobe2 final report. Well logs and core photos from different environments of deposition (above) and an example of a frontal lobe complex fringe.

In particular, the range of thin-bedded fringe successions, and their core and well log expressions, will be investigated further. The interpretation of thin bedded turbidite successions in basin-floor successions is a major uncertainty, particularly away from core control. For example, whether a succession is interpreted as fringe (frontal or lateral), levee/overbank, or shutdown will have significant implications for a geological model.



- Model predicts several SE2 units separated by thinner SE1 units not compatible with larger recorded lobe axis thicknesses.
- Facies association predictions of several stacked >1m structureless sandstone packages consistent with lobe axis architecture.

Figure 10 (left): Trial to establish a neural network using one of the calibrated core and well log datasets from the Lobe2 database

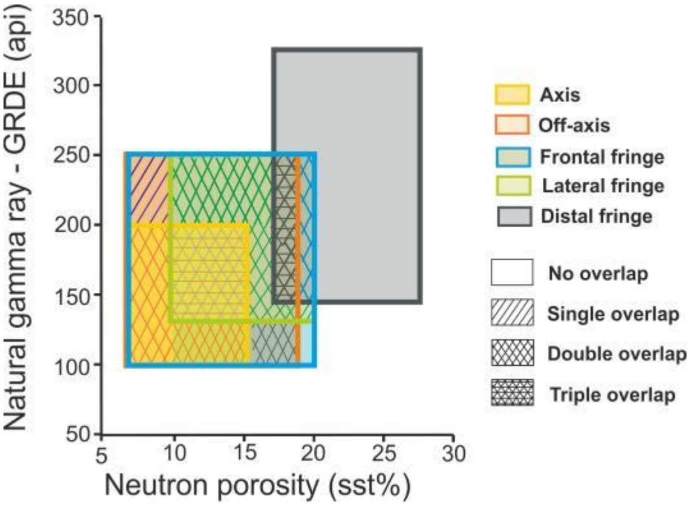


Figure 11 (above): The wireline responses of the different lobe environments. In this simple cross-plot there is overlap. However, using other petrophysical attributes and quantitative data (thickness and trends) we will investigate how uncertainties in interpretation of elements and environments of deposition can be reduced.

2.2 Numerical models of lobe stacking patterns

Rationale: The previous phases of the Lobe JIP established a large architectural element database in a hierarchical framework from stratigraphically and geographically well constrained lobe deposits. This database can be exploited further by extrapolating lobe stacking patterns in 3D from 1D data to interpret the degree and style of confinement. A key advance in being able to do this is the differentiation of frontal and lateral lobe fringes (Spychala et al. 2017b). Lobes can stack a variety of ways, including compensational, aggradational, and longitudinal (progradational and/or retrogradational) (Fig. 12). These will result in very different 1D profiles (Fig. 13). Development of new computer code will use an ‘ideal’ lobe in dimensions and facies proportions, with a pre-existing bathymetry, to stack and extract pseudo-wells. This will build on the 2D method for compensational stacking of channelized lobes by Straub et al. (2009). An additional benefit from this work package is improved prediction in the distribution of organic matter in submarine lobe deposits (Saller et al. 2006; Baudin et al. 2010). Hybrid event beds, which are commonly rich in particulate organic matter, have a somewhat predictable distribution (Kane et al. 2017), and will be tested as an indicator of stacking pattern interpretations (Fig. 14).

Although intraslope (Spychala et al. 2015) and laterally confined (Spychala et al. 2017a) lobe complexes have been investigated, the Karoo database is biased toward unconfined to weakly confined lobe complexes. Therefore, this work package will be supported by the collection of data on lobe stacking patterns and facies distributions from other systems. Systems identified that have an established stratigraphic and palaeogeographic framework, and where the PI's have worked previously, include the Jaca Basin, Spain, the Gres d'Annot, France, and the Neuquén Basin, Argentina.

