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We would like to thank the organisations who have kindly sponsored and participated in this meeting

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Abstracts – Oral presentations

Structure of a near-recent giant submarine landslide on the continental slope of the NE Gulf of Mexico

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Analysis of 3D seismic data from the continental slope in the NE Gulf of Mexico is used to describe the internal architecture of a giant near recent submarine landslide, which illustrates deformation at the small-scale end of the spectrum of gravitation driven deformation on this passive margin. The submarine landslide covers an area of c. 2000 km^2 and can be traced for a distance of 56 km along its transport direction. It reaches a thickness of over 500m, detaching on a weak horizon ramping both down and up stratigraphy. The down-dip part of the slide consists of coherent imbricate thrusts of Pleistocene sediments, organised in an arcuate pattern. The well imaged thrusts record contractional strains of c. 0.7. Despite the large size of the slide the Pleistocene sediments in the toe area have only been translated 9-10 km down dip. Puzzlingly the slide has a very low angle to small preserved head scarp with no well imaged extensional structures. It is proposed that this is an example of a frontally confined submarine landslide that did not override and run out over the palaeo sea floor, but moved downslope by translation and integrating the sediments ahead of the propagating basal shear surface within the frontal and lateral parts of the slump.

Using multibeam bathymetry data McAdoo et al (2000) identified this submarine slide as one of the two largest on the modern US continental margin. However using 3D seismic data the revised estimate of the volume of material moved in the slide is seven times that estimated by McAdoo et al. from its seabed morphology. For the accurate characterisation of submarine slides in slope stability and hazard studies it is clearly important to use seismic as well as bathymetry datasets to assess both type and potential magnitude of slides in an area.

Shear-wave splitting as an indicator of slope stability: a case study from the northern headwall of the Storegga Slide

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Split shear-waves respond strongly to oceanic sediments containing cracks and fractures that are small enough, and dense enough, to behave as a critically fractured system. The main geological controls on the properties of split shear-waves include pore pressure and the degree of differential horizontal stress. We argue that such critically fractured systems are common in marine sediments and that measurements of split shear-waves from ocean-bottom seismic reflection data provide valuable insights into slope stability conditions in the marine environment.

We present ocean-bottom seismic recordings of *P*-to-*S* mode converted waves that display shear-wave splitting arising from the Pleistocene sediments that make up the northern headwall of the Storegga Slide (on the mid-Norwegian margin). The polarisation orientations of the split shear-waves show good agreement across an array of ocean-bottom seismometers that extend up-slope from the northern headwall of the slide. Results show a zone of shear-wave orientations in the ESE-WNW plane near the headwall and a separate zone of orientations in the NE-SW plane further upslope. This distribution correlates well with faults visible in a high resolution coherency-attribute volume derived from coincident 3D seismic reflection data, and also with slide scars visible in coincident bathymetric data. We suggest the orientations of the split shear-waves are parallel to the orientation of conjugate sets of micro-cracks in the sediments, and that these orientations are controlled by the present day slope stresses.

Accurate depth conversion for the change in magnitude of the shear-wave splitting, using P- and S-wave velocities derived by a 2D ray-traced travel-time inversion, allowed correlation with logs from a geo-technical borehole drilled through the centre of the study area. Shear-wave splitting was seen to occur mostly in sediment layers with relatively high *Vp*, high *Vs* and low porosities, suggesting that micro-cracks are concentrated in the more consolidated glacigenic sediments. The likely explanation for the observed shear-wave splitting is the presence of vertical to sub-vertical, fluid filled, micro-cracks or fractures, formed in response to high pore-fluid pressures. High pore-pressures initiate in inter-bedded hemi-pelagic units which have relatively low *Vp,* low *Vs,* and a high water content. Elevated pore pressures decrease effective stress and, consequently, increase the likelihood of slope failure in these layers. The formation of vertical fractures in overlying less permeable glacigenic units, however, allows more efficient de-watering of the hemi-pelagic units and mitigates excess pore-pressure build up.

The use of ocean bottom seismometers, as demonstrated in this case study, should be considered an important tool for investigating kinematic indicators of stress, such as fractures and micro-cracks, normally beyond the resolution of conventional *P*-wave seismic reflection data.

Are chaotic deposits that chaotic? 3D seismic evidences of internal structure within Tampen Slide deposits on the North Sea Fan

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The North Sea Fan at the mouth of the Norwegian Channel includes several large-scale gravitational collapse deposits. These large gravitational collapses have occurred repeatedly since late Pliocene times. Large volumes of debris-flow deposits, laminated hemipelagic and distal glaciomarine sediments were remoulded by the Tampen Slide, the last of the North Sea Fan large-scale gravitational collapses.

