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Oral presentation programme

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11.00		Simon Brocklehurst University of Manchester	Numerical modelling of glacial landscape response to the Middle Pleistocene transition

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Wednesday 22 September		**Speaker**	**Title**
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09:15		Bernard Salcher ETH-Zürich	Drainage density and landscape evolution in the Alps
09:30		Eduardo Garzanti The University of Milan	Mineralogical and chemical variability of fluvial sediments (bedload and suspended load, Ganges-Brahmaputra system)
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Thursday 23 September		**Speaker**	**Title**
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09:45		Elizabeth Hajek Penn State University	Identifying autogenic organisation of surface processes in the stratigraphic record

10:00		Stéphane Bonnet Université de Rennes	The influence of uplift and rainfall on the sedimentary architecture of alluvial fans in physical models
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Landscape resistance: using drainage networks as deformation markers

1.3 Vivi Katherine Pedersen (Aarhus University)
Alpine glacial topography and the rate of rock column uplift: a global perspective

1.4 Emilie Pepin (Université de Toulouse)
Erosion dynamics modeling in a coupled catchment-fan system with constant external forcing

1.5 Francesco Mirabella (Università di Perugia)
Comparing long term deformations and short term fluvial response at the hanging-wall of an active low angle normal fault in the Northern Apennines of Italy

1.6 German Aguilar (Université de Toulouse)
Erosion in the semi-arid Chilean Andes

1.7 Nicolas Loget & Stephane Pochat (Université de Nantes)
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1.8 Hugh Sinclair (University of Edinburgh)
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1.9 Florian Kober (ETH-Zürich)
Temporal calibration of fluvial sequences in the Makran Range

1.10 Florian Kober (ETH-Zürich)
The effect of fluvial, glacial or fluvial-glacial landscape imprint on catchment wide denudation rates

1.11 Valentina Scotti (Università degli Studi Roma Tre)
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2.3 Lauren Raynham (GETECH, Leeds)
Landscape evolution and geodynamic reconstruction of the NeoTethys region from Cretaceous to Recent

2.4 Jonathan Smith (University of Manchester)
A rift-scale analysis of present day sediment routing systems and their evolution through time

2.5 Gerold Zeilinger (ETH-Zürich)
Morphometric parameters and catchment wide denudation rates in catchments affected by crustal bending

2.6 Nikolas Michael (Imperial College London)
Sediment budget of a synorogenic sediment routing system, the Eocene Escanilla Formation, Spain

2.7 Benjamin Clements (Statoil)
A record of continental collision and regional sediment flux for the Cretaceous and Paleogene core of SE Asia

2.8 James A. Chalmers (Geological Survey of Denmark and Greenland, GEUS),
The morphology of elevated passive continental margins

2.9 Georgie Bennett (ETH-Zürich)
Modelling sediment transfer through mountain basins

2.10 Alex Mortley (Port of London Authority)
Diver Shoal – A managed dynamic system

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2.12 Rebecca Hodge (University of Glasgow)
A theoretical model of grain mobility in bedrock rivers

2.13 Cynthia Brezina et al. (University of St Andrews)
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3.2 Stephane Pochat (Université de Nantes)
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3.3 Robert Duller (Imperial College London)
Climatic *versus* tectonic controls on the Neogene succession of the northern Great Plains, Nebraska, U.S.A.

3.4 Tor Oftedal Sømme (Statoil)
Factors controlling stratigraphic architecture on short and long time-scales

3.5 Bartosz Goledowski (Aarhus University)
Climate *versus* tectonic induced variations in Cenozoic sediment supply from western Scandinavia

3.6 Stefan Nagel (ETH-Zürich)
Multiscale basin development in Taiwan

3.7 Tim Redfield (Norwegian Geological Survey)
Modification of passive margin landscapes by active normal faulting in Troms County

3.8 Peter Japsen (GEUS)
Episodic exhumation in both basement and sedimentary basins: Is it possible to trace sediment from source to sink?

3.9 Prenjasi & Sulaj (Polytechnic University of Tirana & Albpetrol Ltd)
Non-seismic discovery of the Delvina carbonate gas condensate field

Oral presentation abstracts

THEME 1: THE ERONSIONAL ENGINE

Invited talk

Three decades tracing erosion and sediment with cosmogenic nuclides – where do we go next?