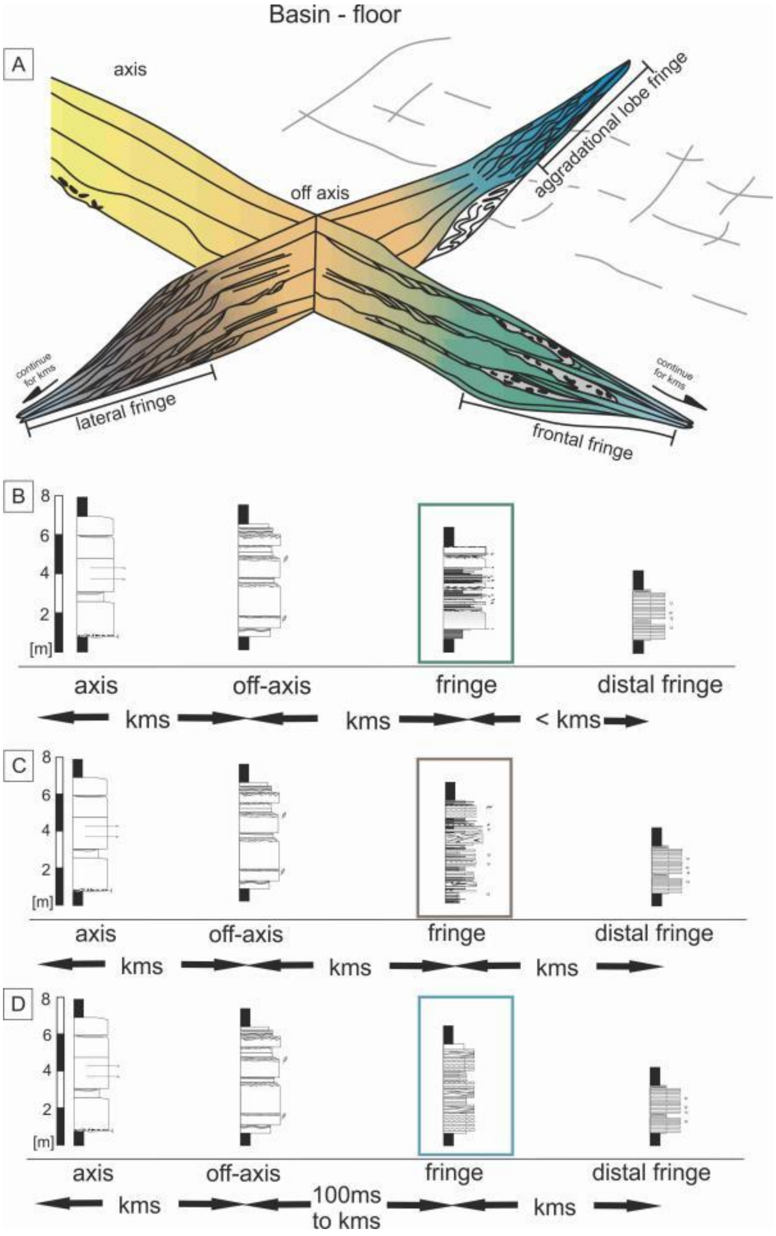


Figure 12: Range of lobe fringes within unconfined to subtly confined basin-floor settings. B: Frontal fringes are characterised by pinch-and-swell geometries and the occurrence of hybrid bed deposits. C: Lateral fringes are characterised by thin-beds with planar- and ripple-lamination and a tapering geometry. D: Aggradational lobe fringes are lateral fringes under the influence of subtle confinement resulting in modified sedimentology and stacking patterns, e.g. climbing bedforms.