The seismic character of slide deposits is typically portrayed as structureless or chaotic. However, 3D seismic data from the northern flank of the North Sea Fan shows recognizable internal, penetrative, structures within the Tampen Slide deposits. It also shows distinctive fabrics at the top and base of the slide deposit, which are the expressions of the internal structures. Horizon and volume attributes were extracted from the 3D seismic data and allowed an integrated characterization of the slide deposits. Three main zones have been defined based on the geometry and interpretation of these fabrics that vary from rectilinear to anastomotic. The spatial distribution of the fabrics is closely related to the presence, at the time of the slide movement, of a topographic high at seabed that controlled the sediment transport. These three zones reflect distinct flow behaviour during the transport of the slide deposits.

The use of geophysical methods and outcrop studies in the recognition and characterization of submarine mass transport deposits: An integrated approach

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Mass-transport deposits (MTDs) vary widely in their volume, lithology, external geometry, and internal architecture. MTDs on the modern seafloor and in the subsurface can only be identified and characterized by geophysical methods (high- and-low frequency seismic, side-scan sonar, image logs, and well logs) and from core. These methods can provide a significant amount of information about MTDs; however, their resolution may be too low (especially in the deeper subsurface) to sufficiently characterize mesoscale internal architecture, kinematics, timing of emplacement of stacked MTDs, or other attributes that can provide insights into both the evolution of the sedimentary basin and of fluid-flow properties of the MTDs. Data from outcrop analogs can be combined with geophysical data to create a robust methodology for characterizing MTDs in the subsurface. The advantages and limitations of the geophysical methods, with respect to detection and characterization of MTDs, are described and examples from three outcrops (Permian Cutoff Formation, west Texas; Cretaceous Upper Gosau Subgroup, Austria; and Eocene deepwater strata of the Ainsa Basin, Spain) are presented to demonstrate the integrated use of outcrop analog MTD data to enhance the interpretation of geophysical subsurface MTD data.

The structural geology of mass transport complexes

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Bill McCaffrey – University of Leeds (wdm@earth.leeds.ac.uk)

Mass wasting is a common process on continental margins – potentially tsunamogenic and, in their ancient, subsurface deposits, create important permeability anomalies within deepwater successions. The internal structure of mass transport complexes and the processes that create them can be addressed using combinations of seismic imaging and outcrop analogues. Classical approaches stress the differences in internal architecture, especially the degree of stratal disruption, as reflecting different emplacement mechanisms (e.g. sliding or flow) and transition in process (the slump-debris flow-turbidity current spectrum) with implicit variations in emplacement rate. There are parallels with the research history into tectonic thrust belts and their internal strains where early work focussed on using strain patterns to deduce emplacement mechanics (e.g. gravity spreading vs gravity sliding). However, an important advance in thrust belts came with the recognition that strains commonly relate to kinematic evolution – especially the role of differential movement in three dimensions, rather than be diagnostic of large-scale mechanics. These issues can be conceptualized in terms of strain localization – which need have no large-scale mechanical significance. Similarly the distribution of layer-contraction and layer-extension structures can relate to local differential movement rather than have specific slope-position relevance. In analysing mass transport complexes, the key components to identify are – exotic material transported from a position significantly higher on the slope, and remobilized sediment from the local slope. Addition of material can play two competing roles: by increasing the mass of the translating material it adds to the driving force; the distribution of deformation into the surrounding material acts to dissipate energy. The degree of substrate entrainment during emplacement, reflects the efficiency of the basal slide surface and its shear strength relative to that of the surrounding sediment. The relative timing of internal deformation and slip can be charted using growth strata. All these behaviours can be examined in terms of strain partitioning, between basal slip and internal deformation. It remains unclear how different strain partitioning styles may relate to strain rate, and the rate of emplacement of submarine mass transport complexes. Examples will be presented from combinations of seismic data, and outcrops, especially from the Miocene basins of Italy.

Rise of Mt Kinabalu drives gravity collapse in offshore NW Borneo

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The Miocene–Recent fold-and-thrust belt of offshore NW Borneo displays outstanding examples of gravity-driven deformation. Continental slope morphologies suggest extremely rapid sedimentation, accompanied by repeated shelf failure. However, the ultimate cause of the deformation is not clear. Subduction ceased in the Early Miocene, after collision of the extended South China continental margin, and since then there has been little motion of North Borneo relative to Sundaland.