Paul Bierman, Eric Portenga, Luke Reusser, Joseph Graly, Lee Corbett and Jaron Borg, University of Vermont

Cosmogenic nuclides, primarily ^{10}Be, have revolutionized our understanding of erosional systems. Both ^{10}Be produced within minerals (*in situ*) and that produced in the atmosphere (meteoric) provide useful information about the rate and spatial distribution of erosion. Early work quantified bare rock erosion rates on single outcrops by measuring ^{10}Be produced *in situ* by cosmic-ray bombardment[1]. A decade later, the *in situ* method expanded to consider the scale of drainage basins through the analysis of fluvial sediment[2]. Soon after, more complex, process-oriented studies began to quantify the mass flux of sediment down hillslopes and the rate of soil formation[3]. Meanwhile, meteoric ^{10}Be was being employed to understand both hillslope and fluvial processes, including human-induced erosion[4]. Recently, both meteoric and *in situ* ^{10}Be have been used as sediment tracers in fluvial networks to help pinpoint the source of sediment in transport[5].

After three decades of data collection, one can look back at thousands of measurements made in samples collected from dozens of field areas. Some themes emerge[6]. Bedrock erosion rates, typically measured in samples collected from outcrops along ridgelines, are usually slower than basin-scale erosion rates inferred from ^{10}Be concentrations in fluvial sediment, which integrates processes active across entire landscapes. Basin-scale erosion rates scale positively with a variety of topographic metrics including average basin slope and relief. Tectonic setting, expressed as the intensity of seismic shaking, correlates positively with erosion. In well-indurated, quartz-rich rocks, lithologic influences are subtle.

Looking beyond erosion rates, we have employed ^{10}Be in several novel ways. In New Zealand and northeastern North America, we have used the concentration of meteoric ^{10}Be in fluvial sediment to fingerprint sediment sources in river systems, in one case showing the influence of massive landsliding and in the other showing that sediment sourced from different elevations is isotopically distinct. In Greenland, high concentrations of meteoric ^{10}Be in silt extracted directly from the ice sheet suggest low rates of glacial erosion and the likelihood of significant interglacial retreat and soil development[7]. In contrast, clasts collected alongside the silt samples contain extremely low concentrations of in situ ^{10}Be suggesting grain-size dependent sources and perhaps erosion histories[8].

While estimating erosion and sediment generation rates as a function of lithology, tectonic setting, and climate may well continue to be the bread and butter of cosmogenic nuclide analysis, using these isotopes as tracers offers great potential to determine better the sources and fate of sediments over 10^1 to 10^5 year time scales.

References

[1]*Nishiizumi, K. et al., Production of ^{10}Be and ^{26}Al by cosmic rays in terrestrial quartz in situ and implications for erosion rates. Nature **319** (6049), 134 (1986).*

[2]*Brown, E.T. et al., Denudation rates determined from the accumulation of in situ-produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico. Earth and Planetary Science Letters **129**, 193 (1995); Bierman, P. R. and Steig, E., Estimating rates of denudation and sediment transport using cosmogenic isotope abundances in sediment. Earth Surface Processes and Landforms **21**, 125 (1996); Granger, Darryl E., Kirchner, James W., and Finkel, Robert, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediments. Journal of Geology **104** (3), 249 (1996).*

Numerical modelling of glacial landscape response to the Middle Pleistocene Transition

Simon H. Brocklehurst[1,], Kelly R. MacGregor[2] and Ann V. Rowan[1]*
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Substantial Northern Hemisphere glaciation commenced ~3-2.5 Ma. It is generally assumed that the major landscape modification and sediment production caused by the growth of glaciers in previously fluvial landscapes would have occurred at this time. However, a second major change in the climate occurred in the middle Pleistocene, ~1 Ma, with a transition from symmetrical 40 kyr temperature variations to larger amplitude, asymmetric 100 kyr cycles (e.g., Clark et al., 2006). This would have permitted much larger, longer-lived glaciers.

