ORAL PRESENTATIONS:

ABSTRACTS

Tidal Signatures from an intracratonic playa lake

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This study of a modern-day, dryland terminal splay complex (TSC) from Lake Eyre, central Australia, indicates that sedimentary and biogenic structures previously considered indicative of marine tidal depositional environments are also generated in an intracratonic playa lake setting. Paired mud drapes (bundles) on cross-beds, cross-bedding reactivation surfaces, lateral bundle thickness variations, herringbone cross-bedding, flaser, wavy, and lenticular bedding, and desiccation cracks were observed in shallow excavation pits on the Kalaweerina Creek TSC. Fluctuations in flow velocity and direction required to generate these "tidal" sedimentary structures are attributed to daily changes in wind direction and velocity causing current reversals in the shallow lake here termed "wind tides", along with longer period wind velocity and discharge variations in the feeder river system. Cross sections through vertical spider burrows and ant nests that crosscut "tidal" sedimentary structures can be easily mistaken for *Skolithos, Gyrolithes, Rhizocorallium and Chondrites* which are mostly found in shallow marine environments. These observations suggest that interpretations of similar ancient deposits may require re-evaluation and alternative depositional environments should be considered when interpreting strata containing these classic marine tidal indicators.

The Messinian Evaporite Complex in the Eastern Mediterranean: A natural laboratory for studying evaporite sedimentation patterns and salt tectonics in a youthful saline giant

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The offshore Eastern Mediterranean area is currently attracting considerable oil industry interest following significant discoveries in the pre-Messinian of the Nile Delta, Egypt, offshore Levant, Israel and the Sirt Basin, Libya. In support of this exploration effort, a substantial seismic reflection dataset, which covers c. 250000 km2, has been acquired. Although these data were acquired and processed to image deeper exploration targets, they are now providing important and exciting new insights into the structural and stratigraphic complexity of evaporite-bearing succession associated with the Messinian Salinity Crisis (MSC), which is relatively shallowly-buried and is spectacularly imaged.

It is widely accepted that the MSC, which occurred during the Late Miocene (5.96-5.33 ma), involved a major evaporitic drawdown and refilling of the Mediterranean in the space of just 300 kyrs. This initiated the deposition of a vast salt deposit that consists of halites in the deep basins (below present day water depths of 3000 metres), and gypsums and anhydrites around the basin margins. Sea-level drawdown and exposure of the basin margins resulted in major and widespread incision and karstification of pre-MSC, Eocene age, carbonate platforms.

Although this general picture of the evolution of the MSC is relatively well known, previous studies have failed to successfully integrate observations from subsurface and outcrop datasets; this has led to a confusing plethora of stratigraphic schemes and much debate over the temporal and spatial evolution of the thick evaporite successions of the Mediterranean. Our integrated approach, which uses 2D seismic reflection, well and outcrop data has allowed us to construct a unifying stratigraphic framework and present a revised regional facies map for the MSC in the Eastern Mediterranean.

The project therefore offers us a unique opportunity to re-evaluate the impact of a major eustatic sea-level fall on the facies distributions that occur during the early stage development of a giant salt basin.

Bedform development in mixtures of clay and sand: The wave case

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Wave tank experiments were conducted to determine how the development rate and size of wave-generated ripples change as a function of yield strength in mixtures of non-cohesive sand and cohesive clay. These experiments focussed on cm-scale rolling-grain and vortex ripples at constant maximum orbital velocity, but increasing clay-to-sand ratio of the bed sediment. The results showed that the first appearance of wave ripples on a flat bed is delayed progressively longer as the clay-to-sand ratio is increased, and above a threshold clay-to-sand ratio the bed remained flat for a duration of at least of 2 hours. However, in the experiments where the wave ripples were able to reach equilibrium size, their height and length were independent of the clay-to-sand ratio in the sediment bed. This is in contrast to current-generated ripples in mixed cohesive sediment, which were found to decrease in size with increasing clay-to-sand ratio. It is inferred that this difference is caused by a more efficient clay winnowing process for the wave case, leading to bed segregation into sandy bedforms 'floating' on original, unaffected mixed sediment. The grain size distribution of the sediment within the winnowed bedforms was similar to that of the wave ripples formed in a clay-free control experiment, thus explaining the equilibrium ripple size similarity. The implications of the laboratory research for wave-generated bedform size predictors and sedimentary facies in wave-dominated environments will be discussed.

Controls on fluvial sedimentary architecture and sediment-fill state in salt-walled mini-basins

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The growth and development of salt-walled mini-basins and their coeval infill via ongoing sedimentation typically results in the preservation of complex stratigraphic architectures that are largely dependent on the relative rates of sediment supply versus rates of mini-basin subsidence and salt-wall uplift. This balance dictates the manner by which accommodation space is infilled as it is generated, the sediment-fill state of evolving mini-basins being defined as underfilled, filled or overfilled. Fill-state can vary spatially within a single basin, spatially between adjoining basins, and temporally during the episode of basin development.

Salt-walled mini-basins present in the Salt Anticline Province of the Paradox Basin (SE Utah) evolved in response to progressive sediment loading of Pennsylvanian-age salt, with the area having undergone a complex history of mini-basin subsidence and neighbouring salt-wall uplift during Permian to Jurassic times. A significant part of the infill of the evolving mini-basins is represented by the Triassic Moenkopi Formation and the preserved succession of a dryland fluvial system in which flow was primarily directed parallel to the elongate axes of actively subsiding mini-basins. In some mini-basins, fluvial channel elements are stacked vertically within and along the central basin axes, the position being dictated by the locus of subsidence in a pattern indicative of the presence of elevated salt walls and an underfilled state. In other basins, rimmed synclines have developed adjacent to bounding salt walls and these served as a focal point for major fluvial channel bodies. Mini-basins at equivalent stratigraphic levels can exhibit different states of infilling: sand-poor basins dominated by fine-grained overbank sediments apparently developed synchronously to neighbouring sand-prone basins, demonstrating effective partitioning of sediment route-ways by elevated salt walls, with some basins acting as long-lived major fluvial fairways.

Models that enable the prediction of the proportion and distribution of sand bodies in these types of salt mini-basins are important for reservoir prediction, where the stacking pattern of sand-prone channel elements governs the connectivity of net-reservoir intervals. Field-derived architectural data from this study are being used to constrain stochastic models that describe sand-body connectivity and predict net-to-gross in Triassic reservoir plays in the Central North Sea.

The influence of climate variation on deltaic architecture: implications from analogue modelling

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Delta architecture is driven by sea level, sediment input and tectonics. In most sequence stratigraphic models only sea level is considered a variable as it is generally dominant. This leads to simplified and potentially false interpretations as sea level variations generally result from cyclic climate variations, which likely vary sediment yield at similar timescales. The current study examines the significance of these climate variations by analogue experiments in a mini-basin with discharge as an additional variable besides sea level.

Four deltas with equal sea level curves and variable discharge curves are generated: 1) constant discharge as in the Exxon concept; 2) high frequency variations in discharge compared to sea level variations; 3) discharge leading the sea level curve by a quarter phase; 4) discharge lagging sea level by a quarter phase. Results from sequence stratigraphic analyses show a variable importance of discharge variations on sediment transport, internal geometry of the delta and the interpretation of system tracts with respect to sea level. High frequency variations (2) show little impact on sediment yield to the delta or on its internal delta geometry. This contrasts with the experiments in which discharge is varied on similar timescales as base level. In the latter case, sediment yield is significantly intensified during parts of the base level cycle while starving the delta during others, which results in strongly contrasting geometries. When discharge leads over sea level (3), the delta receives the bulk of sediment during sea level rise resulting in a strongly aggradational character. Delta front erosion is common during falling sea level but does not lead to incised valleys connected to the fluvial system. When discharge lags sea level (4), the delta receives most sediment during falling sea level resulting in a strongly progradational character during forced regression, with sediment routed to the delta front by connected incised valleys. During rising sea level, the delta becomes sediment starved and is rapidly drowned.

The current research demonstrates a significant but complex influence of discharge on delta architecture in analogue experiments and provides a starting point for examining natural delta systems for the impact of climate variation. The addition of a climate component might improve the accuracy of sequence stratigraphic models and improve their predictive capability.

Two-stage development of the Late Cretaceous to Late Eocene Darende Basin: implications for closure of Neotethys in central eastern Anatolia (Turkey)

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Here we present a type example of an important, but little known type of sedimentary basin formed after ophiolite and related melange emplacement. In this case the ophiolites formed above an intra-oceanic subduction zone and were emplaced southwards onto a passive carbonate platform margin in response to trench-margin collision during the latest Cretaceous. However, the ocean remained partially open and did not suture until millions of years later. The Late Cretaceous-Late Eocene sediments in the Darende Basin formed in this type of setting; i.e. on a continental margin following ophiolite emplacement but prior to suturing of the ocean basin (a modern unsutured example is the Late Cretaceous-Palaeogene of NE Oman).

Sedimentation began during the Late Maastrichtian, probably controlled by active extension along the basin margins. Ophiolite-derived, non-marine clastic sediments accumulated in palaeovalleys, followed by shallow-marine rudist-rich patch reefs and limestones. These, coupled with microbial, often evaporitic, carbonates elsewhere in the basin, record a short-lived shallow-marine transgression, followed by emergence during the latest Maastrichtian. The basin remained emergent during the Paleocene to Early Eocene and resulted in a low-angle unconformity developing. This is in marked contrast with other Central Anatolian basins where deep marine mudstone and turbidite successions were deposited during the Palaeocene (e.g. Ulukisla Basin). Early-Middle Eocene shallow-marine clastics were deposited simultaneously with localised basic alkaline volcanism. Late Eocene marls, shallow-marine Nummulitic limestone, calciturbidites and finally evaporites, successively record deepening, shallowing and finally emergence.

The first phase of basin development (Maastrichtian-Early Eocene) is explained by regional crustal extension. The driving mechanism is seen as slab-pull resulting from northward subduction of the remnant oceanic lithosphere. The Palaeocene unconformity may reflect reduced accommodation space coupled with eustatic sea level fall. The second phase (Eocene) is explained by crustal downflexure to form an under-filled foreland basin during collision of the Tauride-Anatolide microcontinent to the south with Eurasia to the north. Suturing of the Mesozoic ocean (Izmir-Ankara-Erzincan ocean) that separated these

continents effectively ended marine sedimentation during the Late Eocene. However, basin uplift was delayed until after Mid-Miocene time.

Sedimentology of the Neoproterozoic Chuos Formation, northern Namibia: implications for Cryogenian glaciation

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The Neoproterozoic Otavi Group is a carbonate-dominated succession which records two episodes of Cryogenian glaciation along the southern margin of the Congo craton, northern Namibia. Under the snowball Earth hypothesis, these glacigenic successions represent discrete periods of global ice cover, wherein associated ironstone precipitation reflects rapid seawater oxidation following catastrophic ice meltback. Alternative hypotheses propose diamictite and ironstone accumulation as a product of local rift activity during break-up of Rodinia, recording mass flow deposition and hydrothermal iron precipitation, respectively. In the Otavi Mountainland, ironstone deposition is restricted to the base of the older Sturtian glacial succession (Chuos Fm), with a gradational upward transition into the overlying diamictite facies. The latter demonstrates evidence of glaciation in the form of: 1) ice-rafted lonestones and impact-related deformation structures, 2) ice-bed separation features (discontinuous siltstone and sandstone stringers), and 3) highly sheared and attenuated glacitectonites. In the absence of typical glacial indicators (i.e. striated and faceted clasts, striated pavements), these pervasive deformation structures hold key palaeoclimatic significance, both with respect to discerning a glacigenic origin, and to understanding the dynamics and behaviour of a Cryogenian glacial event. In the Chuos Formation, their association with abundant ice-rafted debris, large prograding clinoforms and recurrent reactivation surfaces indicates deposition at or near an oscillating ice-grounding line, whereby inherent slope instability triggers local re-working as massive diamictite facies. Furthermore, the ubiquitous occurrence of stromatolite structures in the underlying ironstones is used to infer that ironstone sedimentation was associated with initiation of, rather than exit from, glaciation. As a working hypothesis, we argue that photosynthetic protozoa encourage soluble iron fixation, CO2 drawdown and concomitant atmospheric cooling.

The Application of Ichnofacies Classification to Deepwater Geohazard Assessment: Making the Most of Core Data

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Several recent publications have highlighted the need for high resolution sedimentological logging to provide calibration of geohazard type, magnitude and frequency for input to risk assessments for deepwater oil and gas developments, and subsea infrastructure such as pipelines and cables (e.g. Thomas et al., 2011). The implementation of ichnology is well accepted in petroleum exploration-focussed sedimentology; however, it has yet to receive proper recognition in the field of shallow geohazard evaluation. Often, bioturbation is deemed to be problematic for geohazard assessments; particularly in the assignment of geochronological testing on sediment cores, due to the adverse mixing effects of biogenic activity, as outlined by Owen et al. (2007).

Several sanitised case studies are presented here, from various passive margin, deepwater settings, that demonstrate how the identification and classification of bioturbation can add significant additional information to an integrated geohazard assessment. This is achieved through the classification of ichnofacies, in tandem with sedimentological logging, which directly inform the understanding of depositional and post-depositional processes, and hence any associated geohazards. The case studies include reference to processes which may adversely impact or affect a subsea development, including turbidity and contour currents, translational slope failure, localised modification of intrinsic geotechnical properties by biogenic processes themselves, and also cover the use of ichnology as a proxy for environmental reconstruction and climate modelling for a spatially and temporally referenced geohazard assessment.

Examples of the application of ichnology to geohazard assessment include:

- Frequency assessment of turbidity current events from overbank or levee settings - where insufficient material is available for dating, or has been eroded entirely, within the canyon thalweg;
- Reconstruction of events such as flow flux or transformation within an individual turbidity current episode;
- As a proxy for determining timescales for waxing of contour flow; and hence periods of anticipated enhanced scour potential;
- Use of ichnofabric characterisation to determine recency of slope failure from samples within slide evacuation scars;
- Understanding the modification of geotechnical properties, from localised significant reduction in undrained shear strength, to apparent overconsolidation due to biological processes

Use of a relational database for the classification of fluvial sedimentary systems and the interpretation and prediction of fluvial architecture

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A relational database for storing fluvial architecture information has been developed and populated with literature- and field-derived data from studies of both modern rivers and their ancient counterparts preserved in the stratigraphic record. The database scheme characterizes fluvial architecture at three different scales of observation, corresponding to different types of genetic unit (large-scale depositional elements, architectural elements and facies units). The database records all diagnostic architectural features, including style of internal organization, geometry, spatial distribution and reciprocal relationships. The database classifies datasets - or parts thereof - according to both controlling factors (e.g. basin climate type or tectonic setting) and context-descriptive characteristics (e.g. river pattern or dominant transport mechanism): the data can be filtered on one or more of any of these classification parameters.

Database interrogation returns quantitative information whose principal applications include: (i) the quantitative comparison of architectural data to evaluate the relative importance of different controls; (ii) the development of quantitatively-justified fluvial depositional models - through the integration of data from multiple sources - that overcome many of the fundamental limitations of traditional facies models; (iii) the generation of constraints required to infer borehole correlations and to condition stochastic models of subsurface architecture, referring to either genetic units or material units defined on categorical variables (e.g. fine-grained fraction >20% by volume); (iv) quantitatively-based identifications of modern and ancient analogues for fluvial hydrocarbon reservoirs, aquifers or placers.

These potential applications are illustrated through a range of case study examples that collectively demonstrate how this relational-database approach can be used as a research tool with which to gain novel insights into the various impacts of both autogenic and allogenic controls on a range of fluvial system types. The approach is exemplified by the sequential application of data filters in order to derive a model for braided perennial systems in arid/semiarid climatic settings. By demonstrating how architectural features change through a series of intermediate stages in the filtering process, we highlight the importance of quantitative characterization of sedimentary systems in both pure and applied perspectives.