New thermochronological data suggest offshore deformation was driven by rapid and significant uplift on land, since the Late Miocene, centred around Mt Kinabalu. U-Pb zircon SHRIMP ages record emplacement of the Kinabalu granite in several short pulses between 7.9 and 7.2 Ma. Apatite (U-Th)/He data show that the mountain was already a topographical feature by 6 Ma. Emplacement was followed by uplift and exhumation of the pluton at average rates of around 0.5 km/Ma, removing a minimum of 4 km of material. Most sediment has gone offshore to the north and west.

We propose that collisional thickening in the Early Miocene formed a lithospheric root, and led to melting. The subsequent loss of the root was responsible for the rapid uplift of NE Borneo, driving deformation offshore.

Submarine salt glaciers in the central Red Sea

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During the early opening of ocean basins such as the Atlantic, restricted exchange of water with the global ocean led to widespread deposition of evaporites containing rock salt, but their configuration within the early rift topography is commonly obscured by kilometres of terrigenous sediment later deposited over them and by subsequent remobilisation of the salt. The Red Sea is a nascent ocean basin, floored by widespread Miocene evaporites up to several km thick, which provides a useful analogue for these early ocean basins. In oceanic segments of the central Red Sea, the evaporites are covered by only thin hemipelagic sediments of similar density to rock salt so the evaporite behaviour is relatively uncomplicated by diapirism.

This presentation will report surveying of Thetis Deep in the central Red Sea with a high-resolution multibeam echo-sounder, which has revealed a remarkable series of viscous-like gravity flow structures, which are here interpreted as submarine salt glaciers (namakiers) originating from flowage of evaporite beds laterally unloaded by development of the rift topography. The glacier margins are marked by strike-slip faults accompanied by drag folds and rotated markers. Their fronts in the floor of the deep are rounded in plan view and profile. Some flow surfaces show small closely spaced features resembling extensional faults. In some areas of declining gradient, the surface shows along-slope ridges and valleys typical of compression folds (ogives). Strike-slip and extensional faults lie, respectively, parallel and orthogonal to the direction of maximum seabed gradient, implying that the direction of potential energy gradient causing movement parallels the seafloor gradient. Where the flows steepen down-gradient, they would be expected to accelerate if they have uniform thickness and rheological properties, but evidence of more intensive extensional faulting or erosion is generally absent in such areas. The flows therefore probably thin as they run out on the steep walls of the Deep. The presence of separate flow corridors suggests the rheology of the evaporites varies more irregularly than the en masse movements of salt sheets implied by previously published lower resolution images from 3D seismic. Such salt glaciers were probably common in the early development of evaporite-hosting oceanic basins, implying a varied marginal deformation and varied salt-rafting of material to the young oceanic crust.

Large submarine slides on a steep continental margin (Camamu Basin, NE Brazil)

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We describe a set of unusually large submarine slides from the Camamu Basin, on the continental margin of NE Brazil. The margin is about 50 km wide and the sea floor has a slope of up to 4°. The sedimentary cover is up to 7 km thick. Neocomian strata, up to 3 km thick, accumulated during continental rifting. Shale in the lower part is equivalent to the main source rock of the neighbouring Reconcavo Basin. Aptian strata consist mainly of coarse clastic sediment and evaporite. Late Cretaceous strata are thin or absent and the Tertiary succession is about 1 km thick, above a prominent Eocene unconformity. The Neocomian and Aptian sequences contain abundant thin-skinned structures, extensional near the continental shelf, and compressional toward the toe of slope. The structures have detached on Aptian evaporite, and also at the base of Neocomian shale. The largest slide is about 5 km thick and 100 km wide. It displays mirror symmetry about a vertical plane perpendicular to the margin. The main phase of sliding occurred between the late Aptian and the middle Eocene. The trigger may have been a regional phase of uplift and exhumation.

New insights into the gravity-driven processes of deformation and sediments remobilisation in the Orange Basin, Namibia, SW Africa