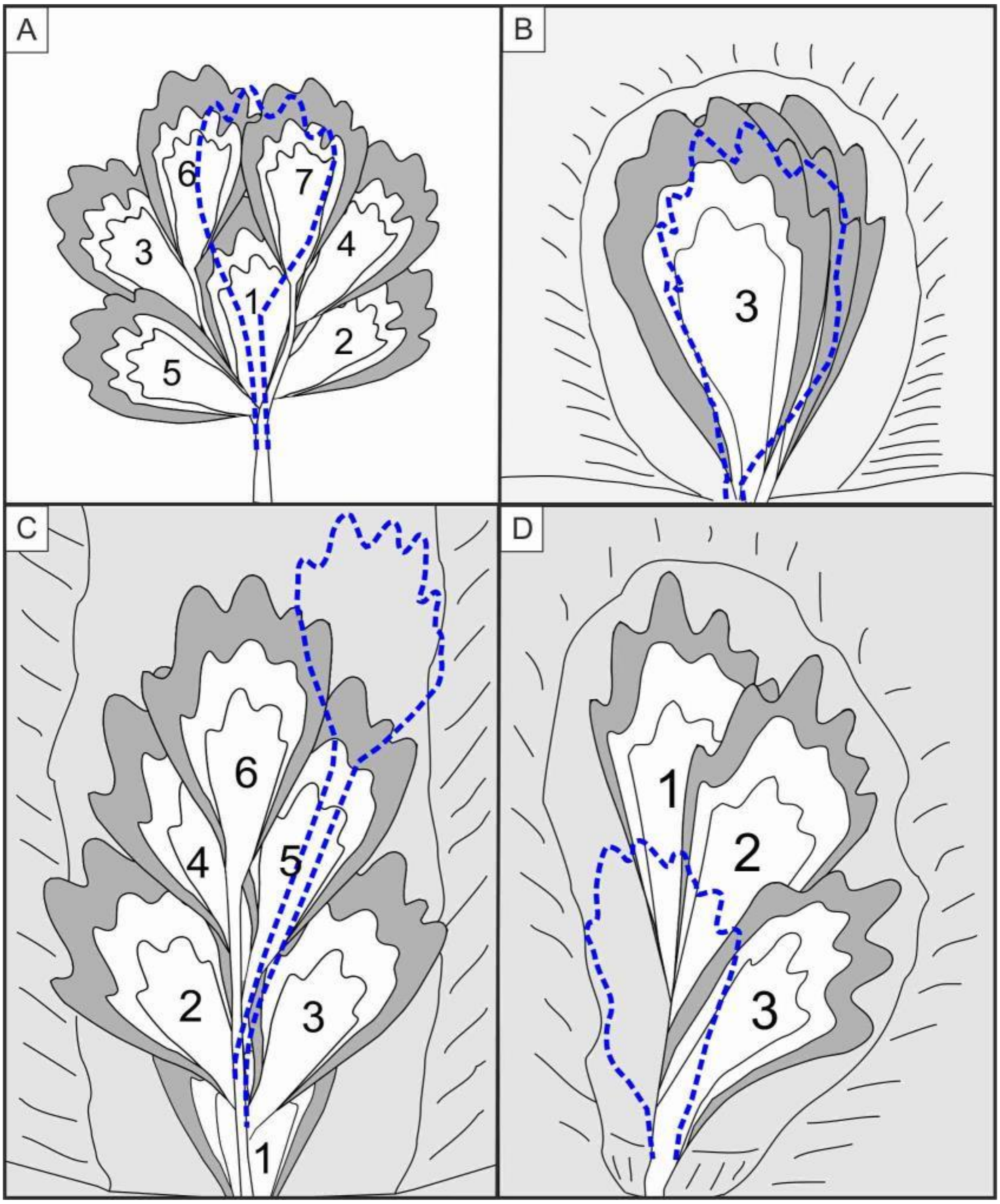


Figure 13: Schematic plan view of lobe stacking patterns. A: Compensational stacking; B: Aggradational stacking; C: Progradational stacking; D: Retrogradational stacking. The dashed blue line indicates the locus of deposition of the next lobe. From Spychala (2016)

Research questions:

What is the best scale of features to be used in accurate electrofacies analysis in basin-floor fan systems, and what is the most effective workflow to use?

How can 1D data be used to reduce uncertainty in interpretation of 3D stacking patterns and understanding of basin geometry during sedimentation?

Deliverables:

1. Refined down-hole recognition criteria in core and wireline log datasets for lobe elements, lobes and lobe complexes.
2. Statistical analysis of thickness trends in lobes tied to an outcrop constrained hierarchy.
3. Modelling from 1D data of the possibly stacking pattern of lobes to infer the degree of system confinement.