Dynamic deposition of fine-grained intervals from the Namurian of the Edale sub-basin.

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Mudstones have been considered as relatively homogenous and deposited mainly by passive settling under low energy conditions. Recent studies have demonstrated that fine-grained sediments are deposited by a range of dynamic depositional processes including bedload sediment transport by currents, and wave-enhanced sediment gravity flows of fluid mud. This study investigates the variation in micro-textures observed within the fine-grained intervals of the Pendleian to Kinderscoutian successions of the Edale sub-basin. During this period the environment evolved from a mud-dominated basinal setting to a sand-dominated major deltaic system.

Here we compare the fine-grained intervals of the Edale Shales to those within the Mam Tor Sandstones and the Shale Grit. Samples studied in thin section reveal hitherto unreported structures and a variety of depositional processes. Parts of the Edale Shales are clay-dominated and deposited primarily by the settling of flocs, preserved as organo-mineralic aggregates, but there is also evidence for current transport. A range of transport mechanisms, including debris flows, are also apparent in the fine-grained intervals between the sandstone packages of the Mam Tor Sandstones and the Shale Grit. We interpret the presence of broken bioclastic material, distinct bedding, and a variety of lens-shaped structures as the product of active transport events.

Lenses of light-coloured material within darker background sediment are apparent in many thin sections and have a variety of origins. The majority of lenses occur in lines, or in distinct beds, always lying parallel to bedding. Lenses may appear as single features but closer observation of longer, or wavy-edged, lenses reveals that they are in fact composites of ‘stacked’ lenses. Some lenses are predominantly erosional features and others are associated with crushed, transported bioclastic material. We suggest that all these lens types are a product of upslope erosion, transportation and deposition and indicate a dynamic sedimentary environment.

Systematic description and interpretation of the fine-grained intervals within these successions enable the re-evaluation of long-held views on the interpretation of geochemical proxies (e.g. U, Mo). Recognising the inherent variability of fine-grained intervals leads to the development of facies models which honour all aspects of the depositional system.

A subsurface assessment of post-rift bathymetric control on deepwater sedimentary architecture

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The bathymetry of the slope and basin-floor determines the routeing and storage of sediment transported by submarine gravity flows. Over relatively long time periods (e.g. >104 yrs) this will determine the sedimentology and depositional architecture of deepwater stratigraphy. However, the manner in which slope bathymetry controls this long-term evolution is poorly understood. From a subsurface perspective, this limits the ability to predict reservoir quality and connectivity in ancient deep-water sedimentary successions. In this study we integrate 3D seismic with wireline log and core data to assess the control that submarine slope relief had on the Early Cretaceous Agat Formation on the Maloy Slope, offshore Norway.

Seismic mapping indicates that the bathymetry of the Maloy slope in the Early Cretaceous was characterised by broad steps (A~0.1-0.2 km, λ~2-4 km) with N-S-trending axes. These topographic features developed in response to differential compaction of mud-dominated, syn-rift and early post-rift sediments across the crests of rift-related fault blocks. Channel and lobe depositional elements are identified from seismic observations and core. Structureless, commonly dewatered, fine & medium-grained turbidite sandstones, and mudstone-dominated debrites ("hybrid beds") are the dominant sedimentary facies. Well correlations, seismic facies mapping and vertical facies stacking patterns indicate that the position, thickness and distribution of the gross depositional elements was influenced by an inherited bathymetry that became progressively subdued over time.

The integrated dataset presented here provides a unique insight into the initiation, growth and abandonment of post-rift deepwater systems along a continental margin, and the influence that remnant bathymetry plays on sediment gravity flow behaviour and depositional architecture.

Meander-wavelength / flow-dimension ratios in freely meandering experimental sandy turbidity currents.

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Flume studies are a prime means of research into the flow processes in and around sinuous submarine channels. Unfortunately, physical modeling of self-formed sinuous submarine channel initiation and development has proved to be extremely difficult; self-formed channels of sufficient scale and stability to sustain detailed measurements of flow-field characteristics have not as yet been achieved. A viable alternative approach for such experiments has been to design experiments with pre-formed channel morphologies in non-erodible substrates, but such experiments inadvertently raise issues of scaling relations between channel morphology and experimental turbidity flow characteristics.
This paper presents the results obtained from a physical model of erodible channels that have undergone sinuous turbidity currents, and aims to determine a quantitative relationship between submarine channel dimensions and meander wavelength by performing statistical analysis.
Sand-carrying (D50=160 Mu) turbidity currents were introduced at an angle into a straight channel that was pre-formed into an erodible substrate consisting of the same sand as suspended in the flow. Pre-existing and resulting channel and deposit dimensions were determined from digital elevation models (DEMs). These DEMs were generated in ArcGIS from contour plots derived from rectified photographs taken during drainage of the flume. The results show sinuous deposition and erosion, which is interpreted as incipient sinuous channel formation. Analysis shows that a relationship exists between channel width and meander wavelength. The experimental meander wavelength scaling is compared with previous studies carried out on various subaerial and submarine channels. This comparison confirms that the observed incipient meandering obeys well-known geomorphological scaling relations.
This indicates that: 1) Characteristic meandering scales are comparable for experimental flows and natural prototypes over five orders of magnitude. 2) The ratio of meander-wavelength / flow-dimension is a fundamental scaling relation that should be taken into account in future flume studies. 3) Studies with freely-meandering, sand-carrying, experimental turbidity currents are achievable.

The role of inherited bathymetry on the architecture of wave-dominated deposits: Book Cliffs and Wasatch Plateau, Utah, USA

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In shallow marine shoreface systems the thickness of the various facies tracts is controlled by a combination of the depth to the respective wave base and the shoreline trajectory. Studying systematic changes in facies thickness within single parasequences and within several parasequences within the same basin can provide insight into dynamics of the depositional systems. Understanding shoreface architecture also has implications for modelling hydrocarbon reservoirs.

Facies tract thicknesses can be measured using conventional field techniques, however such a process is slow and time consuming. In order to collect large volumes of data that are statistically valid, helicopter-mounted lidar-scanning was used to collect data from two very large outcrops from eastern Utah. The first outcrop is a 3 km long section from the Wasatch Plateau which includes the Storrs Member of the Star Point Sandstone and the second is a 30 km long section from the Book Cliffs which includes the Kenilworth Member of the Blackhawk Formation. All of the sections are late Cretaceous in age and were deposited on the margin of the Western Interior Seaway in a sub-tropical climate.

The results of 164 measurements (with 200 m spacing) of shoreface and parasequence thickness suggest two key controls on facies thickness, the sea-level history during progradation and also the bathymetry. A critical aspect of the bathymetry is the position of the final shoreline of the underlying parasequence. Landward of that line, both the parasequence and the facies tracts within it are thin, while on the seaward side there is a marked thickening of both. Bedsets (smaller scale upward coarsening packages) are also common on the seaward side but absent in the shallow water deposits.

The decreased thickness of the shoreface in the shallow water seaward of the pinch-out of the underlying parasequence is proposed to be due to the shallowing of the wave base as wave energy is dampened by the frictional effect of the shallow sea floor. In the deeper water on the seaward side of the pinch-out of the underlying parasequence, the waves are not damped which results in a deeper wave-base and consequently a thicker shoreface deposit.

Facies Distribution in the Zechstein Supergroup in the Norwegian Sector of the northern North Sea Basin

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The Zechstein Supergroup (ZSG) is one of the world's best known evaporite-dominated depositional units. This Late Permian unit documents the repeated evaporation of a large saline water body that occupied the North and South Permian Basins. The facies distribution within the ZSG in the UK North Sea is well known; carbonate- and anhydrite-rich, marginal units pass basinwards across a gentle-dipping ramp into halite-rich, basinal units. However, the ZSG facies distribution in the Norwegian North Sea is unknown, despite the fact that this variability has been demonstrated to be the key control on the structural styles associated with the Late Jurassic rift event in the UK sector of the North Sea. In this study we use data from the Norwegian North Sea to investigate the controls on facies distribution in the ZSG. Our study was based on the detailed petrophysical analysis of electrical log data, constrained by lithological cuttings, from 22 wells. Regional stratigraphic correlation panels were used to investigate the vertical and lateral variability of evaporite-related facies in the ZSG, and 2D seismic reflection data were used to relate the facies distribution to the basin structural framework.

Our study shows that the ZSG is composed of mainly halite, anhydrite and carbonates, with minor amounts of claystone, sandstone and potassium salts. Based on the proportion of halite, four depositional zones are identified and these can be mapped. Overall, the distribution of facies is similar to that identified in the UK sector; at the basin margins the ZSG is carbonate-dominated, whereas towards the basin centre the unit become increasingly halite-dominated. However, abrupt facies transitions and thickness variations are observed adjacent to large, intra-basin normal faults; thin, carbonate-dominated successions occur on fault-bounded footwall highs, whereas thick, halite-dominated successions occur in adjacent depocentres. We propose that the distribution of facies in the ZSG was controlled by: (i) syn-depositional normal faulting, which in turn controlled local variations in water depth and accommodation; or (ii) spatially-variable amounts of halite dissolution, which was driven by post-depositional faulting. Towards the end of this talk we will investigate the validity of both these interpretations and then highlight how the ZSG facies variations may have impacted the structural style of the Late Jurassic rift event.

How do stratigraphic heterogeneities impact on flow in carbonate ramp reservoirs?

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Heterogeneities occur in various combinations over a range of length-scales and make understanding and predicting the production behaviour of carbonate reservoirs challenging. Many of these heterogeneities result from variability in stratigraphic architecture, depositional facies bodies, lithological variation within facies bodies, diagenetic history, mineralogy, pore type and connectivity.

We have developed a hierarchical classification scheme of stratigraphic and sedimentological heterogeneities in carbonate ramps as a first step towards reducing subsurface reservoir uncertainties. The stratigraphic framework often acts as a template for more complex, smaller-scale diagenetic and petrophysical heterogeneities within stratigraphic units. Hence, reconstructing stratigraphic heterogeneities is the first step in constraining heterogeneities in general. Levels one to three of the hierarchy document large- to small-scale stratigraphic architecture, extent and character of discontinuity surfaces, and spatial arrangement of broad environment-of-deposition belts. The distribution of depositional facies and stratal surfaces within the environments of deposition are documented at level four of the hierarchy, and small-scale heterogeneities such as bed geometries and diagenetic features within deposition facies are described at level five. Levels six and seven are composed of heterogeneity at centimetre-to-micrometre scale (e.g. sedimentary structures and pore networks).

The impact of various heterogeneities on reservoir performance is investigated using flow simulation of experimentally designed reservoir models. The hierarchy of heterogeneity is used to provide a framework for the building of high-resolution models in a top-down approach which incorporates more detailed and smaller-scale heterogeneities as we move down the design tree. End-member scenarios of key stratigraphic heterogeneities are constructed, based on project-specific outcrop analogues and published examples, and are incorporated into the high resolution models. Models are constructed using a combination of conventional and surface-based modelling techniques, which enable accurate and efficient capture of heterogeneity geometries. Flow simulation of a series of nested models at different length-scales, combined with experimental design techniques, enables the key stratigraphic controls on reservoir performance to be identified quantified for a range of production mechanisms and fluid types.

Four Basins and a Burial: Reconstructing the Burial Diagenesis of the Derbyshire Platform Using Numerical Models.

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Constraining reactive fluid sources and volumes is a major challenge in the reconstruction of carbonate diagenetic processes. Such quantitative constraints are required to evaluate conceptual models of diagenesis and allow more robust models to be developed. The Lower Carboniferous of the Derbyshire Platform, northern England, provides a data-rich environment where basin-scale numerical models can be used to provide these important constraints. The carbonate succession on the platform hosts economic volumes of Pb-Zn-F-Ba and its tectono-stratigraphic and diagenetic timelines are well established. This provides clear constraints for numerical simulations of fluid flow throughout the history of the system.

The Lower Carboniferous succession on the Derbyshire Platform accumulated upon a footwall high during a period of extensional rifting. Rapidly subsiding basins surrounding the platform accumulated thick, syn-rift sequences of marine, carbonate-mudstones and thin limestones. This sequence was progressively buried by a southward-prograding, fluviodeltaic succession during thermal sag subsidence. Late Carboniferous, Variscan compression led to reactivation of basement faults which resulted in basin inversion. Current conceptual models of mineralisation suggest that overpressure developed within upper syn-rift and post-rift basinal sediments and was released at the onset of Variscan compression.

We use Basin2 to simulate the coupled sedimentological and hydrological evolution of this system. Simulations show overpressure development within the deeper syn-rift basin-fill reaching 7.5 MPa at a burial depth of 2.75 km, with little overpressure development in post-rift sediments. 3.26 km3 per km of platform margin of this overpressured fluid is then released via a permeable fracture zone at the basin margin, which is introduced after maximum burial. Although these fluids represent only 2% of the total volume of the basins, all of this fluid is focussed to a relatively narrow platform margin area. Sensitivity analyses show that overpressures and associated fluid fluxes are slightly reduced by calcite cementation in platform carbonates but are primarily controlled by seal-unit permeability and post-rift deposition rate. Although these results broadly agree with previous conceptual models of mineralization, they emphasise that significant volumes of fluid may be sourced from deeper basinal sediments than previously thought.

Anatomy of an incised valley-fill at an evolving rift margin: Pleistocene of the Gulf of Corinth, Greece

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Incised valley-fills are known to include fluvial, bay-head deltaic, tidal and possibly barrier bar deposits, and the recent facies models of incised-valley systems have portrayed them as barred or non-barred estuaries with a predictable stratigraphic organization of the deposits. However, departures from a norm are equally important, as they reveal less common basin conditions and broaden the range of comparative models. The present study from the southern margin of the Corinth Rift documents a Pleistocene gravelly valley-fill that lacks evidence of tidal activity, shows strong wave influence in its innermost part and is dominated by deposits of a bay-head deltaic system evolving under a stepwise marine invasion. The Akrata palaeovalley reported here was ~3 km long, ~200 m deep and up to ~2 km wide. It was incised into similar older synrift deposits and axially dissected by a modern river valley with extensive cliff outcrops on its both sides. The infilling of Akrata valley commenced with a coarse-gravelly basal alluvium deposited during relative sea level lowstand. The subsequent marine transgression was initially gradual, resulting in four parasequences formed by the vertical stacking of mouth bars of a shoal-water delta, attributed to autogenic lateral shifting of the delta distributaries under a rising sea level. The next parasequence recorded a larger marine flooding that provided accommodation for a broader shoal-water delta with a uniform wave-worked front. This delta was drowned during the episode of maximum flooding, which provided highstand accommodation for a Gilbert type delta that prograded throughout the inundated valley. The delta progradation recorded further relative sea level changes, reflected in sigmoidal and oblique geometries of the foreset topset contact in the delta's valley-long dip section. The case study shows that the infilling of an incised valley in high sediment-supply conditions may be virtually dominated by the bay-head deltaic system and that wave action may have strong impact in the valley interior if permitted by the valley width, water depth and lack of barrier. Such conditions typify valleys incised in the flanks of active marine rifts, but may also be expected in foreland piggyback basins where intermittent pulses of considerable uplift and subsidence alternate on a short-time geological scale.

Identifying lithofacies in Carboniferous mudstones

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Fine-grained sedimentation on broad, relatively shallow-water shelves dominated late Namurian (Carboniferous) environments in northern England. This study examines temporal and spatial changes in the character and distribution of lithofacies in a stratigraphically well-constrained mudstone succession. A biostratigraphic marker horizon can be traced along a 'proximal' to 'distal' transect: from a northern location in the Stainmore Basin, Cumbria, to one in the Bowland Basin through to the North Staffordshire Sub-basin, adjacent to the Wales-London Brabant High, in the Midlands. Using lithofacies variability to understand the controls on sedimentation and distribution of organic matter is important for predicting the location of potential targets for Shale Gas exploration.