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The passive margin of Namibia comprises the Orange Basin, which in the past decade has been investigated through regional two-dimensional (2D) seismic surveys. The results of these studies have indicated that gravity-driven processes are the primary cause of deformation and sediment remobilisation within the post-rift megasequence (Early-Cretaceous to present). Interpretation of recently acquired three-dimensional (3D) depth migrated seismic data from the shelf-break portion of the Orange Basin shows that the post-rift succession has experienced a phase of gravitational collapse during the Late Cretaceous. Different mechanisms of deformation resulted in two distinct seismic sequences with strongly contrasting seismic expressions. The Gravity-Driven Collapse Sequence (GDCs) is characterised by at least three 30-km-long and 20-km-wide megaslides that deformed at least 1.5 km of the succession. The slides detached onto a décollement surface probably located within Cenomanian-Turonian marine shale. The décollement surface links a series of listric faults, arranged in a scooped-shape fashion, to a basin-ward fold-and-thrust belt. A thickness of at least 600 m of highly deformed succession overlies the GDCs above an unconformity and defines the Slump Complex (SC). Lateral variations in the thickness of the SC and the local scoop-shape morphology of the base led to the interpretation of this body as the product of sediment remobilisation through the activation of coalesced slumps, which were probably triggered by the development of a local gradient in response to emplacement of the megaslides. The results of this study on the GDCs and SC using 3D seismic methodology offer new insights into gravity-driven collapse processes affecting passive margins, particularly the morphology of their final products and their mechanical relationships.

Gravity-driven processes at the offshore Amazon Mouth Basin-Brazilian Equatorial Atlantic margin*

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Gravitational deformation affects the entire Upper Cretaceous-Recent marine sequence at the offshore Amazon Mouth basin, including the Amazon deep-sea fan. A linked extensional-contractional system glided along weak overpressured shales, forming remarkable fold-and-thrust belts located along the margin down to about 3200 m water depths. Extension is characterized mainly by landward-dipping normal faults on the shelf/upper slope, whereas downdip contraction generated detached fold and thrusts. Gliding of the sedimentary section occurred along multiple detachment surfaces during different stages of the margin's evolution. During simple analogue experiments of gravity gliding (performed in the presence of two stratigraphic levels weakened by fluid overpressure) the active front of thrust belts initially formed at a distal position, then migrated landwards. Structural differences lay in the degree of thrust-faults stacking. Models having thinner brittle layers were capable of accommodating more shortening in one single large fold–and-thrust belt. Mass movements also affect the upper marine sequence at different scales. Gravity-related fault scarps induced surficial sediment slides along the thrust-fault belts. Megaslides can mobilize thick turbiditic series of the Amazon fans (up to 800 m thick) as debris flows dowslope over areas as large as 90.000 km^2, leaving behind large scars that strongly impact the sea-bottom morphology.

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Depositional controls on structural evolution in gravitationally-failing submarine slope systems.

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Bill McCaffrey – University of Leeds.

It is a relatively recent geological discovery that many otherwise passive continental margins contain major thrust systems that accommodate down-slope movement of sediment many km thick. Detachment, on salt or overpressured mud, permits deformation of the overlying sediment pile that is manifest by extension on higher parts of the slope and contraction towards the base. This contribution examines mud-based systems. Driven by body forces, the distribution of mass within the sedimentary prism, therefore deposition on the shelf and slope, exerts first order control on system evolution. Some develop by gravity spreading, large-scale kinematic thinning of depocentres decoupling on a landward-dipping detachment to link with contractional structures towards the toe of slope. Other slopes fail by gravity sliding, where the basal detachment dips oceanward. In both cases, structural enhancement of accommodation space high on submarine slopes, if sufficient to capture most of the sediment, continually refreshes the body forces necessary for system development. Sedimentary bypass to the toe of slope acts against the system. On profiles, deep-water belts display a wide range of styles that include both down-slope and up-slope directed thrusts (fore-thrusts and back-thrusts respectively), detachment folds, thrust-to-fold transitions and thrust ramps. The generally complete record of sedimentation during deformation provides unique records of the incremental growth, both of arrays and of individual folds and thrusts. In general these demonstrate that deformation can continue through an array of thrusts, rather than form in a strict sequence. Growth sequences commonly develop fanning on-lap patterns indicative of fold amplification by limb rotation. Sediments are not passive markers – they are mechanically important to the structural evolution. Some systems require substantial lateral compaction (volume loss) to achieve the necessary kinematic balance between measured extension upslope and the seismically-resolvable contraction at the toe of slope. Submarine gravity flows by sea bed rugosity, thus the sedimentation is controlled by the deformation structure. In some settings sedimentation is strongly concentrated in ramp-flat architectures and closely-spaced ramp anticlines. In sediment-rich systems emergent thrusts are constantly buried so that thrust trajectories develop with increasingly steep dips through their growth strata. The mechanical consequences of increasing thrust dips can change the activity of folds and thrusts across arrays and cause few thrust trajectories to grow. Thus the activity and geometry of thrust faults is directly linked to the sedimentation that occurs across them. The feedbacks between deposition and deformation are explored using examples from the West African continental margin.