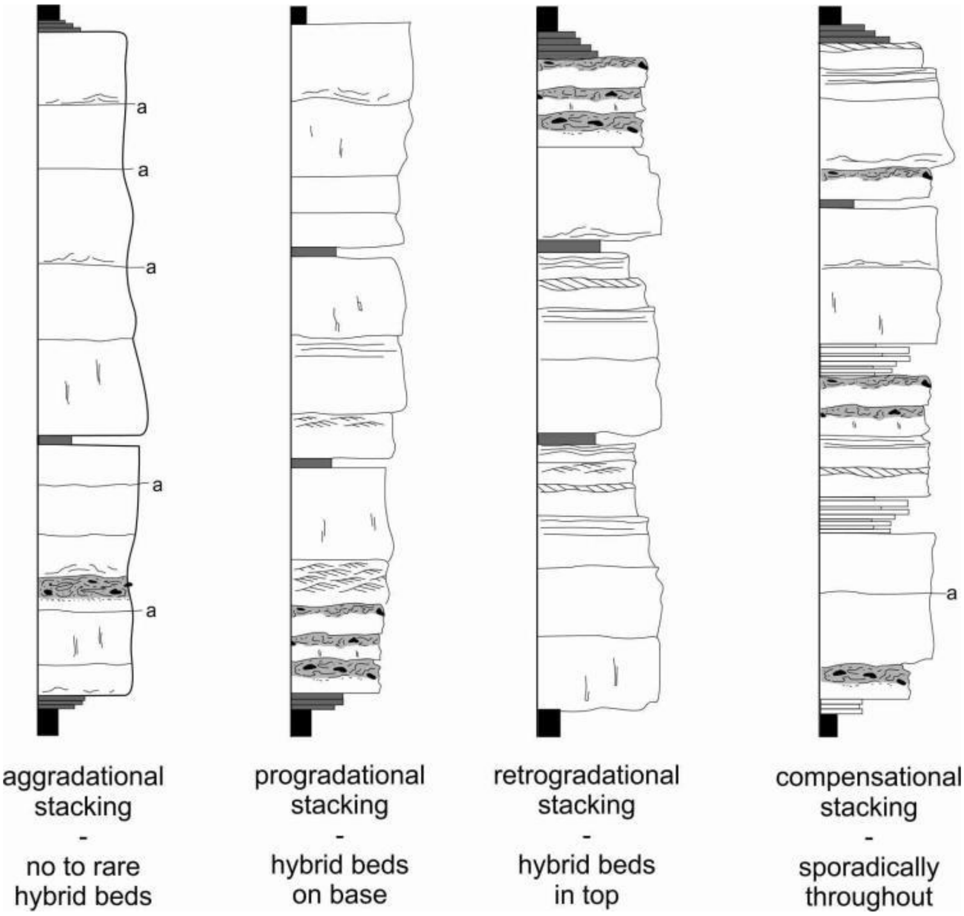


Figure 14: Stacking patterns of lobes and resulting hybrid bed distribution, commonly rich in organic matter, within an axial lobe complex setting.

WP3 – Quantitative analysis of lobe deposits across systems (Lead Christopher Jackson):

A key goal is for the results of the Lobe JIP to be applied widely by our research partners. Therefore, testing and refining outcrop-derived predictive models for the sedimentological and stratigraphic variability of lobes is an essential step, requiring publically accessible high-quality subsurface datasets preferably comprising: (i) *extensive, high-quality, 3D seismic reflection datasets* allowing us to image and map lobes and lobe complexes, and to place these depositional elements in their tectono-stratigraphic context; (ii) *comprehensive well-log and core datasets* to constrain lithological and depositional facies of lobes, allowing calibration of features imaged in seismic data. To permit a more direct comparison with systems studied in the Karoo and Neuquén, these data should come from unconfined and weakly-confined lobe-bearing systems.

3.1: Quantitative comparison across systems

Previous and ongoing research in the Lobe JIP in the Karoo and Neuquén basins has established detailed sedimentological and stratigraphic frameworks, and conceptual models for unconfined-to-weakly confined lobe systems. However, the utility and applicability of predictive models arising from these largely outcrop-based research programs needs to be critically and quantitatively tested against other systems (3.1), including subsurface datasets (3.2).

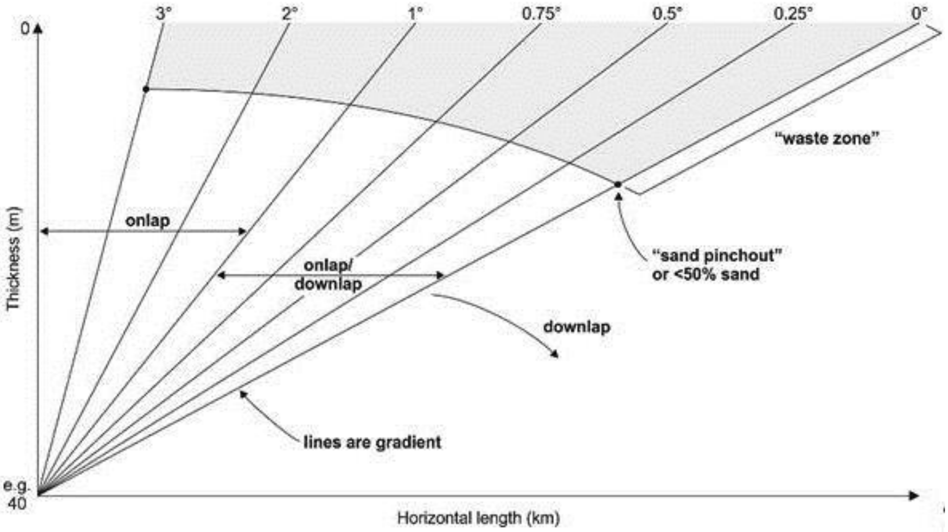


Figure 15. Cartoon to illustrate a working idea to be developed in Lobe3 where data from different systems can be plotted to investigate commonalities and key differences, and to reduce uncertainties in subsurface systems. The example above is to assess different stratigraphic trap analogues, and with help to describe the different 'waste zone' length scales, but could be adapted to include N:G and amalgamation.

Thus we will both leverage existing quantitative datasets from previous Karoo and Neuquén basin data, augmented by data collected during WP1 and 2 from other systems, and data extract during the literature analysis needed for WP0.

3.2 Comparison to subsurface systems

To support 3.1 there is a need to assess suitable subsurface systems, and we will seek to gain access to high resolution seismic reflection data from sponsors in non-prospective intervals and hazard assessment locations. However, one example of public domain data is the NW Shelf of Australia, which provides a superb opportunity to test and refine outcrop-derived predictive models for the sedimentological and stratigraphic variability of lobes. Here, publically available subsurface datasets, comprising wells (including well-log and core data) and 3D seismic reflection data allow assessment of an early post-rift, Upper Jurassic deep-water succession (Angel Formation) in the Barrow and Dampier sub-basins (Fig. 16). A focussed subset of these data (Figs. 17, 18) will also allow assessment of the seismic and sub-seismic architecture of early post-rift deep-water systems, and the impact that inherited rift-related relief has on deep-water sediment dispersal, and stratigraphic and reservoir architecture.