Key lithofacies, common to all locations, include homogeneous clay-rich mudstones, lenticular clay-rich mudstones and thinly-bedded mudstones. Thinly-bedded mudstones can be carbonate-rich or carbonate-poor with beds commonly <3mm. Individual lithofacies packages vary from tens of millimetres to a few metres in thickness, and represent changes in the predominant delivery mechanisms for a given period, from suspension settling to advective transport by turbidity and debris flows.

The lithofacies distribution varies between locations. Closer to the sediment supply, mudstones contain a higher proportion of silt-sized grains, exhibit a greater proportion of homogeneous and bedded lithofacies and have average SiO_2 of 52%. In contrast, lenticular clay-rich mudstones dominate the more distal location and are characterised by lower SiO_2 (ca. 45%). Organic matter is primarily derived from terrestrial plant debris and microscopic spores with a component of marine algal matter. Higher TOC abundances (typically >2%; up to 6.5%) are associated with the lenticular clay-rich lithofacies in all locations. TOC abundances for the bedded lithofacies range from 1.5-2.5% proximally to 2-8.5% in a more distal location.

The proximity to the sediment source has an important control on the abundance of siliciclastic material but similar sediment delivery processes occur across the basin. However, the regional comparison of lithofacies suggests that some processes are localised, or reflect a different source, as shown by the variation in composition of the bedded lithofacies. The lenticular clay-rich lithofacies forms thicker packages in distal settings, creating the potential for a thicker source/reservoir rock.

Fluvial architecture and geometry of the Lower Abrahamskraal Formation, Lower Beaufort Group, Karoo Basin, South Africa

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Kilometre-scale exposures of the Permo-Triassic age Lower Beaufort Group near Sutherland, south-western Karoo Basin, South Africa, were used to determine the geometry and distribution of fluvial sand bodies and sharp-based thinly bedded crevasse splay deposits.

The construction of correlation panels from widespread sedimentary logging over a 350 metre thick stratigraphic succession and the mapping of key surfaces using photomosaics has enabled characterisation of sand body geometry, facies distributions and facies associations. Within the lower Beaufort Group a range of architectural styles have been identified including discrete ribbon sandstone deposits surrounded by floodplain fines and stacked sheet-like sand bodies. These sandstones are interpreted to be from low and high sinuosity channel-belts respectively and are laterally extensive, ranging from 200m to 1200m in length. Some localised clustering of channel-belts adjacent to extensive overbank mudstone deposits is evident. The absence of mature palaeosols within the Lower Beaufort Group represents an environment that experienced rapid aggradation, with local avulsion events. Future work will continue to focus upon determining the main controls upon the rate of aggradation, as well as better understanding the three-dimensional depositional architecture of the Lower Beaufort fluvial deposits.

Porosity characterisation and permeability: a case study of the normal faulted shallow water carbonates of Malta

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Carbonate reservoirs are highly heterogeneous in their internal texture largely due to the range of depositional and diagenetic processes which form them. Carbonate reservoirs can also be complicated by structural damage imposed by faulting. The observed in situ heterogeneity of carbonate reservoirs creates challenges in characterising and up scaling their physical properties, chiefly porosity and permeability. For example: porosity and/or permeability can be enhanced or reduced around fault zones by burial fluids but the patterns are poorly understood.

Sedimentary logs are used to characterise the Oligo-Miocene stratigraphy of Malta. This study focuses on the lowermost two formations: the Lower Coralline Limestone (LCL) and Globigerina Limestone (GL) Formations. The Late Oligocene LCL Formation is a succession of large benthic foram and coralline algae rich grain-, pack- and wackestones. Unconformably overlying the LCL Formation is the Early Miocene GL Formation which is composed of a succession of planktonic foram rich pack- and wackestones. The GL Formation is subdivided into three members (lower, middle and upper) by hardground-phosphatic conglomerate couplets. Geological maps and cross sections are utilised to define the architecture of normal faults (displacements ranging from < 1 m to 100 m) in the two formations. Four fault architectural components have been recognised: fault core, intensely damaged zone bound by principal fault surfaces, weakly damaged zone and protolith.

Measured porosities (He) range from < 5% to > 35% and measured permeability (N2) varies over 5 orders of magnitude (< 2200 mDs). The variability of porosity and permeability data can be partially explained by depositional facies, indicating the importance of primary facies on the petrophysical properties of carbonates. Porosity and permeability vary considerably into the fault zones; however there are no clear porosity-permeability relationships associated with the defined fault architectural units. The types, sizes and shapes of macropores (> 500 μm2 in area), defined by digital image analysis, also vary into the fault zones. Preliminary results suggest pore types are an important factor controlling the permeability. The permeability of carbonates with high proportions of assumed microporosity (difference between core plug porosity and image analysis determined macroporosity) is generally lower than the permeability of carbonates with dominantly vuggy pore types.

Constraints to the timing of India-Eurasia collision as determined from the Indus Basin sedimentary rocks of the Indus-Tsangpo Suture Zone, Ladakh, India.

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The Cenozoic Indus Basin Sedimentary Rocks (IBSR) are preserved in the Indus Suture zone, Ladakh. They have been used in previous research to constrain the timing of India-Asia collision as having occurred by 50 Ma, based on provenance studies which determine the earliest occurrence of mixed Indian and Asian detritus in the sedimentary record and/or earliest evidence of Asian detritus deposited on the Indian plate (Clift, 2002; Clift et al., 2001). Our study (Henderson et al., 2010a; Henderson et al., 2010b; Henderson et al., 2011) disagrees with these previous findings and we conclude that the sedimentary record in this region cannot be used to constrain India-Asia collision at 50 Ma in the manner previously utilised.

The Chogdo Fm of the IBSR, lying beneath the 50 Ma aged Nummulitic Lst (Green et al., 2008), is proposed to contain both Indian and Asian derived detritus (Clift, 2002), and to lie in sedimentary contact with the underlying Indian plate (Clift, 2002; Clift et al., 2001), thus apparently providing two constraints to the time of collision.

Using a variety of provenance techniques, we were unable to discern any unequivocal evidence of Indian detritus in the predominantly Asian-derived Chogdo Fm. Given the overwhelmingly Asian provenance of the Chogdo Fm, its proposed stratigraphic position, in sedimentary contact with the underlying Indian plate, would provide another line of evidence to date the time of collision at prior to 50 Ma. For this evidence to be upheld, it must be shown that a) the material beneath the contact is indeed Indian rather than Asian plate, b) the material above the contact is indeed Chogdo Fm rather than younger IBSR and c) that the contact is sedimentary rather than tectonic. We studied the critical basal contact of the proposed Chogdo Fm at the three locations where previous work had indicated the formation lay over Indian plate. We analysed the beds above and below the contact using a variety of isotopic, geochemical and petrographic approaches to assess provenance. We showed that at none of the three locations could the above assumptions be upheld.

We therefore conclude that there is currently no evidence in the region for mixing of Indian and Eurasian detritus in the >50 Ma aged Chogdo Fm, nor evidence for Asian-derived Chogdo Fm overlying Indian plate in sedimentary contact. Thus, previously proposed constraints to the time of collision at ca 50 Ma, based on these data, in our view should be reconsidered.

Sedimentology and Sequence Stratigraphy of the Krossfjord and Fensfjord formations, Troll Field, Norwegian North Sea

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The sedimentological character and stratigraphic architecture of shallow marine reservoirs are strongly controlled by the physical processes that occur at and near the shoreline (e.g. wave- vs. tide- vs. fluvial-dominated). These processes can be further complicated by syn-depositional normal faulting, which controls subsidence, uplift and accommodation development. We present a subsurface case study from the Middle-to-Upper Jurassic Krossfjord and Fensfjord formations, Horda Platform, offshore western Norway. These formations are dominated by shallow marine to deltaic sandstones, which were sourced from the Norwegian mainland to the east and which pinch out basinwards to the west into offshore shales. The distribution, geometry, and connectivity of these sandbodies are poorly understood, as they have not been the focus of previous work. However, the formations form a significant oil and gas reservoir in the Troll and Brage fields, and a prospective reservoir in the area around the Gjøa Field.

Core, biostratigraphic and wireline log data are used to produce a consistent geological interpretation for the Krossfjord and Fensfjord formations in the Troll Field. In combination, the two formations define an overall regressive-to-transgressive wedge that interfingers basinward with marine shales of the Heather Formation. The facies associations identified in core represent wave- and tide-dominated deltaic, shoreline and shelf depositional environments. Based on facies stacking patterns and abrupt shifts in facies, three regionally extensive flooding surfaces are identified. Analysis of 3D seismic reflection data indicates that both formations contain seismic-scale clinoforms, and that they both thin and pinch out towards the west. However, the limited availability and distribution of core and well-log data restricts the detail and confidence with which seismically imaged architectures can be interpreted. It is therefore intended that these seismic interpretations will be calibrated by numerical modelling of the seismic expression of stratigraphic architectures observed in a range of outcrop analogues from the US Cretaceous Western Interior Seaway. The recognition of pronounced variability in facies character and stratigraphic architecture in the clinoform-bearing outcrop analogues emphasises the need for a robust understanding of their seismically resolved counterparts in the Krossfjord and Fensfjord formations, in order to efficiently develop these reservoirs.

Building a Schema for Outcrop Data - Towards a Standardised Nomenclature for Sedimentology

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Sedimentology, like most aspect of geology includes a vast array of terminology and nomenclature. Whilst the majority of this is well understood by practitioners of the art, there remains significant overlap and ambiguity in the terms geologists use to describe certain aspects of the rock record. Whilst this does not generally present a problem for people working within the subject it does create a very significant challenge when building computer databases. To be searchable, such databases rely on the rigid application of terminology otherwise it is impossible to compare like with like.

As part of the ongoing SAFARI project which is compiling a repository of architectural data from different depositional systems we have set out to describe a standardized nomenclature for clastic depositional systems and to transfer that nomenclature into a series of XML standards. The proposed schema is based around the outcrop and includes a physical description and georeferencing of that location. The standards then use models that describe the lithostratigraphy, depositional setting and sequence stratigraphy of the rocks at the locality. There is also scope for incorporating "other supporting objects" (such as maps, cross sections etc) within the database.

Terminology and categorization are already well defined for much of the description (e.g. lithostratigraphy) and schema already exist for many other aspects such as grainsize, climate zone etc. Much of the focus of the current work has been within the depositional setting model, where a myriad or terms exist and are commonly used. The key challenge is to devise a schema that is rigid enough to be useful, whilst being general enough to be adopted by a significant proportion of the potential user population. The proposed schema is based on a hierarchy from Gross Depositional Environment to Depositional Environment to Sub-Environment to Architectural Element. The schema will be presented and a web based mechanism for comments and feedback will be outlined. An overview of the SAFARI database will also be presented.

The Point Bar to Counter Point Bar Transition: Insights From Modern Meandering Rivers and Implications for the Rock Record

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Fluvial point bars and their upwards-fining deposits represent one of the original facies models, eloquently linking sedimentary processes and products. Motivated to better predict hydrocarbon reservoir distribution in fluvial meanderbelt deposits, the simple point bar model is revisited in order to provide a framework within which to predict both pathways and barriers to fluid flow in the subsurface. Through analysis of modern, and ancient seismically imaged river systems, significant downstream fining around individual point bars is documented. In the examples studied this fining is associated with the transition from point bar to counter point bar. This transition is morphologically delineated across an inflection point that separates convex downstream scroll bars (point bars) to concave downstream scroll bars (counter point bars).

Based on cores from six point bar-counter point bar transects, the downstream shift in grain size is quantified. Two point bars were analyzed on the modern Peace River in northern Alberta, Canada. Where studied, the average width of the river is 500 m, with an average decrease in net sand to gross interval thickness of 77% (0.88 to 0.11) recorded along 890 to 2785 m long segments of the river. Three tidally influenced fluvial point bars from southwestern Washington State, U.S.A., were also assessed. River widths averaged 180 m and net:gross decreased 42% (0.88 to 0.46) over 600 m along the point bar to counter point bar transition.

Subsurface reservoir strata imaged seismically and penetrated by hundreds of drill cores from the Cretaceous McMurray Formation of Alberta consists of a complex amalgam of tidally influenced fluvial meanderbelt point bar and channel deposits. The channel width in the system is 400-600 m and the shift from point bar to counter point bar corresponds to a decrease in net:gross of 61% (0.98 to 0.37). This facies shift has a significant impact on hydrocarbon reserves and recovery from the reservoir. Based on the dataset collected, the shift from sand-dominant to silt-dominant facies along the point bar to counter point bar transition is predictable. Despite the morphologic and reservoir significance of counter point bar deposits, they are generally overlooked in both modern and ancient meanderbelt systems.

Insights into provenance, transport history, depositional processes and diagenesis from high resolution geochemical studies of turbidite mudcaps

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Direct observation of deepwater turbidity currents is difficult owing to their infrequent occurrence, destructive power and deepwater setting. As a result, modern piston core datasets supplemented by geophysical and geochemical studies provide invaluable datasets. These studies show the importance of understanding the role of mud (0-32 μm) in these systems and the insights into the basin depositional history that can be gleaned from its study. Due to hydrodynamic sorting during the flow pathway, the sand fraction of turbidity currents is often unsuitable for use in provenance studies. Turbidite mud geochemistry provides major insights into the source of the turbidity currents, and due to the similar grain-size distribution intra- and inter-basin comparisons of compositions are more robust. ITRAX XRF analysis of turbidites from the mixed siliciclastic-volcaniclastic Moroccan Turbidite System has shown an ability to resolve differences in provenance for the event beds. Comparing the geochemical composition of correlated siliciclastic turbidites before and after exit of the Agadir Canyon has shown that large volume events are erosive (changing geochemical composition) while smaller flows are non-erosive (unchanging geochemical composition). While turbidite muds do not vary in composition between sites solely within Agadir Basin, showing that these flows are principally non-erosion once unconfined, regardless of volume.

The depositional mechanisms exerted on turbidite muds are complex owing to the inherent cohesive properties. Metre-thick mudcaps have been recorded in the Madeira Abyssal Plain. These turbidite muds have been found to pond into the centre of basin and between rift ridges. Previous studies have indicated potential for non-turbulent processes to be in operation. Geochemical studies of these muds has resolved the turbulent primary transport mechanism, laminar flow transformation on deposition, and final post-depositional remobilisation. These turbidite muds comprise TOC >2% in some cases with volumes of >100 km3. Diagenesis can dramatically reduce the TOC through the propagation of oxidation fronts. High resolution geochemical studies have allowed a better understanding of case examples. Indeed, although affected by the action of oxidation fronts the metre-thick nature of the deposits preserves and buries large quantities of carbon.

Sedimentological clues to fluid-assisted brecciation: the brecciated limestones of the Messinian Salinity Crisis re-interpreted as seep limestones

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Brecciation extensively affects the carbonate units developed during the Messinian Salinity Crisis of the Mediterranean Sea. The genesis of the brecciated limestones is controversial: traditionally interpreted as evaporitic collapse breccias, and recently even as the product of mass wasting processes, their relationship to fluid migration has been so far only speculated. The present study, addressed to some key-sections located in Italy (Maiella area; Calabrian Arc; Sicily), placed special emphasis on the comparison of the scales of observation of the fabric. Optical, electronic and cathodoluminescence microscopic techniques were integrated with stable isotopes analyses (d18O-d13C).
The carbonatic beds consist of brecciated marly lime mudstones, cemented and concretioned to different degrees, where brecciation is diffused at the mesoscale but localized at the microscale. The microfacies is mostly represented by a microbial-clotted and peloidal micrite.
The following textural proxies pointing to fluid assisted processes were detected: a) irregular geometries of the geobodies; b) primary fabric overprinting; c) peculiar characters of breccias: absence of gravity segregation and preferential orientation, monomictic and clast-supported fabric;
d) scale- and lithology-independent patterns; e) complex rheology (co-occurrence of brittle and plastic behaviour); f) fabric resembling gas-hydrate infilling sediments; g) association to fluid migration pathways and fluidized portions in the primary fabric.
The geochemical dataset shows wide ranges both in d18O (+7.74 down to -9.64‰ PDB) and d13C values (+4.14 down to -43.7‰ PDB). This can be the composite result of: 1) originally mixed C sources involved in authigenesis; 2) complex fluid-rock interaction; 3) different fluid composition in the different basins: definitely hydrocarbons-charged at places, possibly saline elsewhere.
The investigated bodies result from a fluid migration event that pervasively interested a partially lithified sedimentary column, with localized major inputs. The contextual formation of authigenic phases and the isotopic data converge to depict a fossil fluid seep environment, possibly accompanied by a major event of dissociation of gas hydrates in the Mediterranean Basin. The trigger for fluid migration, leading in turn to the diffused brecciation, is presumably related to high depressurization induced by a major drawdown (up to 1500 m) occurred during the Messinian Salinity Crisis.