We thank colleagues and sponsors of the Turbidite Research Group. Much of the seismic data shown is hosted on the Virtual Seismic Atlas: we thank project sponsors and data providers for this facility.

Salt tectonics in Santos Basin, SE Brazil

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The geological evolution of the Santos Basin in Brazil is strongly influenced by Aptian salt, deposited at the onset of South Atlantic opening. In an overall sense, the salt moved seawards during the Upper Cretaceous creating a variety of extensional structures in the inboard parts of the basin which in turn has had a marked effect on sedimentation.

Four mechanisms can be used to explain the salt structures in Santos – down-dip drainage of salt, gravity sliding of the overburden, loading by shelf progradation and active tectonism. Previous authors have either favoured gravity sliding of the overburden or loading by shelf progradation but neither models fit with structural and stratigraphic evidence from new seismic and well data. Instead, down-dip drainage of salt seems to explain most of the features, including the famous “Albian Gap” which is now interpreted as a hybrid counter-regional fault system.

High quality 2D and 3D seismic data will be used to demonstrate the scale of salt movement in the Santos Basin. In the outer part of the extensional zone, the overburden has been carried distances in the order of 40 km in a basinwards direction leaving behind belts of salt rollers, flip-flop salt diapirs, rohos and counter regional fault systems in shallow water areas. Down dip of these, the salt flowed into a wide zone of contraction which occupies most of the present day deep water.

The importance of gravity tectonics driven by flowing salt rather than sliding overburden may at first seem subtle but actually accounts for some fundamental differences in structural and stratigraphic reconstructions.

Factors controlling the evolution of the Perdido Fold Belt, north-western Gulf of Mexico, determined from numerical modelling

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Christopher Beaumont
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The Perdido Fold Belt (PFB), north-western Gulf of Mexico, is one of the best-studied rifted continental margin fold belts. Although its geometry is known from seismic data, the factors controlling its evolution and its regional relationship to allochthonous salt sheets, including the Sigsbee nappe, are not fully understood.

We use 2D finite-element models comprising a viscous salt layer overlain by frictional-plastic passive margin sediments to study the evolution of the PFB. Model experiments include sediment progradation, flexural isostasy, sediment compaction, loading by the water column, and effects of pore-fluid pressures in the frictional-plastic sediments.

Limit analysis calculations show that the PFB can have formed by gravity spreading if moderately high pore-fluid pressure ratios of ~0.8 developed. The finite-element models produce fold belts with similar folding style, geometry, and deformation rate to the PFB depending on parameters such as overburden strength, continental slope width, salt thickness, and salt viscosity. Variability in the latter two generates two end-member fold-belt types: seaward propagating toe-of-slope folding and synchronous toe-of-salt folding. The models show that allochthonous salt structures can form by extrusion through breached anticlines. The presence of both a now depleted paleocanopy and folds landward of the PFB indicate that the modern PFB is only the nose of an older and larger toe-of-slope fold belt.

An explanation for the initiation and early development of salt withdrawal mini-basins during continental margin gravitational spreading

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Salt withdrawal sedimentary mini-basins are common features of rifted continental margin salt tectonic provinces and are important sources of hydrocarbons. They are typically subcircular, 10-30km in diameter and may contain up to 10km of sediment above an evaporite layer that has been expelled into diapir structures that surround the mini-basin. Although commonly invoked, the early development of these mini-basins cannot be attributed to buoyant Rayleigh-Taylor (R-T) instabilities because the average density of the sediment overburden is in most circumstances initially less than that of the salt. We propose an alternative mechanism involving early sedimentation onto the salt layer during continental margin gravitational spreading. It involves the lateral flow and contraction of sediment and salt spreading to form dynamically induced pressure ridges, and positive feedback that grows and elevates the pressure ridges by sediment loading ponded between them. We show using lubrication theory and numerical models that this mechanism grows mini-basins until the compacting sediment is sufficiently thick and dense for R-T instabilities to take over.

The crux of the mechanism is the formation of the pressure ridges that trap the sediments. The growth of the ridges results from the competition between inward Couette flow of salt into the ridge, driven by the differential velocity between adjacent sedimentary floes, and outward Poiseuille flow of salt driven by the dynamical pressure of the ridge.