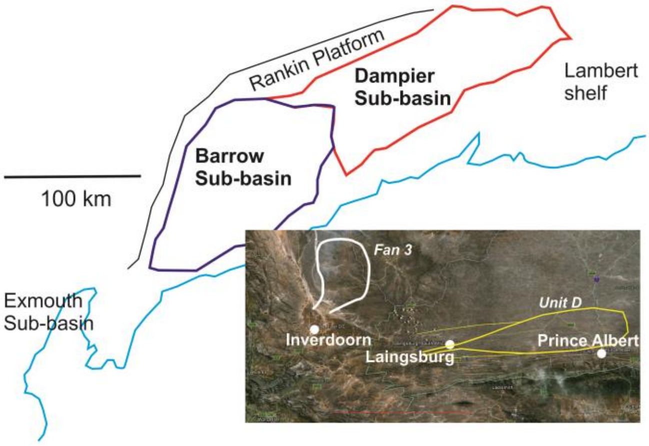


Figure 16: The Barrow and Dampier basins scaled to the Karoo Basin. These are different tectonic settings, but allow the exportability of the concepts and quantitative data derived from the Karoo to be assessed in subsurface (Barrow and Dampier) and outcrop (Neuquén Basin) post-rift settings.

The only published detailed sedimentological and stratigraphic study of the Angel Formation was by Deller (2011). Material presented in the associated PhD thesis, in particular the primarily well-log and core-based analysis of a 'lobe system', provides the basis for further analysis of the broader tectono-stratigraphic context of this post-rift deep-water system. Furthermore, the recent availability of public-domain 3D seismic reflection datasets, and improvements in seismic interpretation mapping tools, mean a reassessment of the Angel Formation as a subsurface analogue will support the subsurface application of Lobe JIP results. In the last c. 5 years, additional seismic interpretation tools (e.g. spectral decomposition) have become available to image and map subtle depositional elements; we will utilise these tools in this project to better integrate seismic and borehole observations, and to map deep-water systems between boreholes. The subsurface dataset comprises 88 boreholes, all of which contain an extensive suite of well-log data. Eleven boreholes contain core (at least 547 m) and four contain image logs. A chronostratigraphic framework, primarily based on dinoflagellate assemblages, defines at least four, intra-Angel Formation stratigraphic zones (<1 Myr duration) and eight mappable stratigraphic surfaces spanning the broader Jurassic interval. This chronostratigraphic framework is critical because it allows us to map age-constrained stratal packages between boreholes, and to define local and regional changes in thickness and stratigraphic architecture.

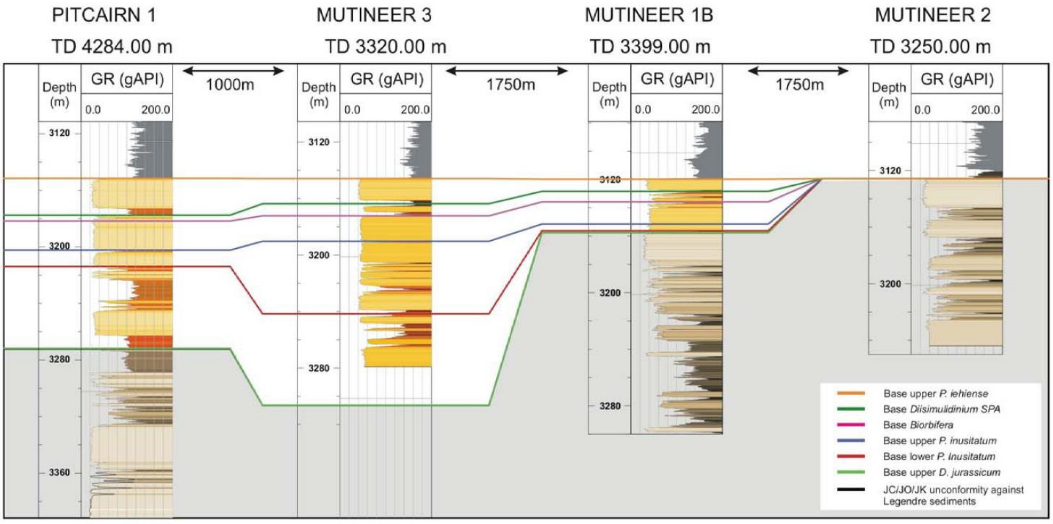


Figure 17: Correlation panel based on biostratigraphy to indicate the unconformable nature of Tithonian sediments against older Jurassic sediments in the eastern Mulineer Field. Figure 8-12 in Deller (2011).