We use a numerical model of glacial longitudinal profile development to investigate the modification of a fluvial longitudinal profile (and associated sediment production) at the start of the Pleistocene, during symmetrical 40 kyr temperature cycles, and the consequences of a shift to asymmetric 100 kyr cycles at the Middle Pleistocene Transition (MPT). We demonstrate that the landscape response to the MPT is heavily dependent on the tectonic setting and the behaviour of the fluvial system downstream of the glacier. With no imposed tectonic rock uplift, the major change in the landscape is the carving of cirque forms and glacial longitudinal profiles at the start of the Pleistocene; the MPT would have had little impact on this morphology. Accordingly there is only a modest change in sediment export associated with the MPT. However, with tectonic as well as isostatic rock uplift, and inefficient fluvial transport and erosion downstream of the glacier, the MPT causes more substantial erosion and sediment production than occurred during the original development of glaciers. This is in good agreement with geological evidence from Alaska and the European Alps for accelerated incision and sedimentation rates associated with the MPT (e.g., Berger et al., 2008; Haeuselmann et al., 2007; Muttoni et al., 2003). The counterexample, with imposed tectonic uplift but efficient fluvial transport and erosion downstream of the glacier, dramatically reduces the impact of the MPT; once again, the major landscape modification is at the onset of glaciation.

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Berger, A.L., Gulick, S.P.S., Spotila, J.A., Upton, P., Jaeger, J.M., Chapman, J.B., Worthington, L.A., Pavlis, T.L., Ridgway, K.D., Willems, B.A. and McAleer, R.J., 2008. Quaternary tectonic response to intensified glacial erosion in an orogenic wedge. Nature Geoscience, v. 1, p. 793-799.

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Episodic thermal and burial/exhumation histories are more realistic than monotonic cooling/denudation histories

Paul F. Green(1), Ian Duddy(1) & Peter Japsen(2)
(1) Geotrack International, *37 Melville Road, Brunswick West, Victoria 3055, Australia*
(2) Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, DK-1350 Copenhagen, Denmark

Results from low temperature thermochronological methods such as apatite fission track analysis and (U-Th)/He dating in basement terrains are commonly interpreted within a context of slow monotonic cooling. Thermal histories derived in this way are converted to exhumation rates using assumed or estimated paleogeothermal gradients, and the results are interpreted in terms of the progressive denudation of the region, yielding long-term denudation rates. Such studies are usually focussed on basement terrain devoid of sedimentary cover. But results from regions where sedimentary outliers are preserved reveal thermal histories involving episodic heating and cooling, implying episodic burial and exhumation.

Results from NW Namibia illustrate this clearly. A Late Carboniferous glacial landscape in Precambrian basement is overlain by a few hundred metres of Late Carboniferous to Early Permian Dwyka tillites of the Karoo sequence, which is in turn overlain unconformably by Early Cretaceous Etendeka basalt. AFTA data from a basement outcrop define a thermal history solution involving three discrete episodes of cooling, from >105°C sometime between 260 and 180 Ma, then from 85-95°C beginning between 165 and 40 Ma and finally from 45-80°C beginning between 45 and 0 Ma. The geological constraints (above) show that the basement sample was close to surface temperatures when the Dwyka (~300-290 Ma) and Etendeka (132 Ma) sequences were deposited. Synthesis of these constraints clearly shows that a monotonic cooling history is not appropriate, and defines an episodic history of heating and cooling. Converting this thermal history into burial and exhumation/denudation histories is more difficult due to the absence of constraints on paleogeothermal gradients. But for any reasonable value of paleogeothermal gradient the episodic thermal history must also provide a broad representation of the burial/exhumation history as well.

Similar examples from Western Scotland, SE Australia and other parts of the world suggest such episodic histories may be much more common than slow monotonic cooling. Corresponding denudation rates will therefore be much higher than the long-term average rates derived from histories which assume slow cooling. Defining thermal histories on the basis of slow cooling provides misleading results that often conflict with geological evidence. Integration with geological constraints is vital in order to provide accurate thermal histories from low temperature thermochronology. Rather than focussing on areas where sedimentary cover is missing, we advocate targeting regions where such cover is preserved, such that a more realistic history can be defined.

Field calibration of sediment flux dependent river incision

Daniel E. J. Hobley, Hugh D. Sinclair, Simon M. Mudd, Patience A. Cowie, University of Edinburgh

In a simple world, the ability of a river to downcut into its bed is a function of the competition between the river's power, and the resistance of the substrate. However, it is increasingly recognised that the amount and type of sediment transported by the river also plays a key role. The sediment on a river bed is mobilised once a threshold discharge is surpassed, and once in motion it can contribute to the erosivity of the flow, providing abrasive tools to enhance erosion, but also forming a cover over the bed that protects it. These competing effects (tools versus cover) should interact to give a peak in erosional efficiency at intermediate relative sediment fluxes. This has been demonstrated both in theory and experimentally (*e.g.*, Sklar and Dietrich, 2001, 2004), and average erosion rate variations consistent with the expected effects of sediment supply have been shown between different catchments (Cowie et al., 2008). However, a comprehensive demonstration of the form and importance of the tools and cover effects in a scenario where we can tightly constrain the driving sediment fluxes is lacking.