3D reconstruction of a Cretaceous scalloped carbonate platform margin (Maiella, central Apennines, Italy)

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Spectacular seismic-scale outcrops of the Maiella Mountain, Italy, allow a thousand metre high Cretaceous escarpment platform margin to be studied in detail. The escarpment abruptly separates shallow-water carbonate platform sediments from slope-to-basin deposits. In plan view, the contact between shallow water and basin sediments has an indented morphology, consisting of three km-scale embayments separated by ridges that resemble a giant spur and groove architecture. In cross section, the geometry of the escarpment changes from an exponential profile along the grooves to a linear profile along the spurs.

The complex architecture of this scalloped margin has been interpreted as the result of large-scale margin collapses. Detailed mapping of the contact between shallow water and slope to basin facies along the Maiella escarpment allowed the reconstruction of a complex 3D geometry of the platform margin. A 3D reconstruction was made for the surface inherited by the major collapse phase. The outcrop-derived 3D view permits the visualisation of the complex morphology of the scalloped platform margin, it allows to quantify the volume of the collapsed margin portion, and to explain lateral thickness changes of slope deposits onlapping the escarpment.

Gravitational collapse of equatorial and south Atlantic carbonate platforms: A new model based on examples from Equatorial Guinea

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Some spectacular examples of detached rafts of Aptian-Albian carbonates have been described by us and others from Equatorial Guinea (Turner 1995, Turner et al. 2003, Dailly 2000), its conjugate margin in NE Brazil, (Gomes 2000), Gabon (Teisserenc & Villemin 1989) and Angola/Cabinda (Duval et al. 1992, Lundin 1992). The rafts overlie the regional end-rift unconformity and they comprise thick successions (up to 4km) of limestones that were emplaced in a relatively deep water setting along extensive gravity-driven slides developed in Upper Aptian (i.e. late synrift) intercalated mudstones and evaporitic salts. That these detachments are gravity-driven is illustrated by the upslope extension in their hanging walls linking kinematically to downslope shortening. The limestones accumulated as part of a cratonic Aptian-Albian lowstand progradational wedge in which shallow water conditions were sustained by modest subsidence rates on a stable platform. Timing of raft emplacement at the Equatorial Guinea margin is constrained by perched basins within the rafts' hanging walls whose synkinematic basinfills are early Cenomanian i.e. early postrift. However, understanding the large-scale geodynamic processes responsible for triggering collapse of these carbonate platforms is problematic. Whilst the Angolan examples are attributed to halokinesis related to late synrift evaporites up to 800m thick, significant evaporites are absent in Equatorial Guinea and NE Brazil.

Recently published palaeothermal data (apatite fission track analysis [AFTA®] and vitrinite reflectance) from the conjugate Equatorial Guinea and NE Brazil margins (Turner et al. 2008) shed light on a mechanism for triggering regional uplift and gravitational collapse during early postrift times. The data reveal a 110-95Ma. episode of cooling, from an elevated palaeogeothermal gradient of 58ºC/km, coincident with the regional end-rift unconformity. This leads us to interpret the unconformity as a product of i) transient uplift due to the movement of the African and South American plates over the anomalously warm mantle of the widely documented St Helena and Ascension Plumes, and ii) 'rift shoulder' uplift and erosion (1400m erosion offshore [Rio Muni-1 well] increasing to 2000m onshore [N'Dote-1 well]). Uplift was enhanced in Equatorial Guinea by local transpression related to the obliquely divergent kinematics of rifting along the line of the Ascension Fracture Zone. In this scenario, therefore, regional uplift provided the trigger for the gravitational collapse of the Aptian-Albian carbonates of the South Atlantic. Once initiated, however, locally variable halokinesis, transpression and other processes were important in modifying the rafts within their individual sub-basins.

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Subduction-related gravitational collapse through exhumation and seismogenic turbidites in the Nankai accretionary prism

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Observations of bedrock exposures within the Tenryu Submarine canyon made during a series of dives in the manned-submersible, SHINKAI 6500, suggest that the evolution of the eastern Nankai accretionary prism involves both typical, horizontal shortening, but also periods of gravitational collapse and exhumation associated with seamount subduction. The Nankai prism is located in the north-western Pacific Ocean, along the convergent margin between the Amur (Eurasian) plate and the Philippine Sea plate. Ruptures of the asperity associated with this plate boundary repeatedly generate M8.0± earthquakes. Such ruptures propagate along out-of-sequence thrusts (OOST) and often generate tsunamis. Our survey also recovered Pliocene (sedimentary age) foliated, low-grade slate and phyllite samples from the OOST zone. Illite crystalinity suggests these rocks were heated to 230°C before being rapidly exhumed along the seismogenic zone by large-scale gravitational collapse of the prism associated with seamount subduction/collision. The survey also observed submarine landslides on trench slope surfaces, near the frontal thrust and OOST zones of the Nankai prism. These smaller-scale gravity slides occur due to slope instability and are likely triggered by earthquakes. The rock samples collected from these locations suggest they formed as seismogenic turbidites, which are deposited in the footwall basins of the large thrusts.