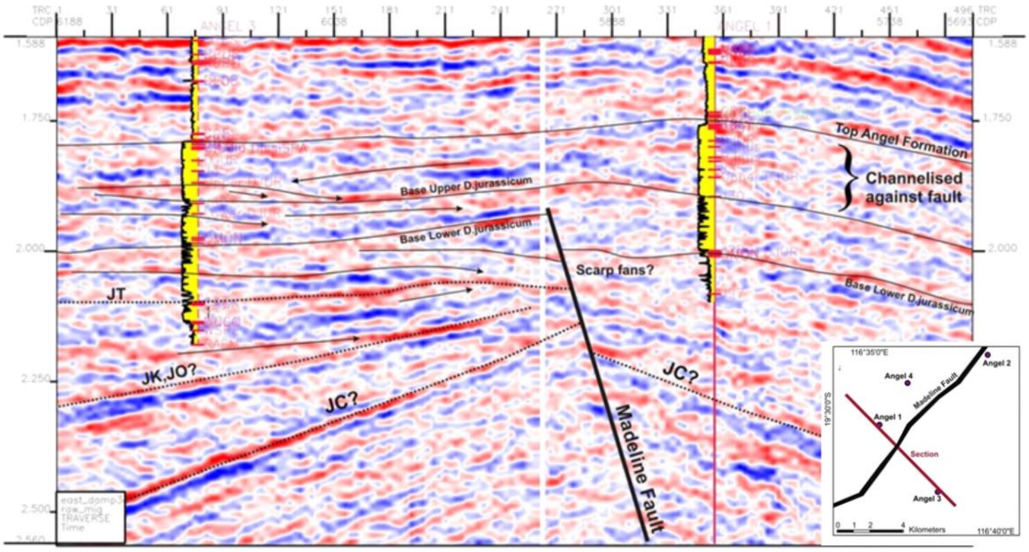


Figure 18: Seismic transect to illustrate the onlap of biostratigraphically-defined zones on the Madeline fault system, which was active during Tithonian sedimentation. Modified from Figure 8-41 in Deller (2011)

Research questions:

- How can architectural and morphometric parameters be used to effectively compare and contrast different lobe systems?

- What sedimentological and petrophysical criteria can be applied from the Lobe JIP to support identification of lobes and lobe complexes in core and well-log datasets from a subsurface analogue?
- What techniques can be used to image and map lobes imaged in seismic reflection data? What level of hierarchical elements can be imaged in conventional seismic reflection data?
- What are the regional intra- and extra-basinal controls on the deposition of post-rift deep-water lobes?

Deliverables:

- Raw quantitative data compiled from existing databases, new data collected in other Work Packages, and the published literature.
- Parameter space plots for different aspects of lobe systems, such as rate of thinning, tied to different configurations. Sponsor companies will be able to readily plot their own data to identify suitable analogues and help to reduce uncertainty.
- Refined down-hole recognition criteria in core and well-log datasets for lobe elements, lobes and lobe complexes, thereby complimenting outcrop-derived deliverables from WP2.
- A suite of stratigraphic and architectural panels for lobe systems in late syn-rift to early post-rift deep-water successions
- An atlas-style compilation illustrating the seismic, core and well-log expression of deep-water depositional elements

WP4 - 3D-Lobe - virtual outcrops and geomodels (Lead: Steve Flint)

Rationale: The last 3 years has seen a mini-revolution in outcrop data collection through the integration of conventional field techniques (logging of sections and projection of correlation panels supplemented by photomontages and seismic-scale mapping, all geo-referenced via GPS) with data collected by UAVs (drone, figs 19, 20). Drone-based photography provides quick and inexpensive extension of fieldwork. Photogrammetric analysis allows the building of 3D and pseudo-3D models to constrain more accurately sandbody geometries, pinch-out styles and stacking patterns, and to integrate subsurface data (research boreholes).

One challenge with large, multi-component integrated datasets is efficient, easily accessible storage, such that going forwards, sponsors can easily utilise the information from core to seismic scales help to better constrain lobe geometries and architecture and allow development of virtual learning tools. In Slope Phase 4, we developed a Petrel-based data repository for this purpose, and the same approach will be used in Lobe3.