Carbonate clumped isotopes applied to sedimentary systems: promises and challenges

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Clumped isotopes is a novel paleo-thermometer based on the laws of thermodynamics and that offers a number of advantages over traditional techniques: it is accurate to within a few degrees, can be applied to any carbonate phases (unlike fluid inclusions) and does not require prior knowledge of the fluid isotopic composition (one of the major pitfalls of traditional oxygen isotopes).

Accurate temperature reconstructions are critical for many sub-disciplines of sedimentary geology. Paleoclimate and paleoceanography rely on understanding variations in sea-surface, deep-ocean and terrestrial temperatures. Changes in high-latitude ice volumes can be deduced from benthic foraminifer oxygen isotope records if these latter are corrected for the temperature of seawater. Diagenetic transformations play a major role in controlling the petrophysical properties of carbonate rocks or cementation of siliciclastic sand horizons. A more accurate reconstruction of temperature and diagenetic fluid isotopic compositions would result in improved subsurface predictions of reservoir rock properties

For the last 2 years, the carbonate research team at Imperial College has been working in the framework of the Qatar Carbonate and Carbon Storage Research Centre (QCCSRC) at developing clumped isotopes for diagenesis. This presentation will give an overview of clumped isotopes, present published examples of applications to highlight the potential and promises of clumped isotopes, but also review the many technical and scientific challenges that need to be overcome to apply this method. Current research projects done at Imperial College that aim at a more streamlined approach to clumped isotopes, including automation of the technique using a prototype system called the IBEX (Isotopologues Batch EXtraction), will also be presented.

Clumped isotopes are likely in the future to become mainstream in the same way that oxygen isotope analysis used to be difficult a few decades ago but are now routinely applied to solve many geological problems. The road to understanding and routinely applying clumped isotopes is however full of promises for new discoveries, and a deeper understanding of geological processes from the reservoir to the molecular scale.

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The interaction between deepwater channel systems and growing thrusts and folds, toe-thrust region of the deepwater Niger Delta.

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Gravity-driven seaward-verging thrusts, landward-verging back-thrusts and associated folds often characterize the slope and deepwater settings of passive margins. These structures, found in the "toe-thrust" region of the system, exert a significant control on sediment gravity flows because they create and determine the location and configuration of sediment depocentres and transport systems. Consequently, a quantitative understanding of the interaction between sediment gravity flows and seabed topography is required to understand these systems effectively. Here we make quantitative measurements of the geomorphic response of submarine channels to growing tectonic structures with the aim of providing new constraints on the long-term erosional dynamics of submarine channel systems.

This study exploits 3D seismic data in the outer toe-thrust region of the deepwater Niger Delta to analyze the interaction between Plio-Pleistocene channel systems and actively growing folds and thrusts. We first mapped folds and thrusts from the seismic data and we used this data to reconstruct the history of fold growth. We then used the sea-bed seismic horizon to build a 50 m resolution Digital Elevation Model (DEM) of the sea floor in Arc-GIS. We extracted channel long- profiles across growing structures from the DEM, and made key measurements of channel geometries at regular intervals along the channel length.

Initial results show that changes in submarine channel longitudinal profiles are directly correlated to underlying seabed thrusts/folds. Channels gradients are typically linear to slightly concave, and have an average gradient of 0.90. Actively growing thrusts are associated with a local steepening in channel gradient (up to 200% change) and extends 0.5 - 2km distance upstream of the thrust. Within these "knickzones", channel incision increases by approximately 50%, with a corresponding width decrease of approximately 25%. Our data shows that submarine channel systems dynamically adjust their geometry and basal gradient in order to keep pace with growth of tectonic structures and our results provide new data to test models of turbidite incision.

Lateral variability of basin margin clinothems from the Karoo Basin, South Africa

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The lateral variability of basin-margin scale clinothems (W1-W7) in the Permian lower Waterford Formation has been studied in detail across a 1000 km2 area. Dip exposure of these clinothems occurs along the limbs of a series of east-west trending, post-depositional synclines and anticlines. Correlating logged sections by walking out parasequence flooding surfaces has established a 2D shelf to slope basin profile for successive clinothems W3 and W4 along the northern limb of the Baviaans syncline. W3 is a fluvial dominated parasequence in its most proximal exposures and exhibits large scale extensional deformation at the clinoform rollover with limited delivery of sediment beyond the shelf-edge. In contrast, W4 comprises wave/storm dominated shoreface deposits in its most proximal exposures, and prograded onto the upper slope with widespread erosion. Variability in shelf-edge architecture and facies distributions of clinothems W3 and W4 in the Baviaans input area indicate that the fluvial dominated W3 was unable to supply sediment beyond the shelf-edge. In contrast, the wave/storm dominated W3 shows significant evidence for sediment bypass and channelization beyond the shelf-edge.

Extensive regional correlations across strike lack any compelling evidence for the shelf-edge break in W3 and W4, which indicates that the Baviaans area has a more landward shelf-edge break with an embayed coastal morphology. This lateral variability in architecture and facies may be linked to along margin differences in the location of sediment input points, or infilling of an inherited bathymetry generated by mass failure events in the Baviaans area.

An Integrated Characterisation of the Paleocene Submarine Fans of the Lista and Maureen Formations, UK Central Graben

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The Paleocene submarine fans of the UK Central Graben are important petroleum reservoir units recording the cyclic input of sand-rich turbidite flows into the post-rift basin. Provision of extensive seismic, well and core datasets by Shell UI Europe has enabled a regional-scale re-evaluation of these deposits. This project aims to map the distribution and quality of the Maureen and Mey sandstone members and advance our understanding of the syn- and post-depositional dynamics within the submarine fans.

The use of regional seismic data allows for observations of the extent, thickness, net to gross, bathymetric interaction and temporal evolution of the submarine fans. Seismic interpretation benefits from correlation with cores and petrophysical data. Core sections (28 wells) have been studied to evaluate facies and how these relate to connectivity, grain size distribution and porosity/permeability trends. Furthermore, integration of a regional well database (338 wells) allows for mapping of formation thicknesses and sand quality. In turn, this has enabled seismic mapping to be ground-truthed enabling a more quantitative approach to attribute analysis.

The Lista sandstones are shown to be deposited in western and eastern fairways defined by the underlying topography with minor sidefans cross cutting this trend. The core and well facies can be divided into end-members based on the proportions of sandstone and mudstone. Analysis of these facies shows that porosity is related to grain size. As the grain size falls distally the quality of the sandstones also decrease. The Maureen interval exhibits a complex seismic signature but integration with well data shows that the main fairways are similar (although slightly offset) to those in the Lista interval. This system also displays complex sedimentological relationships between various chalk facies, mudstones and sandstones. Despite this, a similar relationship between porosity and grain size exists although there is some modification by calcitisation.

Examples are presented of potential scientific advances including clarification of our understanding regarding the spatial and temporal evolution of the submarine fans. Observations are made concerning the impact of basin geometry and salt-induced bathymetric variations on sand quality distribution as well as the validity of previous models. It is hoped that this work will also allow industry workers to consider the remaining prospectivity of these intervals.

Investigation of the Distribution and Composition of Organic Matter in the Namurian Upper Bowland Shale – a Potential UK Gas Shale

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The Upper Bowland Shale Formation is a source rock for oil and gas reservoirs in Northern and Central England, but may also contain reserves of unconventional gas. For realistic reserve estimates and to identify depositional 'sweet spots', the amount, distribution and composition of organic matter (OM), and their control on gas generation potential needs to be investigated. These parameters, and hence the location of prospective shale gas, supposedly relate to changes in biological productivity and palaeoenvironment. Previous studies have noted systematic differences in the type and origin of organic matter attributing these to changes in environment during the deposition of thin but widespread goniatite-bearing 'marine bands' and the intervening sediments.

110 mudstone samples were obtained from a 40m thick Lower Namurian core section from the Widmerpool Gulf. Methods include thin section lithofacies interpretation, carbon isotope analysis on bulk OM and individual organic components and palynofacies characterisation on isolated OM.

Two main lithofacies groups are identified: (1) a siliciclastic group that includes clay-dominated mudstones interbedded with millimetre-scale, graded silt-bearing mudstones, silt- and sand-bearing mudstones, and centimetre-scale silt-rich mudstones and; (2) a calcareous group of carbonate-bearing clay-rich lenticular or mottled mudstones and calcareous mudstones. The siliciclastic lithofacies group is interpreted to represent a period of frequent influx of sediment via distal pro-delta turbidity currents. This group is overlain by the carbonate-bearing lithofacies group containing the marine bands that are interpreted as predominantly hemipelagic mud deposition in relatively deeper water during rising and higher sea level.

The interbedded siliciclastic group has organic carbon content of 1.5-2.5%, with up to 10% occurs in a few discrete intervals associated with macroscopic plant debris, and heavier more variable, C-isotope values (mean δ13C: -27.7±1.4‰). OM composition varies from plant debris-rich to amorphous particle-rich assemblages. The calcareous group is characterised by a higher organic carbon content (4-5%), lower C-isotope values (mean δ13C: -28.6±0.9‰) and high abundances of granular amorphous OM typically produced by marine algae.

These data suggest that differences in sedimentary processes delivering sediment to the basin influence the type of organic matter as well as affecting the total organic carbon content.

Sandstone body architecture of distributive fluvial systems (DFS):

examples from Spain (Miocene) and USA (Jurassic).

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The deposits of distributive fluvial systems (DFS) in aggradational settings have a high preservation potential and therefore provide suitable analogues for fluvial hydrocarbon reservoirs. The sandstone body architecture of two DFS successions formed in different tectonic and climatic settings (the Huesca DFS in the Miocene of the Ebro Basin, Spain and Salt Wash DFS in the Jurassic Morrison Formation in Utah and Colorado, USA) have been studied in transects radially from their apices. These provide information about the types and dimensions of sandstone bodies, their organization and their relationships: in turn this provides an insight into the behavior of DFSs.

The main difference in the sandstone body architecture between the two systems is the degree of amalgamation. Isolated sandstone bodies enclosed by floodplain fine-grained deposits are characteristic of the Huesca system while the Salt Wash succession is mainly represented by thick amalgamated sandstone bodies (5-20m) within which individual channel-fill units are difficult to distinguish.

Three sandstone body types have been distinguished on the basis of processes of formation and dimensions: Type 1 – sandstone bodies with width to thickness ratios <15 formed by channelised flow in laterally stable channels; Type 2 - 2-4.5m thick sandstone bodies with width to thickness ratio >15 formed by channelised flow in laterally migrating channels; Type 3 - 0.1-2m thick sandstone bodies with width to thickness ratio >15 formed by poorly confined and unconfined flow in terminal or lateral splays. All three types are identified in the Huesca system, but in the Salt Wash system Type 1 sandstone bodies were less often observed and the succession is dominated by thick sheet-like sandstone bodies (3-6m) of Type 2; thin sheet-like sandstone bodies of Type 3 are also not common due to the low preservation of floodplain deposits.

The downstream and vertical variations in sandstone body architecture are a result of internal organization of the DFSs and are mainly controlled by autogenic processes such as channel avulsion and depositional lobe switching. The depositional architecture of the Salt Wash succession is strongly influenced by the low rate of accommodation creation.

Geometrical modelling of turbidite channel systems – implication on reservoir characterisation

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Turbidite hydrocarbon reservoirs are complex features, which need to be described in detail and represented as clearly as possible. The morphology and internal distribution of elementary distributary channels is dependent on depositional settings, leading to diverse arrangements at different scales.

Reservoir modelling usually requires a description of sedimentary heterogeneity on a scale smaller than that given by seismic resolution. Therefore turbidite channel storeys require a description based on the scales of individual channel bodies.

The morphology of well-imaged turbidite complexes was analysed geometrically to improve the understanding of their individual channel evolutions and assess depositional processes involved. The derived measurements are then treated statistically and compared with channel storey characteristics. Based on this geometric analysis, we have established a relationship between the channel storey confinement degree and the stacking architecture of elementary channel sand bodies. This relationship allows appreciating reservoir architecture and connectivity for different depositional settings characterized by channel storey confinement.

Less-confined channel storeys are thereby characterized by lateral migration patterns with low vertical amalgamation, resulting in a tabular amalgamated reservoir architecture which connectivity is related to preserved elementary channel margin heterogeneities. As confinement increases, down-dip and vertical movement components increase, leading to ribbon reservoir architectures and vertical amalgamation of sand bodies. Resulting reservoir characteristics are highly variable along channel storeys, depending on down-dip and vertical component ratios.

The various depositional patterns recognised in channel migration packages, exhibit different dynamic responses when modelled in a reservoir simulator. These dynamic differences are related to the different preservation rates of bank collapse sediments within each elementary channel bodies. According to these preservation differences, the vertical stacking pattern of channels imposes a better degree of connectivity than the true lateral migration. This effect has been incorporated into a full field simulation models by using geometrical based algorithms (LOSCs). Recognition and modelling of detailed sedimentological heterogeneities, and their distribution along full field models, associated with their own uncertainties, produce a better history match.

A Neoproterozoic glacial succession with a clear advance-retreat sequence: the Omutirapo Palaeovalley of northern Namibia

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The Sturtian glaciation is the oldest of three Neoproterozoic glaciations which are considered to have developed as global ice-house events during the Cryogenian (mid-Neoproterozoic). At Omutirapo in northern Namibia, a mixed carbonate-clastic succession of Tonian to?lower Cryogenian age occurs (the Ombombo Subgroup). This succession is truncated by a palaeovalley of about 2 km width and up to 400 m depth and this is filled by diamictites and various siliciclastic deposits of the Chuos Formation. We logged a total of 1000 m of the palaeovalley fill from 4 transects up to the contact with the overlying 'cap carbonate' (Rasthof Formation). The strata consist of a basal (~50 m thick) series of ferruginous diamictites, bearing rounded and rarely striated clasts, passing upward into intercalated clast-rich and clast-poor diamictites (~100 m thick) punctuated at intervals by intra-diamictite shear zones. The shear zones include both rotational and necking structures, with local clast injection (and fracturing) by quartzitic dykes, and are hence attributed to subglacial, rather than tectonic, deformation. Above, dropstones become progressively fewer, then absent, then progressively more abundant in green silty shales (maximum 150 m thick). This motif is interpreted to record glacial retreat followed by re-advance. Thus, coupled with the occurrence of clast-rich diamictites and shear zones toward the top of the succession, these data imply the re-advance of ice sheets and their re-occupation of the Omutirapo Palaeovalley, in turn suggesting a clear two-phased glaciation.