Gravitational collapse at convergent margins in NW Pacific: Examples from Boso trench triple junction and Japan trench

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Oceanic plate subduction boundaries are the places for strong down-going pull, where various kinds of gravitational collapse occur, although in some other cases strong horizontal compression for accretionary prism formation may occur under specific conditions. Here are several examples of gravitational collapse around the Japanese trenches which were explored by swath mapping, drilling, submersible observation, seismic profiling etc. In addition to the accretionary prism formation along the Nankai and Sagami troughs with enough clastic sediments supply from Izu collisional belt, there are two unique examples of gravitational collapse on the Boso trench-trench-trench triple junction and Japan trench. First, thick clastic sediments are piled up to an unusually deep basin (7-9 km water depth) which is on the Philippine Sea plate oblique subduction boundary and the triple junction. Materials from the overriding North American plate are collapsing into these deep areas by normal faults, and finally sliding onto the trench floor triple junction. Second, the presence of 15 Ma trench slope sediments along the leading edge of the accretionary prism in the Japan trench suggests that younger sediments were removed by collapse into flexure-related horst-and-graben structures developing on the surface of the subducting Pacific plate.

Shale mobilisation in gravitational fold and thrust belts: insights from the South Niger Delta

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Geometrical models for thrust fault propagation, fault bend folds and detachment folds have been applied to deepwater gravitational fold and thrust belts to constrain the mechanisms of fold growth. These models rarely consider how deformation within the detachment zone itself affects fold kinematics.

Using 2D and 3D seismic data from the South Niger Delta, we describe a 32 km wide symmetrical detachment fold, that has an amplitude of 2.2 km and is cored by 1000 km^3 of mechanically weak shale. Numerous thrust propagation folds occur within the fore and backlimbs of the symmetrical fold structure. Analysis of growth strata above the detachment fold suggests there were two distinct phases of fold growth: an initial period of thrust propagation folding, which was subsequently modified by structural thickening within the underlying detachment zone.

Results suggest that shale-cored anticlines cannot always be modelled purely as thrust propagation folds or ductile detachment folds. “Hybrid” fold growth mechanisms that incorporate thickening within the detachment are likely to be common. Such processes significantly change the geometry of strata affected by the earlier thrust propagation folds and therefore have an important impact on the extent and characteristics of the hydrocarbon traps in gravitational fold and thrust belts.

Numerical models of rifted continental margin shale tectonics with application to the Niger Delta

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Rifted continental margin shale tectonics is investigated using 2D numerical finite-element models that couple fully-saturated porous compaction to sediment deformation (Morency et al, 2007 JGR *112*, B10407, doi:10.1029/2006JB004701). Mechanical and viscous compaction is coupled to deformation of the sediment skeleton through the effective pore fluid pressure. This approach allows an investigation of the relationship between overpressure generation, sediment failure, and the resulting margin-scale structural style. The models include syn-rift tectonic and subsequent thermal subsidence and flexural isostasy. Progradation of sediments with spatially varying mechanical and hydraulic properties allows investigation of sediment wedges comprising shelf sands with contemporary shale units on the slope.

The numerical models are used to investigate how the following factors influence the behaviour of an idealized large-scale rifted-margin deltaic tectonic system: (1) the thickness and hydraulic properties of the shale; (2) shale viscosity; (3) delta geometry and progradation rate, and; (4) hydraulic and mechanical properties of shelf sediments. Under certain hydraulic and mechanical conditions the distal shale sequence can become highly overpressured and begin to flow viscously forming a mobile shale substrate, modelled as a Bingham fluid. The results illustrate the relative importance of these factors in driving large-scale gravity spreading in models designed to approximate the evolution of the Niger Delta shale tectonic system.

Toe thrusts and slides on the Niger Delta slope: influence of the underlying oceanic crust and igneous intrusions

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PGS have recently interpreted a 10 000 km^2 area of merged 3D seismic data on the toe thrust of the Niger delta in water depths of 1250 to 3000 m. The seismic shows the Cretaceous ocean crust and sediments overlain by the Akata shales and then the Agbada sands and shales.

The thrusts cut the lower part of the Agbada Formation into blocks of uniform thickness but generally die out before reaching the surface and sole out in the Akata Shale.