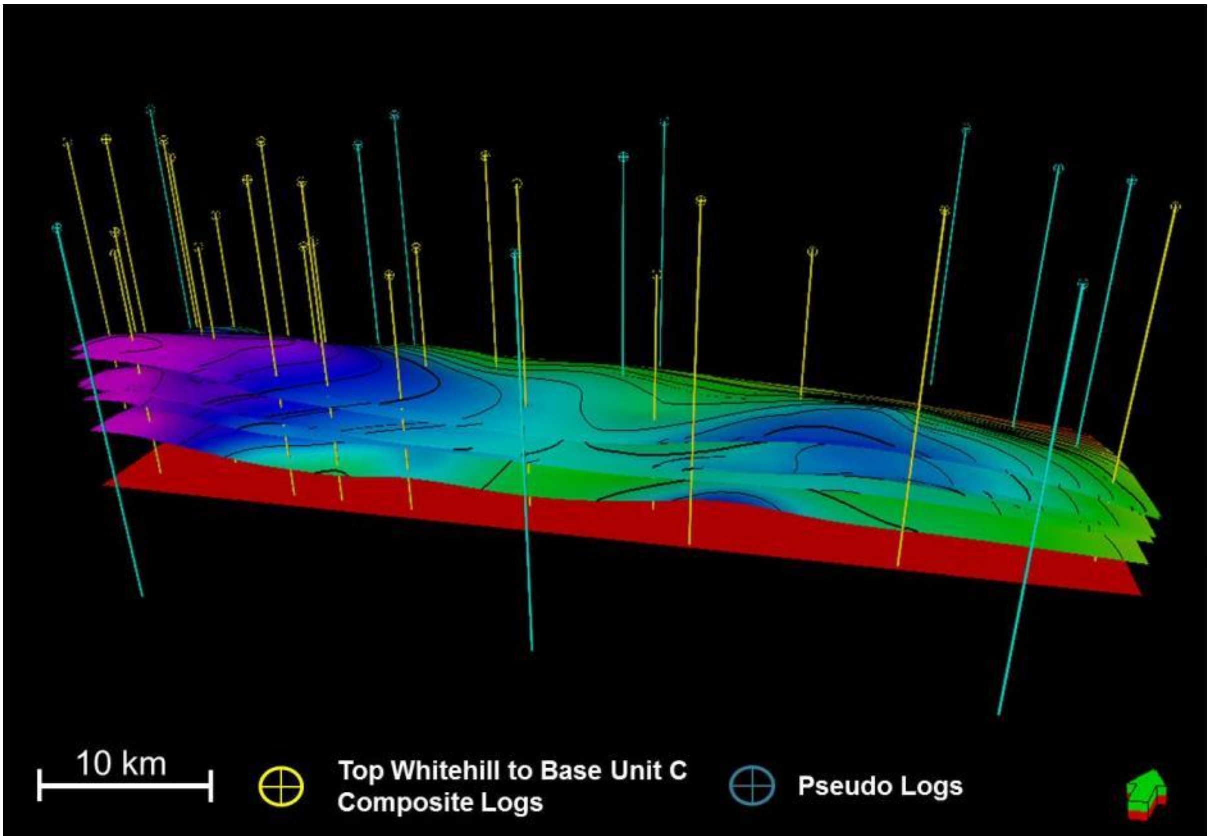


Figure 19: Example image from the Slope4 Petrel model that compiled the data from the Laingsburg area. This datacube houses the data in a single archive, and permits geological modelling approaches using subsurface parameters. A similar datacube will be constructed that houses all Lobe JIP data from the Karoo Basin.

4.1 3D Lobe

UAV surveys and photogrammetry will be used to build digital outcrop models, tied to research boreholes. We will build a database housed in GoogleEarth and Petrel with isopach maps, correlation panels etc. as viewable data. This will be available as a quantitative data repository for sponsors into the future, for use in forward seismic modelling, building dynamic reservoir models and for training.

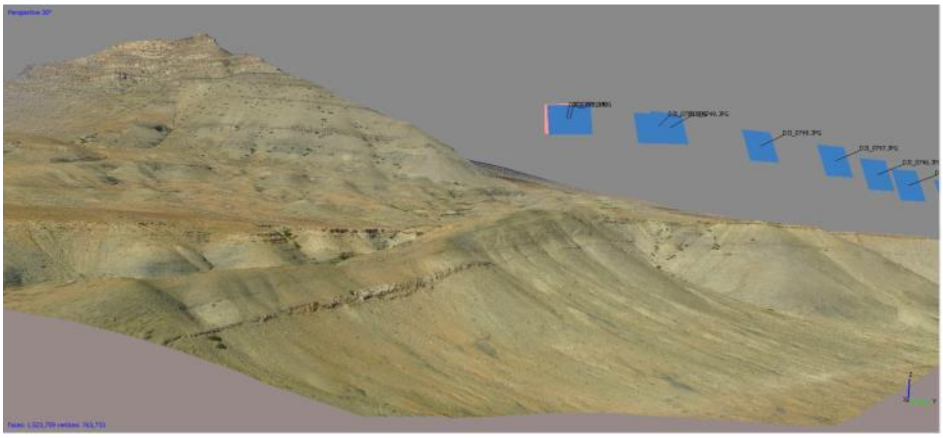


Figure 20: Photogrammetric model showing pinch-out geometries of lobes, Fan 4, Tanqua depocentre

Applying the detailed outcrop and core dataset to subsurface reservoirs can be achieved in a number of ways. One method not yet approach using the Lobe JIP database is the development of training images for lobe deposits, which can be employed in multipoint statistical procedures during construction of geologically realistic reservoir models.