Facies, architecture and sequence stratigraphy of an ancient tide-dominated delta: lower Dir Abu Lifa Member (Eocene), Western Desert, Egypt

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Stacked progradational packages in the Eocene Dir Abu Lifa Member (Western Desert, Egypt) represent lower delta plain deposits dissected by major fluvial-tidal distributary channels within a tide-dominated deltaic setting. The complex facies architecture within the channels and their lateral relationship to interdistributary zones will be presented. Mutually evasive distributary channels were filled with lateral migrating tidal bars. Tidal indicators are ubiquitous, including abundant mud drapes, sigmoidal bundles and rhythmites. Each channel fill contains a consistent internal architecture that varies from channel axis to channel margin. Erosive channel bases are often lined by mudstones. Above these mudstones, planar to sigmoidal cross-bedded sandstone occurs. However, inclined heterolithic strata dominate the channel fills. Inclined beds are characterized by wavy- to lenticular-bedded layers, interpreted as sub- and inter-tidal bar deposits. Scours filled with mudstone incise into the uppermost part of tidal bars, representing "blind" tidal creeks. The dip angle of inclined beds and overall grain size both decrease towards the top of the channel-fill successions, which is capped by supra-tidal marsh deposits. Lower delta plain deposits comprise laterally extensive coarsening upward successions dominated by heterolithic strata with pedogenically modified tops. Each progradational package is capped by an intensely bioturbated sandstone that records transgression. Distributary channel belts can be related to laterally adjacent prograding delta plain deposits, and the occurrence of pedogenic horizons inside and outside the channelized facies allows correlation between both areas. Despite deep (up to 25 m) erosional relief, the channel belts are not confined to incised valleys. However, channel belts associated with successive episodes of delta progradation are vertically stacked.

Fault-Propagation Folding and Syn-Rift Sedimentary Response: An Outcrop Case Study from the Hadahid Monocline, Suez Rift, Egypt

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The early growth of normal faults is typically associated with the development of fault-propagation folds and the deposition of wedge-shaped syn-rift deposits that typically thin and onlap towards at-surface, monoclinal growth folds. Stratigraphic traps may develop on the limbs of these growth folds, although, due to limited seismic resolution and sparse well data, the architecture and facies distribution of early syn-rift stratigraphy is difficult to constrain in the subsurface.

To improve our understanding of the along-strike variability in structural style and the control that fault-related folding has on the architecture of early syn-rift strata we focused on a 2.5 km long segment of the Hadahid Monocline in the Suez Rift, Egypt. Field mapping and sedimentary logging indicate that the monocline dips 40-60 degrees towards the SW and that an, overall deepening-upwards, early syn-rift succession onlaps the monocline limb.

Marked variability in the magnitude of erosion along the pre-rift/syn-rift contact and the overall geometry of early syn-rift succession allow us to recognise four stages in the tectono-stratigraphic evolution of the Hadahid Monocline: (i) T1 - base-level fall and sub-aerial erosion of pre-rift stratigraphy prior to the onset of faulting or folding; (ii) T2 - base-level rise and the initiation of shallow marine sedimentation during a period characterised by limited at-surface deformation; (iii) T3 - initiation of at-surface growth folding in response to the onset of fault-tip propagation, development of a hangingwall syncline and deposition of wedge-shaped syn-rift units that thin and onlap toward the growth fold; and (iv) T4 - amplification of the growth fold, linkage with the adjacent fold segment, continued deposition of cross-sectional wedged-shaped syn-rift package, and formation of a single, coalesced, proto-hangingwall, synclinal depocentre.

This study highlights the control that fault-propagation folding and changes in base-level has on the architecture of early syn-rift stratigraphic traps in extensional settings. In addition, here we emphasise the value of well exposed outcrop examples in reducing uncertainty of future hydrocarbon exploration and production.

Use of modern analogues in correlation and palaeogeographic analysis of an evolving coal-bearing paralic succession, Paleocene, Svalbard, Arctic Norway

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Correlation using sequence stratigraphic principles requires facies deposited in different environments to be considered as coeval packages. Closely spaced data points may have deposits formed in the same setting but widely spaces ones would be assumed to be different facies in different environments. When attempting correlation some idea of the length scales of different deposits in two dimensions is required, especially in paralic environments, which may comprise a complex patchwork of sub-environments. In this analysis of Palaeocene coal-bearing strata from the Central Tertiary Basin of Svalbard, modern environmental analogues have been used to assist in carrying out the first comprehensive sequence stratigraphic analysis and paleogeographic reconstructions for the Firkanten Formation, the oldest unit in the basin.

Data from cores drilled for coal exploration and outcrop reveal that the Firkanten Formation consists of thick coal deposits, carbonaceous mudstone and sandstone with rare conglomerate beds. Facies analysis indicates deposition in a coastal plain with mires and swamps that graded into tidally influenced lagoons. The coastal plain was protected from wave reworking by sandy barrier bars and a fine-sand dominated foreshore/shoreface environment.

Within this succession there are no chronostratigraphic surfaces that can be used and lithostratigraphic correlation fails even between closely spaced boreholes. Consequently modern analogues of similar environmental settings were used as scale models to constrain the likely width of facies belts in the palaeogeographic reconstructions. Sequence stratigraphic correlation was carried out in a 3D grid in parallel with creating paleogeographic reconstructions requiring numerous iterations before a consistent evolutionary model could be developed.

These reconstructions show a gradual back-stepping coastline with a low-relief wave-induced coastal plain environment from marginal to shallow marine. This transgressive succession can be divided into parasequences bounded by minor flooding surfaces that can be grouped into parasequence sets bounded by major flooding surfaces. There is no evidence for relative sea-level falls within the succession and it is suggested that the tectonic subsidence exceeded rates of eustatic sea level fall. Aggradation is the dominant pattern with creation of thick successions of coastal plain deposits and the thick coal successions.

Controls on fluvial reservoir performance in dryland terminal fluvial systems

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Fluvial depositional systems form heterogeneous reservoirs whose behavior and performance can be difficult to predict. Research on the connectivity of fluvial sandbodies has been driven by the need to define critical thresholds of economic viability and robust development strategies that maximise recovery in low sand:shale successions. However, even in sand-rich reservoirs, where sandbody connectivity is high and tank-like behaviour might be expected, the reservoirs commonly fail to perform as initially predicted.

In sand-rich fluvial reservoirs the geometry and connectivity of the higher permeability (generally coarser grained) lower bar and thalweg deposits defines the flow conduits that drain a lower permeability matrix of upper bar and floodplain sandstones. High initial flow rates may be dominated by these coarse grained features, with longer term rates dependent on the inflow from the finer grained, lower permeability "background" facies into these conduits. In dryland, terminal systems such as the Triassic in the North Sea the geometry of the lower bar and thalweg facies change with position on the fluvial system, ranging from widespread sheets along the bases of proximal, mobile channel belts to more isolated bodies in more distal, avulsive settings.

Bar-draping fines, mudclast lags, reworked calcic palaeosol material and abandonment plugs are commonly occurring features in these Triassic reservoirs, and are a product of the ephemeral to intermittent discharge characteristics of the dryland fluvial systems. These features form very common, low permeability elements which short term well tests sense as lateral flow barriers within individual channel belts. However, long term production typically demonstrates that these have a less detrimental effect than initially indicated and that flow eventually finds routes around these features to drain larger areas than the tests would have predicted.

In many fields the reservoirs are stratigraphically compartmentalized. Major barriers recognised across large areas are the result of regional interfingering of the fluvial systems with distal floodbasin fines (e.g. playa) as they expanded and contracted in response to long-term, climate-driven changes in discharge. In smaller fields the channel belts may be larger than the field extent, in which case bar-top fines capping single channel belts are capable of forming field-wide vertical flow barriers. The former can be predicted, the latter form more random barriers.

Sedimentological character of an event bed produced by a high density turbidity current deposition, Buzzard field, UKCS.

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Basinwide thick turbidite sandstone beds are uncommon but important features of confined deepwater sheet systems. They can be seen in both outcrop and subsurface datasets and provide stratigraphic markers, and are often extremely important reservoir intervals making it essential to understand their geometry and depositional processes. The Lower B4 megabed in the Upper Jurassic Buzzard field is an example of a thick basinwide sand sheet. It has been studied using full wireline log suites from over 40 wells across the Buzzard basin, 9 of which have core penetration through the megabed interval. Detailed core logs, grain size and poroperm data have been used to characterise depositional character, to document facies changes across the basin, and to interpret the processes involved in deposition of the megabed.

The Buzzard basin is bounded by E/W extensional faults and has an eastward palaeoslope giving rise to a broadly eastward sediment transport direction. The Lower B4 megabed consists of structureless and laminated sandstone up to 85ft thick. The bed is wedge-shaped, thickening distally but maintaining a constant thickness laterally across the basin. It can be divided into five distinct intervals: coarse grained high permeability layer, structureless fine-medium sandstone, laminated fine-medium sandstone, upper dewatered layer and a "scalped" top zone. Both the bed base and bed top are sharp contacts, with no fine cap; the bed base is largely non-erosive but is commonly underlain by a zone of sandstone injection. The structure of the megabed is characteristic of a deposit produced by a single high density turbidity current.

The flow evolved through the basin resulting in a variable facies succession within the megabed. The coarse grained high permeability interval was deposited by a basal tractional layer largely confined to the axial and proximal area. The fine-medium sand intervals were transported in a higher velocity turbulent layer which was able to outrun the basal layer and deposit ahead of this basal layer. The presence of tractional laminae is dependent on the suspended load fallout rate. Fluid trapped within the interval rose to the top of the bed producing the upper dewatering layer, with deformation increasing upwards. The scalped top is produced by an overriding MTD which is unrelated to the megabed deposition. By mapping these subtle facies variations, we are able to model the permeability distribution; a key aspect of reservoir development.

Preservation of a drowned barrier complex: implications for interpretation of shallow marine facies

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Landscape response to relative sea level during the Quaternary is documented using an integrated dataset of multibeam bathymetry and 2D seismic reflection profiles from the Hastings Bank area in the northern English Channel. Mapping and interpretation of nine seismic stratigraphic units calibrated to lithological information from multiple vibrocores, has enabled the identification of fluvial, shoreface, barrier, beach ridge, washover fan, back-barrier and tidal environments of deposition. The interpreted landscape evolution is as follows: (i) fluvial incision of bedrock during sea-level lowstand; (ii) progradation of a shoreline and development of a barrier complex as sea-level rises; (iii) recycling and breaching of the barrier complex; (iv) rapid drowning of the barrier complex; (v) landward migration of the shoreline through continued sea-level rise; and (vi) complete abandonment and sub-marine preservation of the barrier complex during sea-level highstand. The previously undocumented, yet exceptionally well preserved, drowned barrier complex at Hastings Bank records phases of barier initiation, instability and retreat, and documents coastal response to high rates of sea-level rise. Barrier retreat is characterised by a phase of overstepping where rapid rates of sea-level rise drown the barrier and resultant deeper water depths limit reworking by waves, followed by a phase of discontinuos retreat where the shoreline steps back through continuous rollover puncuated by minor overstepping events (overstepping by rollover). The evolution of Hastings Bank is used as a foundation to construct a conceptual model, outlining the mode of barrier retreat and preservation potential as function of the balance between sediment availability and rate of relative sea-level rise. Validation of this model using data from coastal and shallow marine facies is required in order to constrain rates of relative sea-level rise and sediment supply, with the aim of predicting preservation potential of shallow marine facies.

Quantifying the relative role of multiple source areas on the budget, calibre and composition of sediment of an ancient routing system: Field examples from the Spanish Pyrenees.

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Constraining spatial and temporal trends in depositional volume, grain size and composition within ancient sediment routing systems is a key challenge for sedimentologists and stratigraphers. Central to this is the role of different sediment source areas in determining the locus, magnitude and characteristics of down-system depositional stratigraphy.
We tackle this challenge in the Escanilla Formation - part of a middle-upper Eocene, 200 km-long sediment routing system sourced primarily from the Axial Zone of the Spanish Pyrenees and deposited on top of a tectonically active fold and thrust belt in the south-central Pyrenean unit. This sediment routing system encompasses a wide variety of depositional environments from proximal fanglomerates, alluvial fan complexes, braided river and lacustrine deposits in the Tremp-Graus and southeast Ainsa Basins to deltaic slope and deep marine turbidite deposits in the western Ainsa and Jaca basin. We focus our study in the fluvial segment of this routing system.
We use sedimentary logs, interpreted panoramas and available chronological information from palaeomagnetic and biostratigraphic analysis as a template for presenting new sedimentological data in the form of grain size trends, clast lithology variations and variations in detrital thermochronology and geochronology signals. Based on field mapping we delimit the fairway of the sediment routing system and divide it into time intervals. Within this 4D stratigraphic framework we trace grain-size and sedimentary facies from the proximal areas to the distal depozones. We calculate a sediment budget for the Escanilla and relate it to observed grain-size and facies trends in order to understand the controls on down-system evolution.
Two major source areas contributed to the stratigraphic architecture of the proximal alluvial fan complexes of the Gurp and Sis paleovalleys and the distal fluvial depocentres (Viacamp and Lascuarre) of the Tremp-Graus and eastern Ainsa basins. We calculate the sediment efflux from these fans and hence their relative contribution in the stratigraphic record in these basins. A preliminary sediment budget shows a good match between the sediment efflux of mountain catchments and the sediment deposited both in the wedge-top basin and exported to deep sea depocentres in the west. Future work is aimed at better constraining the total sediment budget and its partitioning in terms of grain size fractions and depositional environments.

Spilling into confinement: processes in internal levees to submarine channels

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Submarine channel-levee systems are commonly simplified into axial (channelised areas) and marginal (external levees and overbank). However, a common observation from seismic sections is that in large (km's wide and 100's m deep) confined slope systems there is a significant component (>50%) of an opaque seismic facies. Interpretations of this component of the fill include terrace deposits, mass transport deposits, abandonment and internal levee deposits, although analogues at outcrop are rare. One well-documented example is exposed in Unit D, Fort Brown Fm., Karoo Basin, South Africa. Unit D at the C/D ridge is a deeply entrenched slope valley with a dominantly heterogeneous fill (70%). Six behind outcrop research boreholes cored through Units C and D along the C/D ridge allow detailed characterisation of sedimentary facies and interpretation of sedimentary processes operating during deposition. This high-resolution database allows detailed analysis of the significant heterolithic component that makes up >70% of the fill. Interpretation of sedimentary processes, lithofacies distributions, and unit thickness supports an internal levee interpretation. There is also a trend from channel-proximal to channel-distal settings. In channel-proximal locations, beds are 5-20cm thick and generally exhibit normal grading from very fine-grained sandstone to siltstone. Climbing ripple cross-lamination is common and examples of multidirectional current ripple lamination are present. In channel distal localities, sandstone content decreases markedly (from 50%-<5%), siltstone bed thicknesses are 2-20cm, fine-grained sandstone beds are less than 1cm and ripple lamination is rare. Individual bed thickness decreases upwards as the levee becomes siltier, with fewer occurrences of ripple lamination suggesting increasing confinement or waning in flow density. This change in facies suggests that there are several stages to levee development through time, related to a combination of allogenic (e.g. sediment supply) and autogenic (e.g. channel migration) processes.

Impact of clay mineral diagenesis and burial history on shale gas prospectivity, producibility and reserves: a Golden Zone perspective

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The advent of significant North American shale-gas production had an enormous impact on US domestic as well as international gas-markets. The geological controls on the prospectivity and producibility of shale-gas reservoirs remain however, problematic. Shale-gas reservoirs are essentially mature source rock intervals that have retained hydrocarbon gases. They have inherently low permeability, which has a strong control on their producibility; composite source-rock, seal and reservoir lithologies. Low permeability combined with very strongly-held capillary-bound formation water gives shale-gas reservoirs extremely poor reservoir characteristics that are entirely predictable from clay mineral diagenetic and petrophysical models. Permeability is so low that these rocks are likely to retain overpressure from deeper burial environments even after uplift and erosion. Overpressure is observed in several shale-gas basins where uplift and erosion of shales occurred, and when preserved may be a vital factor that determines the economic producibility of many shale-gas resources. The reduction of rock confining stress following uplift and erosion is a further reservoir characteristic that helps to facilitate fracture propagation and thereby increase the bulk permeability and allow access to greater gas volumes. Reports that the shale-gas reserves occur mainly within the kerogen matrix of the mature source rocks, rather than within the water-wet mineral-bounded shale pores, support these views. If correct, this implies fundamentally different hydrocarbon reservoir dynamics than that of conventional gas reservoirs, and therefore a need for the development of innovative numerical, petrophysical as well as geological reservoir modelling.