The thrusts are spaced between 2 and 8 km apart and strike consistently NW-SE with vergence normally towards the SW. The implied NE to SW direction of shortening is not compatible solely with sediment loading from the direction of the Niger river to the north and may rather be related to the dip slope of the underlying ocean crust.

Two transfer faults have been identified offsetting the thrusts in a NE_SW direction with the vergence direction reversing across one of them. These transfer faults lie parallel with the oceanic fracture zones. In the southeast the thrusts change strike direction to SW-NE and are more closely spaced at 2 to 3 km apart. This may be a result of compression against the flank of the Fernando Po Fracture zone.

A 50 km long east-west oriented pericline, merging with the end of a north-south anticline may have resulted from sliding above an intruded sill.

Geometry and kinematics of thrust fault systems: 3D seismic investigation in the Joint Development Zone, deepwater Nigeria

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We have used special attributes, particularly coherence, to guide a detailed interpretation of the geometry of thrust fault planes and contiguous wall rock volumes imaged in 3D seismic data from the deepwater thrust belt, Nigeria. A ubiquitous feature of their surface geometry are corrugations with wavelengths 2-4km, amplitudes 100-300m, and with long axes that are parallel to the local slip azimuth. A similarly ubiquitous feature of horizon geometry in the wall rocks of the thrust faults are what we term ‘eyelet’ structures – periclinal folds developed directly adjacent to fault planes, with comparable dimensions to those of the fault plane corrugations (i.e. large enough to form significant hydrocarbon traps).

Eyelets can be anticlinal and synclinal, they are attached to both hanging wall and footwall cutoffs, and they have along-axis lengths much less than those of their ‘parent’ faults. Across-fault juxtaposition of eyelets leads to local variations in throw along the length of a fault (i.e. maxima where hanging wall anticlinal eyelets align with footwall synclines and vice versa). Eyelets have been interpreted as structures accommodating along-strike fault displacement gradients but why, therefore, should they be so much smaller than the faults to which they are attached? One possibility is to interpret them as relics of the early stages of fault growth, before unconnected segments linked-up to form continuous, throughgoing fault surfaces. But they could also be manifestations of the translation of horizons over curved fault surfaces.

Badley Geosciences’ *TrapTester* software has been used to map the Gaussian curvature of fault surfaces picked from the JDZ seismic data. Gaussian curvature is defined as the product of two mutually orthogonal principal curvatures, k_1 and k_2 that represent lines of zero surface torsion, τ. Imagine translating wall rocks across a fault surface exhibiting a Gaussian curvature that is positive (‘synclastic’ e.g. hemisphere) or negative (‘anticlastic’ e.g. *Pringle* crisps): convergent/divergent particle motion paths will induce permanent strain, the nature and intensity of which will be dependent on geomechanical rock properties, τ and the rate of change in Gaussian curvature in the fault transport direction. Down-plunge culminations and depressions are a characteristic feature of fault surface corrugations thereby facilitating changes in Gaussian curvature in the fault transport direction.

In this talk, we will present examples of the geometry of JDZ fault systems and fault surfaces, and of wall rock eyelet structures. Amplitude and special attribute volumes will be used to demonstrate the close relation between areas of intense and/or changing fault surface curvature, and the location of wall rock eyelets. We conclude that whilst eyelets are a commonly recognized feature of fault-related wall rock deformation, particularly in gravity-driven fault systems, the mechanism(s) responsible for generating them has yet to be fully understood.

Abstract - Poster presentation

Are continental slope failures efficient mechanisms for releasing gas hydrates? Evidence from North Atlantic mass movement deposits

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Various authors have suggested that the release in landslides of gas hydrates contained in continental slope sediments may play a role in driving climate change, but this proposal has been controversial. A key question has been whether the landslides will transport gas hydrates to deep water and so stabilize them through pressure increase, rather than releasing them to the atmosphere. We investigate these problems using data from the literature on the timing of continental slope landslides in the North Atlantic region since 45 ka and changes in atmospheric methane content, and also seismic and acoustic data on deposits from some of these landslides. Post – 12 ka slides are concentrated at high latitudes and are linked to local sea level variation, rapid glaciogenic sedimentation, and intense isostatic rebound seismicity associated with the deglacial transition. Pre – 12 ka slides occur in mid- to low- latitude margins and are plausibly linked to eustatic sea level variations and rising sea temperatures, so gas hydrate dissociation may be a significant trigger. Seismic profiles and acoustic data from the landslide deposits show that most are disintegrative and would have released any contained gas hydrate, making them potential sources of increases in atmospheric methane.