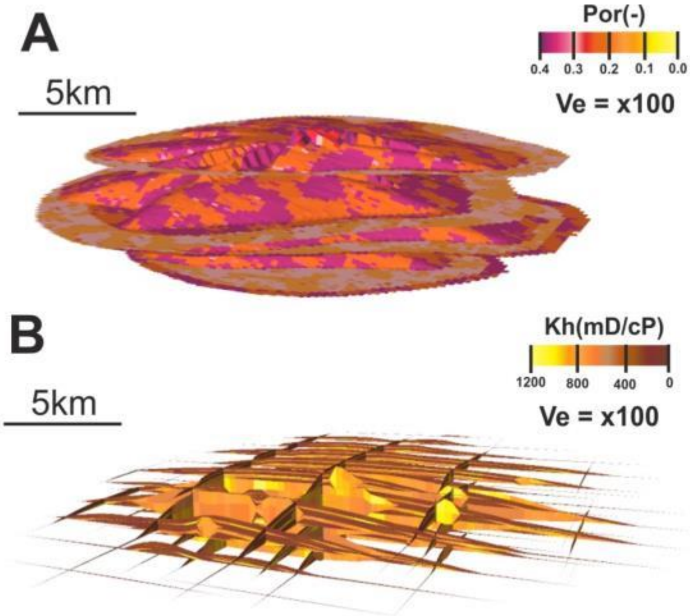


Figure 21: A - Example porosity realisation of BFL-Model B2 showing stacked lobes and a decrease in porosity from axis to fringe. B - Fence diagram of a horizontal permeability (Kh) realisation of BFL-Model B2, showing clear differences between axial and fringe facies. A total of 25 petrophysical property realisations were performed for every submodel. From Hofstra et al. (2017)

4.2 Virtual training module

Distance learning is a rapidly growing approach in UK Universities and considerable experience is now available in this mode of learning and knowledge exchange. Lobe 2 trialled a semi-professional video capture of a Sponsors' field workshop in 2015 (https://youtu.be/5YHGTSIqAhI). WP4 will produce a ‘blended learning’ deliverable that includes virtual field experience to understand the key findings of the research, set within the well understood framework from previous studies.

The Karoo will form the base case for understand lobe systems and will be supplemented by virtual presentations of how key characteristics differ as a result of different degrees and types of confinement, tectonic setting, etc. Seismic data from WP3 will be brought in, along with research borehole information to cross the scales of observation and to fully understand sub-seismic variability. In addition to being a new and novel additional vehicle for knowledge transfer, the module will serve as a powerful introduction to areas ahead of future field schools.

Deliverables:

Support to WP1 and WP2 by extending the analysis of pinch-out styles for lobes in different settings into 3D and near-3D to better understand local variability

Support to WP3 by comparing seismic scale geometries with equivalent outcrop geometries, while embedding the sub-seismic detail within the models.

Training images of different lobe types for use in MPS geological modelling

Costings:

3 x 3.5 year PhD studentships, WP1, 2, 3:	£ 285k
Staff time for 3 years, overheads	£ 196k
PDRA (2-year – Uni. of Leeds based, WP4)	£ 220k
Consumables, conferences and fieldwork	£ 91k
TOTAL	£ 792k

Rate per company: £33k per annum for 3 years minimum = £99k total

With five companies, we will employ a PDRA (WP2 and 4) and 2 PhD students (WP1 and 2). Initial indications mean we are confident of reaching >5 sponsors, when we will be able to employee a third PhD student (WP3).

Buy-in costs for new sponsors is estimated to be an additional £36k payment.

Timing of Deliverables

The project will commence in January 2018, and will complete December 2021. The final project report for the work will be available at the end of year 3 (December 2020), although individual deliverables will be sent out went ready. Interim progress reports will be sent out every 6-months on a password-protected website.

Report and thesis preparation:

This will be undertaken during the last 6 months of the project period, by the whole study team. The report format will be an interactive HTML document with accompanying databases. Sponsors will also receive electronic copies of the PhD theses.

Sponsors' field training and steering group meetings

To aid data dissemination during the lifetime of the project, we will continue to organize and lead field courses for sponsors’ representatives as for previous phases, which will be combined with annual steering group meetings. All costs of the trip leaders are in the project budget, so the cost to sponsors will be only travel and subsistence for the representatives. Sponsors field courses will run in the Karoo, Neuquén and Jaca Basins. Individual sponsors may wish to fund additional staff training courses.

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