Dolomitisation and Dedolomitsiation of Shallow Marine, Upper Albian-Lower Turonian Carbonates of the Jeffara Escarpment, Southern Tunisia.

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Reservoir architecture of mid-Cretaceous carbonate reservoirs in Tunisia is in large part controlled by dolomitisation. Despite this fact, very little work has been conducted to determine the extent and timing of dolomitisation and its impact on reservoir quality.

This study examines superbly exposed section along the Jeffara escarpment of southern Tunisia, which provides an excellent opportunity to study the extensively dolomitised Upper Albian-Lower Turonian shallow water carbonates of the Zebbag Formation (Rhadouane, Kerker and Gattar Members), which are potential outcrop analogues for reservoirs currently under production and appraisal in North Africa.

During the mid-Cretaceous Tunisia was situated around 11ºN, and covered by a shallow epeiric sea that formed as part of the southern Tethyan margin.

Facies analysis of the Rhadouane (Albian-Cenomanian) and Kerker (Cenomanian) members reveals stacked upward-shallowing packages from bioturbated skeletal packstone-grainstones to algal laminated wackstones-grainstones, with rare ooid shoals, tidal bars and evaporite horizons. Facies analysis within the Gattar (Lower Turonian) Member has proved difficult due to the pervasive and fabric destructive nature of the dolomitisation. Dolomitisation within the lowermost Rhadouane (Albian-Cenomanian) and Kerker (Cenomanian) Members is incomplete and non-fabric destructive.

Planar dolomite fabrics throughout the Zebbag Formation suggests dolomitisation occurred at temperatures <50ºC, and lack of compaction features suggest a limited amount of burial. Stable isotopic analysis of Δ13C and Δ18O of dolomite gives values ranging between 0.83 to 3.92° and -1.97 to -0.33° respectively suggesting a marine origin of fluids. Later fractures provided conduits for hotter dolomitising fluids, recrystallising planar-e dolomite to non-planar dolomite.

Dedolomite and calcitisation is common within the Zebbag Formation occurring in thick, ~1.5m beds, within large non-strata bound fractures and as replacement of cores of dolomite rhombs by calcite. Dedolomite layers are laterally discontinuous, and return to pure dolomite compositions over a distance of centimetres. Stable isotopic analysis of dedolomite gives values ranging between -8.11 to -7.28° for Δ18O and -8.12 to -2.91° Δ13C. Highly depleted Δ18O values suggest that dedolomitisation occurred at elevated temperatures and/or via

meteoric ground waters and negative Δ13C suggests possible interaction with soil derived CO2.

Squeezing oil from shale: the sedimentology of the "Alberta Bakken"

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The Exshaw Formation of Western Canada comprises a heterogeneous succession of black shales in the lower part, and siltstones and limestones in the upper part. It is late Famennian to middle Tournasian in age, straddling the Devonian-Carboniferous boundary. The Exshaw Shale is considered the primary source rock of the Western Canada Sedimentary Basin. It was deposited during an anoxic event associated with the Late Devonian extinction.

The Exshaw Formation is equivalent to the lower and middle members of the Bakken Formation of southern Saskatchewan. The Bakken occupies around 200,000 square miles of the subsurface Williston Basin, and is a prolific source rock when thermally mature. It also hosts producible oil reserves. Total reserves of the Williston Basin are estimated at up to 24 Billion barrels, with perhaps 4 billion barrels recoverable. By the end of 2010 production rates had reached 458,000 bbl/day.

The Bakken comprises a striking succession of two shales sandwiching a dolomite. The shales are organic-rich, open marine shales deposited in anoxic conditions, while the middle dolomite member was deposited in shallower conditions as a coastal, carbonate bank. The low porosities (around 5%) and permeability (averaging 4 milliDarcies) are enhanced by natural fracturing, and horizontal wells drilled into the dolomite "carrier bed" access this fracture network at depths of three kilometres. Recovery is however likely to be less than 5% of the overall reserves. Successful horizontal wells have also been drilled into limestones of the underlying Big Valley Formation.

In southern Alberta the Exshaw Formation is unconformably overlain by the Banff Formation, and unconformably overlies the Wabamun Formation. The detailed stratigraphy comprises an underlying anhydrite passing up into limestones of the Three Forks Formation. These are unconformably overlain by the lower Exshaw shale, which is organic rich but not calcareous. This is overlain by a fine grained cemented siltstone. The Upper Exshaw shale is silty and organic rich, overlain by fissile dark grey shale. This passes up into lime mudstone and then into interbedded limestone beds and less abundant siltstone beds.

A sedimentological interpretation of these beds will be presented, together with a discussion on how the divergent character of the Bakken and Exshaw sediments affects potential drilling, completion and production.

Evolution of a distributive fluvial system on the Colorado Plateau, USA

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The Jurassic Morrison Formation outcrops extensively across the Colorado Plateau of the Western United States. The Morrison Formation consists of, from oldest to youngest, the Tidwell Member, composed of lacustrine and fluvial facies, the Salt Wash Member, composed of predominately fluvial facies, and the Brushy Basin Member, composed of lacustrine and fluvial facies. Previous and current work on the Salt Wash has established that the member is distributive fluvial system sourced from the southwest of the plateau showing a radial paleocurrent pattern flowing in a north, east and south-easterly direction.

This current study on the Salt Wash Member reveals two scales of progradation within the succession. Firstly, a large scale progradation of the Salt Wash Member is seen over the Tidwell Member and the marginal marine Stump Formation in the north. Within the proximal and medial areas a complete progradational sequence is not observed, and there is a sudden transition from the Tidwell Member to large scale fluvial channels of the Salt Wash Member. This is thought to be the result of low accommodation and lateral cannibalisation of previous channel deposits. However, in the distal areas a complete progradational package is observed from the marginal marine to coarse conglomeratic fluvial sandstones. These coarse conglomeratic sandstones that top the progradational package here are not commonly observed in the medial areas suggesting by-passing of coarse sediment, the presence of an axial river system or a secondary source area in Central Utah. The progradation of the Salt Wash over marginal marine deposits in the distal areas, implies a marine connection and control over the architecture of the deposits, as opposed to the downstream lacustrine control suggested by previous authors.

As well as the documentation of the large scale system progradation a second, much smaller scale progradation can be observed within the medial and distal portions of the Salt Wash Member. These smaller scale progradational cycles are observed throughout vertical successions and represent the progradation of channel belts into floodplain areas. These two different scales of progradation together provide a record of the filling of the basin, at both the small scale with regards to channel belt migration to build the fan itself up, as well as the larger scale of the fan building out into and filling the basin.

Climate change as a controlling parameter in sediment supply: The Nile Province

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The Nile is considered to be the world's longest river, 6,690 km from its source in Burundi, along the White Nile, to its delta on the Mediterranean Sea. Its drainage basin covers approximately 2,880,000 km^2 (Sestini, 989) including parts of Ethiopia, Sudan, Uganda, Tanzania and Egypt, amongst others, spanning many different geographic regions and climate zones.

The relationship between sediment delivery to the ocean and controlling factors such climate, tectonics, human impact etc. is complex (Syvitski and Milliman, 2007) and changes with time as these controls change. This study examines changes in Nile sediment flux since the Oligocene using accumulation rates in the Nile Submarine Cone (NSC) as a proxy. The study involved interpretation of 2D and 3D seismic data covering the majority of the NSC, through a combination of biostratigraphic and other well data and based on cycles at the 3^{rd} order scale. Once the seismic mapping was completed the horizons were depth-converted applying a variety of different algorithms to assess potential errors and quantify uncertainty. The resulting volumes were then decompacted, and sediment volume calculations performed to obtain sedimentation rates per unit time.

Dramatic variations in sediment delivery rate over the past 30 million years or so are immediately apparent. Although a late Miocene increase may be due to drainage basin capture in the Nile headwaters as a result of the Messinian sea level fall in the Mediterranean, the huge increase in sediment delivery since about 3.5 Ma can be ascribed to the onset of the East African Monsoon. High sedimentation rates during the late Pliocene are associated with wet periods that can be identified in ODP wells 967 (Eastern Mediterranean) and 721 (Arabian Sea), and with the change in vegetation from woodland to grassland. The subsequent (Pleistocene) fall can be ascribed to the dessication of the entire northern third of the drainage basin which has delivered little sediment to the NSC since the early Pleistocene.

A Late-Holocene record of marine washover events from a coastal lagoon in Jamaica, West Indies

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Coastal lagoons provide excellent repositories of marine washover events within the sediment record. There remains, however, an underrepresentation of these records within the Caribbean. To address this shortcoming a multi-site, multi-proxy project has recently been initiated at coastal lagoons on the south coast of Jamaica. This research aims to (1) provide records of washover events within the region, and (2) investigate the potential for attributing palaeowashover deposits to event type within the local setting. Manatee Bay (17°51'02"N, 76°59'15"W) comprises an enclosed lagoon separated from the coastline by a contemporary mangrove forest. To the north the lagoon is bordered by almost pristine limestone dry-forest communities. The depositional environment of Manatee Bay comprises woody (mangrove) peats that have accumulated ~1.0 m over the late Holocene and are punctuated by marine washover deposits. A suite of 15 sediment cores recovered from Manatee Bay provide records of multiple marine washover events that are characterised by stratigraphically distinct coarse bioclastic sand units. The bioclastic sand units that are dominated by plates of the calcareous green alga Halimeda spp., benthic foraminifera, and soft coral and sponge spicules, are likely to have originated from the compositionally similar sands of the offshore seagrass beds and beach areas. The depositional history of the lagoon suggests spatial variation in the thickness and number of overwash events associated with proximity from the coastline and alongshore variations in the coastal geomorphology.

Characterisation of terminations of hybrid turbidites against confining slopes using natural gamma-ray profiling

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Hybrid event beds are a common component of deep marine clastic sequences, and are interpreted to reflect the development of different rheological zones within particulate gravity currents. An idealised hybrid event bed includes a basal massive sandstone, succeeded by a banded sandstone, a muddy debrite and a laminated siltstone cap, though there are many variants on this scheme. When such beds occur in confined basins, their character and distribution can be strongly affected due to interaction between the parental current and the confining slope. The Crete-de-la-Barre section (Annot Sandstone, SE France) allows investigation of the lateral margin of a turbiditic sand body confined in a small basin. Tabular bed architecture at the km-scale and good outcrop quality allow virtually every bed to be correlated across a transect at a high angle to the confining topography for around 1.5 km. Hybrid beds are common within 1000 m of the confining slope. Debritic divisions thicken toward the palaeoslope and can make up over half of the entire bed thickness some 10-50 of meters from their pinch-out.

Sedimentological graphic logs were recorded at several localities along the cliff to capture the lateral facies variability within individual beds. However, clay abundance within each recognised facies is difficult to estimate in the field. Nevertheless this is important for both better understanding the behaviour of the flow that deposited such beds and for a more detailed characterisation of rock properties. Measuring natural gamma ray emissions for a selected number of beds has been undertaken with two similar portable gamma-ray detectors to evaluate if the resulting data could be used as a proxy for vertical and lateral clay trends. A number of beds were scanned at different positions with a vertical resolution of 8 cm. Data for one hybrid bed for which a large number of measurements is available show that gamma-ray emission of the basal clean sandstone division increases toward the bed pinch-out. Although further testing is required to better validate this methodology, it is likely that at least in this system gamma-ray trends can be interpreted as variations in mud content which cannot otherwise be detected in the field. Gamma ray profiles can therefore be tied to the sedimentary lithofacies model and can provide better characterisation of the rock properties next to beds pinch-outs.

Sand-prone subaqueous deltas: a subsurface example from the lower Sognefjord Formation, Northern North Sea, offshore Norway

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The Upper Jurassic Sognefjord Formation forms the main reservoir in the super-giant Troll Field, Horda Platform, offshore Norway. The unit has previously been interpreted as a delta system fronted by a spit. Here we integrate core sedimentology and 3D seismic geomorphology to refine the depositional model of the lower part of the formation.
We distinguish three, 10-40 m thick, wave-dominated regressive-transgressive packages bounded by major flooding surfaces. In the west, these packages consist mainly of well-sorted, cross-bedded, coarse-grained upper shoreface sandstones; in the south-east they become dominated by hummocky cross-stratified, fine-grained lower shoreface deposits. The presence of coarser, more poorly sorted sandstones in the north-east indicates greater proximity to a fluvial sediment input point. No evidence of subaerial exposure is observed.
Each of the three packages corresponds to a set of seismically resolved, westerly-dipping clinoforms; the major flooding surfaces form the seismic "envelopes" of the clinoform sets. All of the packages thicken westwards, until they reach a maximum where the clinoform "envelope" rolls over to define a topset-foreset-toeset geometry at the position of maximum regression. Both individual clinoforms and reflections bounding the clinoform sets are oriented sub-parallel to the edge of the Horda Platform (N005-N030).
Individual clinoforms form near-linear segments of 1-13 km strike extent. In the eastern half of the area, clinoforms are thin (10-15 m) with large dip extents (1.0-3.0 km) and gentle dips (1°-4°). Towards the west, clinoforms gradually become thicker (15-35 m), narrower (0.2-1.5 km) and steeper (5°-11°). Topsets are consistently well developed, except in the westernmost area, where some clinoform foresets are top-truncated. Stratal geometries imply forced regression within each package, but normal regressive stacking of packages.
We interpret deposition by fully subaqueous, wave-dominated, linear clinoforms that prograded westwards across a shallow-marine platform. Clinoforms were fed by a river outlet at the north-east and sculpted by the action of currents sub-parallel to the clinoform strike. Facies differences towards the west were mainly driven by increased wave energy and proximity to the river outlet. Although the clinoforms are sand-rich, both their geometry and the inferred depositional regime resemble mud-dominated shelf clinoforms observed in modern wave- or tide-dominated deltas.

Modelling falling stage topset aggradation: Implications for distinguishing forced and unforced regressions in the ancient record

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Distinguishing between forced and unforced regressive strata is important for prediction of sediment bypass and reconstruction of relative sea-level histories. Conventional sequence stratigraphic models distinguish between forced and unforced regressive strata through presence of aggradational topset (no aggradation during forced regression) and style of shoreline trajectory (descending in forced regressive strata and flat to rising in unforced regressive strata). However, because present models contain implicit assumptions about sediment supply and the response of coastal plain and fluvial depo-systems to falling and rising relative sea-level, it is possible that these two scenarios are an over simplification of a more complex reality.

This work investigates how topset aggradation might develop during relative sea-level fall using a simple diffusional stratigraphic forward model. Multiple two-dimensional model runs, (2My duration, and constant sediment supply and discharge rates representative of small to medium river systems) suggest that sediment transport rate may be a key control on topset aggradation. Modelling a range of sediment transport rates for amplitudes of relative sea-level fall from 0 to 100m shows that with relatively high rates of sediment transport, multiple model runs create strata with 9% to 0% of total deposited supply volume deposited as topset. Conversely, relatively low sediment transport rates lead to higher volumes of topset deposition ranging from 37% to 10%. However, critically, high sediment transport with no relative sea-level fall leads to topset aggradation very similar to that resulting from low sediment transport and high amplitude relative sea-level fall. This is an example of non-uniqueness, showing that topset aggradation can occur during falling relative sea-level as well as steady to rising relative sea-level, depending on rates of sediment transport. This result has been tested and verified with different rates of relative sea-level fall and with additional three-dimensional model runs.