This study uses an exceptional natural laboratory in the Ladakh Himalaya, NW India to investigate the role of sediment during channel incision into a post-glacial landscape. Downcutting proceeds into the upper surface topography of the moraine, mobilising the underlying homogenous, coarse, loose, poorly sorted glacially derived substrate, but never encountering true bedrock. It is demonstrated that incision into this coarse sediment is best modelled as a detachment-limited process. However, the model requires both an incision threshold and a sediment flux dependent term driven by evolving sediment flux downstream as material is added to the channel from the hillslopes.

This sediment flux function in the modelled incision law is uniquely described for three analysed catchments using both forward and inverse modelling approaches. The resulting functions show many features which are compatible with previous theoretical and laboratory studies but which have not before been independently verified from real field data. They also suggest that the position of the peak in incision efficiency in relative sediment flux space may be more variable than is widely assumed in the literature. On the basis of its occurrence here, sediment flux dependent incision is considered fundamental in understanding the fluvial response to tectonic or climatic perturbations in many mountain rivers.

References:

Cowie, P.A., Whittaker, A.C., Attal, M.A., Roberts, G., Tucker, G.E., and Ganas, A., 2008, New constraints on sediment-flux dependent river incision: Implications for extracting tectonic signals from river profiles: Geology, v. 36, p. 535-538.

Sklar, L. S., and Dietrich, W. E., 2001, Sediment and rock strength controls on river incision into bedrock: Geology, v. 29, no. 12, p. 1087-1090.

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Pleistocene-Holocene geomorphologic interactions between mountain catchment and foreland in the Argentinean Andes, 33°S.

E. Pepin, S. Carretier, G. Herail, R. Charrier, M. Farias, V. Regard, V. Garcia, L. Giambiagi*
**speaker. LMTG-UNIVERSITE DE TOULOUSE-CNRS-IRD-OMP, 14 Av. E. Belin, F-31400 Toulouse France*

Interactions between erosional and depositional landscapes are an interesting issue in Geomorphology. For instance the relationships between an erosional mountainous catchment providing sediment and the alluvial fan which control the mountain base level are still not well known. These sub-systems are interdependent and are continuously changing because of climate, tectonics or boundary conditions variations. Thus, understanding the geomorphic signature of climate or tectonic changes in a mountain requires studying the whole catchment-fan system. The catchment-fan system of las Tunas, Argentina is located southern of Mendoza city, between latitude 33°S and 34°S a tectonically active area where the deformation is propagating into the foreland. This natural example illustrates how strong catchment and foreland sedimentation dynamics are linked. Indeed the alluvial fan of las Tunas has been strongly entrenched and three main levels of terraces are clearly visible. These terraces are connected to fill and strath terrace along the main stream of the mountain catchment and until more than 10 km upstream the fan apex.

The goal of this study is two folds: 1- to determine the origin of entrenchment and sedimentation cycle in the whole catchment-fan system, 2- to propose, an evolutional model in order to explain the current landscape. GPS topographical profiles of each terrace have been measured in the foreland section. A detailed study of the topography has been made using SRTM and GDEM data. Three depth versus ^{10}Be concentration profiles allow the abandonment age of the three main terraces to be determined. In addition, six ^{10}Be additional surface samples and Ar/Ar dating of two ash samples give additional ages of depositions. These data indicate that sedimentation and entrenchment in the mountain and in the foreland are intimately linked and evolve synchronously. The last main entrenchment occurred at 19ka, just after the last glacial maximum. Finally, this study suggests that despite its active tectonic context, the catchment-fan sedimentary dynamics (entrenchment and sediment deposition) is mainly controlled by quaternary climate variations, consistently with another study in Tien Shan, and numerical model results.

Keynote speaker

Rock into Landscape: weathering, erosion and sediment transfer of particulate and dissolved materials from an active mountain belt.

Niels Hovius, *Department of Earth Sciences, University of Cambridge*

Systematic monitoring of hillslope mass wasting and river loads over extended periods and with increased resolution during large events helps refine and extend the map of internal dynamics and external feedbacks in Earth's surface and near-surface system. Our focus is on Taiwan where tectonic and climatic forcing of weathering and erosion are at a global maximum, resulting in an archetypical bedrock landscape. Although weathering in such landscapes is thought to occur at or near the surface, we find that silicate weathering fluxes in Taiwan are derived importantly from deep within the fractured rockmass. Meanwhile, absence of modern clays in river suspended loads indicates that soils are scarce and poorly developed. Nevertheless, total weathering fluxes from Taiwan are among the highest recorded, in correlation with local erosion rates. High rates of hillslope mass wasting and fluvial sediment transport are driven by earthquakes and cyclonic storms. The biggest trigger events cause instantaneous erosion and seed a weakness in the landscape that is removed over time in predictable fashion. This gives rise to patterns of erosion that cannot be understood in terms of bulk characteristics of climate, such as average annual precipitation.

Instead, these patterns reflect the distribution and history of seismicity and extreme precipitation. For example, the 1999 Mw 7.6 Chi-Chi earthquake has resulted in elevated rates of sediment transport that decayed to normal values over seven years since the earthquake. Very large typhoons, some with enhanced precipitation due to a monsoonal feed, have caused a similar, temporary deviation from normal catchment dynamics.

Crucially, these events do not only mobilize large quantities of clastic sediment, but they also harvest particulate organic carbon (POC) from rock mass, soils and the biosphere. In Taiwan, most non-fossil POC is carried in hyperpycnal storm floods. This has promoted rapid burial and preservation of POC in turbidites throughout the Holocene, representing a draw down of CO_2 from the atmosphere that is potentially larger than that by silicate weathering in the same domain. Oxidation of fossil POC during exhumation and surface transport could offset this effect, but in Taiwan the rate of preservation of fossil POC is extremely high, due to rapid erosion and short fluvial transfer paths. Meanwhile, coarse woody debris flushed from the Taiwan mountains is not buried efficiently in geological deposits, representing instead a concentrated flux of nutrients to coastal and marine environments, and promoting pulses of specific biological activty.

As a consequence, the rocks formed in geological basins reflect the interplay of atmospheric, tectonic, geomorphic and biological processes, not only in their physical attributes but also in their organic and inorganic chemistry, mineralogy and fossil content.

Response of sediment routing systems to tectonic perturbations: time-scales, fluxes, stratigraphy and granulometry

John J. Armitage (1), Robert Duller (1), Alex C. Whittaker (1), Alex Densmore (2), Philip A. Allen (1)
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(2) Department of Geography, Durham University, South Road, Durham DH1 3LE, UK

The sedimentary record within basins is a long-term archive of past erosional, transportational and depositional processes, but the inversion of stratigraphy for forcing mechanisms is unclear. The simplest way to decode the interaction between forcing mechanisms and landscape response is to target a relatively simple system with a closed mass budget. The frontal catchments and hangingwall fans of extensional normal fault-bounded basins provide such a system. We show, from a landscape evolution model tuned to the Basin & Range province (USA), and from field observations in the central Apennines of Italy that the response to tectonic perturbation recorded in the sedimentary archive is strongly influenced by the grain size distribution and discharge of sediment released from the catchment.

We have developed a physical model of an idealised normal fault-bounded basin. Erosion within the catchment is calculated assuming it is driven by the concentrative effects of the flux of rainfall through the catchment and by hillslope diffusion, acting on a tectonic displacement field associated with cumulative co-seismic slip on a single fault. We solve for erosion using a continuum approach and crucially by incorporating field evidence of grain size we predict sediment release from the catchment. This sediment discharge is deposited in the hanging wall basin by filling tectonically generated accommodation. We use pdfs of grain size based on observations from the Apennines and model the down-system variation in grain-size as due to selective deposition. With this simple approach we explore the effects of a change in slip rate on the fault, changing rainfall within the catchment and finally the boundary conditions at the fan toe and the fan apex. Consequently, we are able to add sedimentological texture to the hangingwall basin-fill that can be directly tested through field observations.

We find that the first order control on the grain size in sedimentary successions is the pdf of sediment released from the catchment. Furthermore, we find that sediment flux and its response time to perturbations in tectonic forcing are critically controlled by the feedback between the fan profile and the catchment outlet. We conclude that the transient backstepping caused by a slip-rate increase simulated in previous studies is associated with a pronounced fining of grain size, followed by a cycle of coarsening-up. This opens up further possibilities of linking tectonic perturbations of different types to stratigraphic patterns in the basin-fill. The primary structure of the sedimentary time-series represented by stratigraphy may essentially be a record of transient landscape behaviour.