This has some important implications for interpretation of relative sea-level history and sediment bypass. The results suggest that shoreline trajectories are likely to be a more reliable method to distinguish forced from unforced regression, and that interpretation and prediction of sediment bypass history may be more complicated then current sequence stratigraphic models suggest.

Large-Scale Fluvial Architecture of the Blackhawk Formation, Utah, USA

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Fluvial depositional systems in outcrops are characterised by their lateral and vertical stacking patterns which are themselves a function of often complex, interrelated controlling mechanisms. These controls include changes in base level, climate and source input. A dataset of more than 400 dimensional measurements has been collected and analysed from the non-marine Blackhawk Formation of central Utah. Data have been collected using a helicopter-mounted lidar system which allows the rapid collection of large volumes of data whilst still providing full 3D control on measurements.

Cretaceous strata of the heterolithic Blackhawk Formation and the overlying Castlegate Sandstone of the Wasatch Plateau and Book Cliffs areas in central Utah have been scanned and geometric data have been extracted from 35 km of virtual outcrops. Dimensions of the mapped sandbodies range from 5 to 700 m in width and from <1 to 23 m in thickness. The distribution of the individual sandbodies in the stratigraphic column reveals a number of trends including 1) an upward increase in maximum sandbody width; 2) a slight upward increase in sandbody thickness; 3) an upward decrease in the number of channels per 10 m interval and, 4) a slight upward decrease in the frequency of erosion surfaces. Previous authors have attributed vertical changes in the fluvial style within the Blackhawk/Castlegate system to be due to either gradual or abrupt changes in accommodation. The results presented here suggest that successive preserved fluvial systems are larger but the absence of an increase in erosion frequency suggests that while an upward decrease in accommodation may have contributed to these changes it is not the only control. The results of this study suggest that the entire succession is the deposit of a large distributary fluvial system on a vast alluvial plain. Such settings are common in modern alluvial systems. The identification of distributary fluvial systems has important implications for the prediction of reservoir quality and connectivity in ancient systems which form hydrocarbon reservoirs.

Giant Intrusions: Facies, architecture and flow processes

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Sand injection in the subsurface is a topic of significant investigation currently within earth sciences and large-scale sandstone intrusions have been documented in a wide variety of sedimentological settings. The ca. 40,000 km2 North Sea Basin province, the 2000 km2 Faeroe-Shetland basin intrusion province and the Panoche intrusion complex along a ~150 km lineament in California demonstrates the scale of some provinces. The sandstone injections hosted in the Jurassic strata of SE Utah could equally be classified as a large sandstone intrusion province, cropping out over 20,000 km2, occurring in the Carmel Formation and the Gunsight Butte Member of the Entrada sandstone.

Fieldwork was carried out in SE Utah to establish the facies present in a giant intrusion complex. The variety and distribution of facies described is broader than previously thought and provides compelling insights into the flow processes occurring during sand injection. Particularly the concentration and rheology of flows and parameters required for transport of clasts larger than 4 m in pipes. The architecture of the intrusion complex studied is described as pipe dominated, although major sills do occur. The total intrusion depth is estimated based upon source rock analysis and evidence for extrusion at other localities, thus completing the tripartite architectural elements of a large-scale sandstone intrusion province.

Carbonate mud production by marine fish: more questions than answers

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Mud-grade carbonates are volumetrically important sedimentary components in many modern and ancient shallow marine carbonate environments. The origins of carbonate mud in limestones are often problematic to resolve due to the obliteration of original grain textures during diagenesis, and mud sources in modern settings are necessarily used as analogues. Numerous sources of both aragonite and high-Mg calcite mud have been identified and are well understood. In addition, our recent work identifies marine bony fish as a prolific, but previously unrecognised, primary source of mud-grade carbonates in shallow tropical open marine settings. Here we consider factors controlling the growth of these crystals and the potential sedimentary implications.

Carbonate precipitation occurs continuously within the intestines of all marine bony fish as a by-product of their physiological requirement to constantly drink seawater. These carbonates are ultimately excreted into the open marine environment as mucus-bound mud-grade low- and high-Mg calcite crystals that exhibit a diverse array of crystal morphologies, many of which are unique in the tropical marine environment. By combining production rate data with site-specific fish biomass data, it is estimated that fish presently excrete 6 million kg $CaCO_3$/yr across the entire Bahamian archipelago, representing up to 70% of carbonate mud production in certain environments. However, although similar carbonate crystals are abundant in surficial sediment samples from the Bahamas, the ultimate fate of these carbonates has yet to be determined.

A key consideration with respect to the sedimentary significance of these carbonates is that of their preservation potential. High-Mg calcites are metastable in seawater and their stability is widely considered to decrease with increasing $MgCO_3$ content. Those with >18 mol% $MgCO_3$ are often considered to be subject to processes of rapid dissolution. Measured $MgCO_3$ content in fish-derived Mg calcites varies with fish species, ranging from 1 to 40 mol%. Thus it is reasonable to speculate that they will have different preservation potentials according to their chemical composition. It is therefore important to understand the controls on crystal growth within different species. Potentially important factors include: i) microbial communities within the gut; ii) availability of bicarbonate within the gut; iii) mucus membrane composition; and iv) sequestration of cations for physiological purposes.

Orbital pacing of the Ainsa basins Upper Hecho Group submarine fan deposits, Spanish Pyrenees

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The sediment flux to a basin is controlled by a complex combination of tectonics, climatic variability and stochastic events, thereby creating a cryptic geological record. Deconvolving the effects of individual factors controlling sedimentation can often be challenging, due to a variety of reasons including a lack of outcrop, a poor understanding of the regional tectonic framework and insufficiently detailed geological maps. Many of these deficiencies can be overcome within the deep-marine Ainsa basin where detailed research over the last decade has provided a very extensive knowledge base.

The Ainsa basin comprises ~4 km of middle Eocene deep-marine sediments which accumulated within the tectonically active South Pyrenean Foreland Basin and thrust-top basin. Basin stratigraphy is a succession of ~25 discrete sandy submarine fans and interfan deposits belonging to the Hecho Group. Deep-marine sedimentation is believed to have occurred over an ~10 Myr duration, suggesting that each submarine fan occurred every ~400 kyr. With this pacing being comparable to the long eccentricity Milankovitch cycle, Pickering and Bayliss (2009) hypothesised that sand supply was paced by climate and/or sea-level variability whilst tectonics control the loci of deposition. Here we test this hypothesis within the Upper Hecho Group (Banaston, Ainsa, Morillo and Guaso submarine fan systems) using a refined basin age model and the creation of floating orbital time scales between submarine fans. Using calcareous nannofossil and large shallow benthic foraminifera, the Upper Hecho Group is believed to have been deposited over a 7.9 Myr duration (early Lutetian to latest Lutetian/early Bartonian): this yields an average sediment accumulation rate (SAR) of 43.2 cm/kyr. Stratigraphic time series analyses of interfan fine-grained sediments indicate the presence of short eccentricity, obliquity and precession Milankovitch cycles. These floating time scales provide average SARs of 36, 28 and 25-33 cm/kyr for the Banaston, Ainsa and Guaso systems respectively. Applying these age models to the three systems suggest that submarine fan deposition potentially correspond to specific eccentricity minima. As in the Pleistocene, such Milankovitch forcing could be linked with ephemeral glacio-eustatic lowstand conditions, associated with increased coarse sediment flux to the deep-marine Ainsa basin.

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New stratigraphic constraints and depositional model for Lower Cretaceous peritidal deposits of central Oman: implications for facies heterogeneities in carbonate systems

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Data from outcrop studies provide valuable information on the lateral and vertical variability and stacking pattern of carbonate facies. The current study focuses on the Barremian-Aptian carbonate platform that outcrops in a 500x1000 m long butte in the Haushi-Huqf area of central East Oman, and that conceptually delineates aspects of peritidal carbonate distribution and associated facies heterogeneities. The geometries recorded include tidal flat beds broadly continuous over 10s of km, but also infilled storm scours 10s of meter long and shoal facies that pinch out laterally. The vertical evolution of the carbonate system is characterized by the stacking of 7 different types of meter-scale facies sequences. The large-scale stratigraphic succession displays an overall vertical trend of subtidal facies at the base, intertidal-supratidal in the middle and subtidal facies at the top of the succession. This facies change is interpreted as representing a nearly complete eustatic cycle combined with a change in platform geometry and the development of microbial mounds on the shelf. Stable isotopes of carbon offer new time constraints suggesting the Qishn Formation in the Huqf area is a lateral equivalent to the Shuaiba Formation and was deposited during the earliest Aptian. The results presented highlight that low-angle carbonate systems of the Middle East, usually assumed to have broad and homogeneous facies belts, can in fact present several closely juxtaposed environments of deposition conferring meter-scale lateral and vertical heterogeneities to the rock unit. Constraining these complex geometries is critical to improve carbonate reservoir flow models for hydrocarbon recovery.

Development of a confined turbidite system prone to hybrid event beds, Carboniferous, U.K.

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Sedimentary gravity current deposits exhibiting both turbiditic and debritic characteristics (collectively known as hybrid event beds [HEBs] have been recognised in deep-water fan systems from a variety of basins over the last decade. Features of such deposits (e.g. evidence of high flow matrix strength and shearing during emplacement) imply that at least part of the parental flows were not fully turbulent, at the time of deposition. Bathymetry is often considered to play an important role in triggering downstream transformations from turbulent to transitional or laminar flow, through promoting flow bulking and clay enrichment following incision and/or through forced flow decelerations due to gradient reduction or flow interaction with obstacles.

Understanding the mechanisms driving the onset of transitional and hybrid behaviour is important as this may help better predict the distribution and extent of associated clay-rich sandy facies that typically have poor reservoir properties. Furthermore the distribution of such deposits can provide insight into the wider system response such as the presence and persistence of upstream slope disequilibrium related to tectonism or sediment supply changes that may link with sea-level or climatic changes.

New research in the bathymetrically complex Southern Pennine Basin, Northern England, Carboniferous, documents the character and distribution of HEBs in a basin floor to base-of-slope fan system that banked against a downstream confining slope. Comparative field outcrop studies of basin margin and centre settings indicate the following: 1) flow bulking and clay enrichment over above-grade slopes is considered to have been the principal driving mechanism of flow transformation; 2) forced bathymetry-driven flow decelerations had no apparent further effect on flow transformations; 3) length scales (flow run-out distances) in the basin were sufficient to allow autogenic flow transformations prior to any additional influences of confining bathymetry - which would otherwise have resulted in forced flow transformations and differing HEB characteristics and distributions; 4) HEB character may be influenced by, and thus record, changing substrate type; 5) HEBs can also be sources of heterogeneity in relatively more proximal sand-rich settings; 6) HEB characteristics may provide a means by which models of basin infill can be assessed (e.g. progradation vs. aggradation; progressive vs. out-of-sequence deposition).

Carbon capture and storage: have our coal and burn it?

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In countries which rely heavily on coal to generate electricity, carbon capture and storage (CCS) could be a technology to allow continued growth, but also CO2 emissions reduction. In Britain the Government predicts that CCS could be an industry the size of present day North Sea oil. According to 2006 figures, rocks under the UK North Sea could store about 22 billion tonnes of CO2 which is 180 years production of CO2 from the UKs 20 largest point sources (e.g. power stations). However basins with high potential for CCS need to be surveyed and this is a central role for geological surveys, being an expansion of their traditional role as inventory-maker of subsurface natural resources. The role of the survey includes accurate storage capacity estimation to attract company investment and improve general financial investor confidence, as well as developing basin-wide modelling to handle multiple use of pore space, for example oil and gas production, natural gas storage and water extraction.

In depth sedimentological studies are also coming into their own as the importance of reservoir heterogeneity, sedimentary geochemistry and long term interactions between CO2 and reservoir materials are realised. Until now modelling of subsurface CO2 injection and migration has for the sake of simplicity assumed homogeneous reservoir rocks, and modelling has concentrated on interactions over years rather than hundreds or thousands of years. In this talk I will show some modelling and simulation of (1) buoyant CO2 in physical trapping; (2) CO2 dissolution in formation waters over thousand-year timescales; (3) pressure in closed and open reservoirs; and (4) heterogeneity, for example in the Mid-Triassic Helsby Sandstone Formation exposed around Runcorn, which is an onshore equivalent of a possible target for future CO2 storage for point sources in Liverpool, Manchester and Deeside.

The flows that left no trace: very large-volume turbidity currents that bypassed sediment through submarine channels without eroding the seafloor

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Turbidity currents are one of the most important flow processes for moving sediment across the surface of the Earth. Submarine channels are often conduits for these flows, exerting a first order control on turbidity current flow processes and resulting deposit geometries. Here we present a detailed examination of the Madeira Channel System, offshore northwest Africa, using shallow seismic profiles, swath bathymetric data and a suite of sediment cores. This shallow (< 20 m deep) channel system is unusual because it was fed infrequently, on average once every 10, 000 years, by very large volume (> 100 km3) turbidity currents. It therefore differs markedly from most submarine channels which have well developed levees, formed by much more frequent flows. A northern and a southern channel comprise the Madeira Channel System, and channel initiation is associated with subtle but distinct increases in sea-floor gradient from 0.02º to 0.06º. Turbidity currents passing through the northern channel deposited thin (5 to 10 cm) ripple cross-laminated sands along the channel margins, but deposited no sand or mud in the channel axis. Moreover, these flows failed to erode sediment in the channel axis, despite being powerful enough to efficiently bypass sediment in very large volumes. The flows were able to reach an equilibrium state (autosuspension) whereby they efficiently bypassed their sediment loads down slope, leaving no trace of their passing.

Predicting Reservoir-Quality Facies in Low Net-Gross Fluvial Overbank Successions

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The distribution of sand bodies within fluvial overbank settings is strongly controlled by processes that dictate the style and frequency of overbank flooding via the breaching of levees, the generation of crevasse splays, and the development of minor tributary channels. In particular, size, longevity, spatial distribution and style of connection of splays to primary channels govern the distribution of sand bodies within overbank settings. The presence of reservoir-quality facies in otherwise mud-prone fluvial overbank successions is important as such sand bodies can provide significant connectivity between neighbouring major channel elements in an avulsion-prone channel belt.

Although determination of 3D architecture and overbank connectivity is crucial for reservoir prediction in low net:gross floodplain settings, typical well spacing in hydrocarbon provinces (several km) is too great and the total number of wells too few for the development of accurate predictive models. Likewise tertiary splay and minor distributary channels (~3m thickness) are below the vertical resolution of seismic data.

Results from a subsurface case study demonstrate 3D architecture of reservoir-quality overbank deposits in low net:gross settings. A study of secondary and tertiary fluvial elements deposited in interseams of the Late Permian Rangal Coal Measures (Bowen Basin, Queensland), utilizes a suite of densely spaced well data from a database of well logs acquired during coal prospecting at the South Blackwater Mine. Where well-spacing was too great to allow accurate correlation and hence modelling of tertiary channel elements, dimensions from modern analogues (including Cumberland Marshes, Saskatchewan, and the Ob River, Siberia) have been used as a proxy to produce stochastic models of potential sand-body distributions. The dimensions of modern analogue secondary and tertiary channels form the basis of a database which is being used to model probable spatial distributions of such channels in seismic data.

An integrated workflow is presented for the modelling of sub-seismic features using a combination of well, analogue and seismic data to model potential distributions of sub-seismic reservoir quality deposits. Preservation and connectivity of tertiary channels is shown to vary as a result of channel thickness and width, channel percentage of infill and frequency of crevassing. These in turn are governed by allogenic controls, most notably accommodation space and climate.

Cyclic step arrays: the critical jump in understanding submarine flows.