From grains to plates: arc-continent collision and the detrital record Taiwan

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The Coastal Range in eastern Taiwan contains the remnants of the Pliocene-Pleistocene retro-foredeep basin of the ongoing collision between the Luzon volcanic arc and Eurasian continental margin (Penglai orogeny). The preserved sedimentary record unconformably overlies arc volcanic rocks and is 5-6 km thick. We dated detrital apatite and zircon from six Plio-Pleistocene stratigraphic sections stretching from north to south in the Coastal Range using multiple thermochronometers (Fission-track; U-Pb; (U-Th)/He) to document changes in source and exhumation rate through time.

Zircon fission-track grain ages in 2 – 4 million year old sediments from the Coastal Range between 23.78° and 23.14° N were not reset by the Penglai orogeny and reflect the early-stage removal of the sedimentary cover.

Sediments younger than 2 million years old in this northern region yield Pliocene zircon fission-track grain ages and suggest that exhumation, transport and deposition occurred within 0.4 to 1.5 million years (Kirstein et al., 2010). In the Southern Coastal Range, south of ~23 °N, new fission-track and U-Pb age data demonstrate that this relationship between depositional age and resetting of the zircon fission-tracks ceases. Instead reset grains are only found in samples deposited < 1.1 million years ago. Deconvolution of apatite fission-track grain ages from the same samples indicate Miocene and Pliocene peak age components reflecting either sediment provenance from the Luzon arc or thermal resetting of apatite due to the initiation of subduction and arc-continent collision.

The recorded onset of rapid exhumation in the Pliocene in the northern Coastal Ranges is contemporaneous with major tectonic and climatic changes in the region.

In the Southern Coastal Range the age distributions are consistent with southwards progression of arc-continent collision but in a punctuated rather than sequential manner.

Reference:

Kirstein et al., 2010, Basin Research 22, 270-285.

Keynote speaker

Tectonic and Climatic Control of Erosion Rates -- Implications for Basin Analysis

Kelin X. Whipple

A steady-state balance between rock uplift and erosion is a natural attractor for landscapes at the catchment to orogen scale. This balance implies that at steady state climate can only influence erosion rates if rock uplift rate is itself in part dictated by climate-controlled erosional efficiency. Even so, ultimately erosional mass flux must equal the tectonic rock influx, which is most likely independent of climate. Thus at steady state, erosional flux delivered to depocenters is dictated by tectonics, not by climate – a simple, robust conclusion that is easily forgotten. Steady-state conditions, however, may rarely be achieved in natural systems, and even so could only be sustained as a long-term (order 1 Myr) average in the face of shorter term variation in tectonic activity and climate fluctuations.

Deviations from steady state at a range of timescales will thus be the norm as landscapes respond to changes in tectonic and climatic conditions and will dictate the temporal (and spatial) patterns of sediment delivery. How distinct is the sediment flux response to change in climate versus a change in tectonics? Can one develop “fingerprints” of each response in terms of mass flux delivered to depocenters? While knowledge of the expected system response is incomplete, and in detail expectations differ for active and inactive mountain ranges, for ranges of difference size, and for different tectonic settings and rheologies, some general expectations can be outlined. For example, consider a tectonically active system subject to either an increase in tectonic mass influx rate (or relative rock uplift rate) or an increase in erosivity. Both are changes that will result in an increase in erosion rate and total sediment export from the hinterland over some period of time. In response to a tectonic change, erosion rates will gradually increase (over 100s to 1000s kyr) until steady state is achieved, or until conditions change again.

Conversely, in response to a climatic change, erosion rates will increase immediately in proportion to the change in erosional efficiency. However, over time (again 100s to 1000s kyr) this initial impulsive response will gradually decay and total sediment export from the hinterland will return to the pre-climate change value (equal to the tectonic mass influx).
In addition, the tectonic case will result in increasing topographic relief and perhaps range width and will be associated with greater foreland subsidence, trapping much sediment in proximal basins. Conversely, the climatic scenario will result in decreasing topographic loads and isostatic rebound of the foreland, contributing additional sediment and shifting deposition to more distal basins.