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Field scale submarine channel gravity currents are notoriously difficult to measure and thus directly investigate due to their inaccessible location and infrequent nature, which is compounded by present sea-level high-stand. An exception to this is the almost continuous density-driven current that results from the inflow of saline Mediterranean water, via the Bosporus strait, into the Black Sea. This flow has carved a sinuous channel system in water depths of 70 to 120 m containing a series of prominent scours at the upstream end. Despite being driven by the salinity contrast, the flow is sufficiently energetic to transport and rework coarse sand within the channel network. The relatively shallow depths of the channel and the continuous nature of this current provide a unique opportunity to study three-dimensional flow dynamics and the interaction of the flow with a seafloor channel network. Thus, it provides a rare analogue for channelized dilute sediment-laden turbidity currents.

There has been speculation for nearly half a century that hydraulic jumps are an important process in submarine density currents. Hydraulic jumps have been implicated in causing the development of submarine fans, large scale (km-scale) scouring, the formation of cyclic steps and channel genesis. However, until now this has been inferred from a combination of small scale laboratory experiments and making inferences about flow processes from the geological record and modern bathymetry. We provide the first direct field evidence of hydraulic jumps in a submarine density current. The largest jump imaged is in phase with a 100 m scour in the seafloor, this scour comprises one in a field of scours. As seafloor gradient declines, rather than undergoing a single jump, multiple jumps develop and scour the seafloor, forming a cyclic step array. Strong vertical velocities across the jumps, combined with a smaller than predicted decrease in forward velocity should be sufficient to maintain sediment in suspension well beyond the scour field, thus explaining the commonly observed transition zone between the base of submarine canyons and ultimate fan deposition.

Source-to-sink analysis of modern and ancient sedimentary systems

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The application of a source-to-sink methodology for the analysis of sedimentary systems include qualitative and quantitative assessment of external and internal forcing factors that are involved in the production, transportation and deposition of sediments, from catchment erosion to deep-marine fan deposition. The temporal aspect of source-to-sink analysis can cover the entire spectrum, ranging from daily processes and events, to long-term basin fill over tens of millions of years. The temporal aspect is crucial for interpreting the linkages between source sediment production and sink deposition. On short timescales (hundreds to thousands of years), the resulting stratigraphy is mostly event-driven and tectonic and eustatic controls are often negligible; segment morphology is often well contained and age control is generally good. On intermediate timescales (tens of thousands to millions of years), eustatic, climatic and tectonic factors work in concert to control stratigraphic development; preservation of segment morphology is largely area dependent. When long timescales are considered (millions to tens of millions of years), tectonics is the main driver of sediment production, accommodation and preservation. Studies on ancient systems are often hampered by poor time control, lack of high-resolution data and lack of segment preservation due to denudation, erosion and tectonic deformation. Thus, whereas source-to-sink analysis on modern systems investigates the mode of sediment dispersal in areas where the actual extent and geomorphology of the landscape and seascape is relatively well constrained, the analysis of ancient systems partly involve the reconstruction of the onshore and offshore segment morphology. These differences are illustrated here by examples from the Quaternary Golo system off Corsica (France) and the Late Cretaceous More-Trondelag deep-marine fan systems along the Norwegian North Sea margin. These studies demonstrate how source-to-sink approach may help improving the interpretation of stratigraphic variability in modern and ancient sedimentary systems.

Emplacement dynamics of landslides around volcanic islands and implications fof tsunami hazard; insights from the most detailed geophyical mapping yet of such landslide deposits

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Most of the material erupted in volcanic island arcs is ultimately deposited as marine sediment. The marine sedimentary record therefore provides an archive of volcanic events, which may include deposits from pyroclastic density currents, tephra fallout and flank collapse. The largest events preserved in the marine record are landslides associated with volcanic edifice collapse. Such events are among the largest mass movements known on the Earth's surface. For example, deposits off Dominica, south of Montserrat, cover an area of 3500 km2, far exceeding the largest known subaerial volcanic debris avalanche deposit (from Mount Shasta, with an area of 675 km2). Volcanic island landslides may generate devastating tsunamis. However, accurate assessments of tsunami hazard rely on a full understanding of landslide failure processes and emplacement dynamics.

We have used geophysical data to investigate the record of large landslide deposits offshore Montserrat, exploring internal deposit structures and landslide deposit relationships. The high-resolution data is among the most detailed yet collected over submarine volcanic landslide deposits, and has been interpreted in preparation for drilling of these deposits during IODP Leg 340, planned for February-March 2012.

Our results show that the largest landslide deposits (maximum volumes of 20 km3) include a dominant component of seafloor sediment, and occurred in multiple stages. Both these factors imply a reduced potential for tsunami generation. Similar failure dynamics are indicated by deposit morphologies further south in the Lesser Antilles, offshore Dominica, Martinique and St Lucia, and may be widespread. At Montserrat, deposits were triggered by deep-seated volcanic edifice collapse, and contain individual blocks with volumes >107 m3. The frequency of the largest failures corresponds to the development of individual volcanic centres on the island: one deposit is of Soufriere Hills age; the previous one of Centre Hills age. Following these largest failures, other smaller flank collapse deposits occur, interbedded with extensive pyroclastic fans. However, there have been prolonged periods during the history of Montserrat characterised by low levels of marine volcaniclastic input, reflecting long-term cycles of edifice growth and destruction.

Multi-scale analysis of mudstones and shale gas reservoirs.

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Fine-grained organic carbon-rich sediments (mudstones) are increasingly being targeted as hydrocarbon "reservoirs" as either gas-bearing or oil-bearing shales. Such hydrocarbon sources are predicted by many analysts to provide plentiful and long-lasting reserves globally, including in the UK, as evidenced by recent reserve-announcements, market forecasts and gas-price adjustments in the USA.

Reservoir quality within gas- and oil-bearing shales is controlled by a number of factors, including organic-matter content and type, maturation, sedimentary and diagenetic heterogeneity and frackability. Mudstones have been shown to be highly heterogeneous rocks, in contrast to previously prevailing wisdom, composed of highly reactive organic and inorganic components, sedimentary fabrics resulting from many depositional mechanisms, and pore-structure evolved during both early and burial diagenetic processes. As a result, they are challenging reservoirs. A key requirement for characterising these reservoirs, and mudstone successions in general, is to make observations and analyses at a range of scales, from basin-scale through to pore-scale. This presentation will provide an overview of the approaches that can be taken and examples of resulting data that can be generated to inform this endeavour.

Outcrop study of mudstone successions has allowed sequence stratigraphic frameworks for mudstone variability to be constructed, and the distribution and nature of stratal surfaces and associated diagenetic alteration to be recognised. Low magnification thin section observations have shed light on the depositional mechanisms operating in mudstones, which include advective processes such as storm-deposition and wave-enhanced sediment gravity flows, and marine-snow productivity events in the water column. Electron microscopic analysis has highlighted that the diagenetic pathways taken by marine unconsolidated muds are a key factor in controlling the mineralogical, chemical and physical properties of resulting mudstones. Here, we argue that these pathways, particularly during early diagenesis, are largely pre-determined by the initial mineralogical composition of the sediment. Finally, the novel application of X-ray tomography allows the 3 dimensional distribution of mineral and pore networks to be quantified and modelled, with significant insights into reservoir quality and potential permeability pathways.

Stylolitization of late Eocene to early Miocene carbonate-bearing lithologies from IODP Hole 317-U1352C (Canterbury Basin, New Zealand)

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Stylolites are irregular discontinuity planes that are thought to result from localized stress-induced dissolution during burial or tectonic compression. The genesis of stylolites and the controls on stylolitization are still debated. Moreover, the impact of fluids resulting from stylolitization, and thus the interplay of stylolitization with fractures, porosity, cementation and fluid flow is complex. All of these processes are important diagenetic effects that can alter intrinsic properties of the host rock, with implications for hydrocarbon prospection. The current study takes a macroscopic, petrographic and geochemical approach on late Eocene to early Miocene carbonate-bearing rock samples from the Integrated Ocean Drilling Program (IODP) Hole 317-U1352C (Canterbury Basin) to get a better understanding of the stylolitization process. The results indicate an inverse relation between stylolite amplitude and the clay content in the host rock. Evaluation of the stylolite spacing shows clustering of stylolites. The majority of the stylolites are bedding parallel and probably started developing during mid-late Miocene, whereas the oblique stylolites with perpendicular peaks might be linked to the late Pliocene to early Pleistocene regional northwest-southeast shortening. Quantitative image analysis suggests that the amount of limestone dissolved during stylolitization is larger than the cement in the host rocks, implying a significant amount of fluid probably escaped the open system. No evidence is found for fluid flow along stylolites, at least not for fluids that were not host-rock buffered.

Role of salt tectonics in controlling fluvial system evolution in the Salt Anticline Province of SE Utah and SW Colorado

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The proximal part of the Permian Cutler Group of southeastern Utah and southwestern Colorado is characterised by a succession (up to 4000 m thick) of conglomerates and sandstones of mixed fluvial and aeolian affinity that infill the foredeep of the Paradox foreland basin. The style of accumulation of much of this succession was influenced by active salt tectonics associated with movement at depth of the Pennsylvanian Paradox Formation. Throughout Cutler times, progressive salt withdrawal in the area east of Moab resulted in localised subsidence, culminating in the creation of a series of salt-wall-bounded mini-basins known as the Salt Anticline Province. Assessment of the role played by active salt tectonics in controlling fluvial system evolution has been possible through the collection of a suite of 81 sedimentary logs (total logged thickness of ~6000 m) and 10 architectural panels (representing an outcrop belt ~5 km in length).

Cutler Group sediments in the Salt Anticline Province undergo dramatic thickness variations, being less than 250 m thick over salt highs but approaching 4000 m thick in adjacent mini-basin depocentres only 500 m away, laterally. Facies associations and architectural relationships demonstrate a range of styles of syn-sedimentary salt movement that resulted in predictable changes in fluvial system behaviour. Multi-lateral and multi-storey channel complexes in the salt mini-basin centres indicate overfilled basins subject to repeated sediment reworking along major fluvial fairways. By contrast, isolated channel elements separated by overbank elements prevail adjacent to salt diapirs and indicate only infrequent episodes of sediment reworking. Onlapping and unconformable relationships seen both at outcrop and in subsurface data demonstrate at least 5 phases of Cutler Group sedimentation. Facies and palaeocurrent analyses reveal complex drainage patterns, which demonstrate how successive phases of salt uplift repeatedly forced the diversion of fluvial systems along route-ways parallel to the uplifted salt walls. During tectonically quiescent episodes, fluvial systems rapidly filled available accommodation in ponded mini-basin depocentres before re-establishing preferred flow pathways over buried salt highs.

This research serves as an outcrop analogue study with which to potentially develop generic architectural models for use in understanding subsurface salt provinces such as those in the Triassic of the Central North Sea.

Plastic deformation, erosion and acceleration of turbitidy currents moving over soft, cohesive, horizontal substrates

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That many aquatic environments have soft, muddy substrates, has been largely ignored in process-based models of Earth-surface flow. However, a soft cohesive substrate with fluid-mud properties is believed to interact differently with a passing turbidity current than a sandy substrate in terms of erosion and deformation.

Changes in flow and substrate properties caused by flow-substrate interactions, are closely related to changes in bed shear stress, flow turbulence properties, substrate erodibility, flow density and rates of deposition. This study aims to quantify the interaction of turbidity currents with soft, muddy beds in terms of changing flow properties, bed erosion and plastic deformation.

Laboratory experiments were carried out in the Hydrodynamics Laboratory at Bangor University (Wales, UK). Kaolin-clay laden turbidity currents with increasing initial concentrations (from 0.4 to 12.5 vol%) were created and monitored while moving over soft, fluid-mud like, kaolin-clay deposits with initial concentrations between 6 and 13 vol%. Ultrasonic Doppler Velocity Profilers (UDVP), Ultra High Concentration Meters (UHCM) and an HD video recorder were used to observe the interactions between flow and substrate at various contrasts in clay concentration.

Four types of flow-bed interactions are identified: 1) no interaction, 2) formation of a solitary bed surface wave travelling in front of the turbidity current ('leading wave'), 3) shear waves at the flow-bed interface, and 4) mixing and erosion. The type of interaction that occurs is believed to be controlled by the difference between the flow and bed concentration.

The most notable result is the acceleration of turbidity currents over a horizontal, plastically deformable, cohesive substrate. The boundary conditions at which this acceleration takes place are under investigation, but the data suggest that erosion and changes in the geometry of the flow, associated with plastic deformation (i.e., shear waves), are key to explaining the changes in turbidity current velocity.

The results of this study may explain the large continuity of some turbidite deposits in modern oceans and the geological record and provide insights into the facies characteristics and architectural properties of these turbidite deposits.

Reactive transport modeling as route to predicting carbonate diagenesis

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Reactive transport models (RTMs) can improve our capability to predict carbonate diagenesis by 1) helping to develop better conceptual models based on chemically and physically realistic scenarios, 2) providing quantitative estimates of rates and distribution of diagenesis, and 3) describing diagenetic geobodies which can be used to populate reservoir models. This presentation explores elements key to developing meaningful RTMs, using examples from early meteoric diagenesis.

Vadose diagenesis is driven by flows which are essentially vertical and can be captured in 1D models. However, most systems need to be simulated in 2D or 3D, with systematic differences in diagenesis predicted for different platform geometries. Predictions of diagenesis from RTMs are only as good as the processes included in the model. For example, PCO2 is a major diagenetic driver and thus it is important to incorporate the effects of root and microbial respiration into models of vadose diagenesis. Furthermore, reaction rates in natural systems can be orders of magnitude slower than in the laboratory, reflecting the reduction in both reactivity and contact between reactive fluid and mineral surfaces over time. This is seen in comparisons between early meteoric diagenesis in systems dominated by inter-granular porosity and those with significant secondary permeability. Temporal changes in boundary conditions (e.g. relative sea-level and climate) are a particular challenge for modeling early diagenesis. For example, shallow meteoric alteration occurring over thousands of years is driven by seasonal alternation between periods of recharge and evaporation that cannot be represented by some average condition.

When configured correctly to capture key elements of the diagenetic systems, RTMs can contribute to better prediction of reservoir quality. The challenge now is to incorporate more sophisticated feedbacks between diagenetic alteration and key rock properties, such as permeability and reactivity, at a range of scales.

Genesis and formation of the flutes on cohesive mud beds

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Most of the previous studies on the genesis and evolution of bedforms have focused on aggradational bedforms within cohesionless sediments, with very few investigations that concern erosive bedform genesis and evolution. Those studies that do exist have primarily been based upon flume-scale experiments using plaster of Paris as a base material and there have been no systematic investigations on the influence of bed material properties, notably shear strength, on erosive bedform generation and evolution. The research presented here details the genesis and formation of erosional bedform features within natural (soft clay) cohesive sediment beds under the effect of both open-channel plain water flows, and sediment-laden (D50 = 150 mm) flows. A series of flume experiments are presented where the un-drained shear strength of the bed material is systematically varied under constant flow conditions. The results are conclusive: plain water flows alone do not form erosional structures in beds with appreciable shear strength. Particulate-laden flows do form erosional features in such beds, and the shear strength of the bed material plays a key role in determining the erosional features developed. Harder mud substrates tend to form features analogous to bedrock river channel bedforms such as pot holes, flutes, furrows, broad gullies and mud waves. Softer substrates form features similar to those produced in the harder mud substrates experiments, but they tend to be both less prominent, less variable and more flutes like in morphology. As in the classic flute models, these features possess a principal furrow/depression on the upstream end with a steeply sloping lee side and gentler upstream-facing foreside tail. However, notable differences between the classic flute model and those formed in the natural muds used here are noted, with an absence of i) a medium ridge, ii) lateral ridges, iii) lateral furrows, and iv) rounded rims. Moreover, the features on mud bed do not array in order so regular as those produced on plaster of Paris. The results therefore point to a need to revise our classic model of flute morphology and also highlight a boundary to their formative conditions, with implications for interpreting such features in the ancient.

ORAL PRESENTATIONS:

ABSTRACTS

POSTER PRESENTATIONS:

ABSTRACTS