THEME 2: DYNAMICS OF THE SEDIMENT ROUTING SYSTEM

Thresholds, memory and self-similarity: building sediment dispersal systems

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The first-order growth of alluvial fans and deltas (collectively fans) is well-described by mass conserving models, which are capable of predicting mean growth rate using a radially-averaged approach. Convergence toward this diffusion approximation requires thousands of years, however, over which channels must somehow fill space to make a fan. This is typically accomplished in two, inter-related ways: (1) channels migrate laterally via deposition-driven avulsion, and (2) channels create a distributary network that disperses a localized sediment source over a broad area. How channel paths are selected, and what governs the ultimate number of active channels, is poorly understood. We examine results of a noncohesive experimental fan that exhibits a repeated cycle of shoreline progradation, channel backfilling and flooding, and avulsion to a new channel path. The avulsion cycle produces fluctuations around an equilibrium slope analogous to sand piles. Slope fluctuations may be understood as a system oscillating between two threshold states, while the period of these fluctuations is predictable from conservation of mass.

The selection of a new flow path appears to follow a directed random walk initially, however accumulating abandoned channels through time act as significant attractors for future flow. Once a network of 3-5 channels is created, the system oscillates among them indefinitely. Thus, there is a memory of past channels that dictates future channel paths, and a critical channel density is required to distribute sediment over the entire fan. The pattern of shoreline growth reflects reoccupation of persistent channel locations. Fan lobes grow in self-similar manner that can be described using a simple geometric model.

Together, this work provides a complete description of the statistical spatio-temporal dynamics of experimental fan growth. Because all of the relevant dynamics depend on conservation of mass, geometric constraints and thresholds, we can generalize these results to natural systems in a straight forward manner.

Connection Between Floodplains and Delta Plains with Examples: Indus, Yellow and Niger

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Floodplains represent areas surrounding a river that flood annually or at least every few years. Engineered stop banks are designed to stop or control this flooding. We know much about river flooding frequency and location from the global survey (since 2000) performed daily by the Dartmouth Flood Observatory using MODIS instruments aboard NASA's Terra and Aqua spacecraft. NASA/JAXA's AMSR-E (Advanced Microwave Scanning Radiometer) mission from mid-2002 to the present allows for a time series of estimated discharge passing a fixed measurement site for many of the world's rivers, including the arrival times, amplitudes, and duration of river flood waves.

The Space Shuttle SRTM data has allowed the terrain of flood plains to be studied in detail. Flood waves transport much sediment, reworking the channel (meanders, braids), occasionally overbanking and forming crevasse splaying (fingers, fans) leading to standing water and sediment deposition as cover deposits.

SRTM data is capable of sensing paleo channels that can be sometimes dated using geo-located historical maps. Channel switching is still not well understood, although human activity, earthquakes and gradient capture are the primary candidates.

Floodplains extend onto their delta plain. Floodplains are within the zone of flow "convergence", in contrast to delta systems where flow "divergence" dominates — channels split into distributary channels, sometimes with downstream rejoins, and are more under the influence of transverse pressure gradients and momentum. Delta plains differ from floodplains in that the action of tidal energy and wave energy offer additional controls on channel switching.

The morphology Indus (Pakistan), Yellow or Huanghe (China) and Niger (Nigeria) floodplains and delta plains are examined with these new space-borne tools, augment by historical ground surveys. The systems offer highly different histories of human intervention, and very different drainage basin characteristics. Their morphologies reflect these differences. The Indus is subject to river switching by earthquakes; its delta is being rapidly reworked by tidal energy now that little water or sediment flows onto its delta plain. The Yellow River has become super-elevated to its floodplain through human intervention; its delta is rapidly disappearing under the influence of subsidence. Most of the Niger River discharge is generated by monsoonal rain falling directly onto the delta plain; the main river delivers most of the sediment but carries comparatively little water.

Controls on sediment supply from relay zone catchments along extensional fault systems

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It is well established that the structural evolution of linked extensional fault systems impacts the size of footwall catchments, the location and persistence of sediment entry points from the footwall into the hanging-wall basin (e.g. Cowie et al., 2006). Here we aim to understand better the controls on sediment volumes and spatial variations in erosion rates in these settings to shed light on the provenance and grain size distributions of rift basin sediments. Locations where faults link, "breached relay zones", set the relative uplift rate and thus local base level where a river emerges from the footwall through these zones and enters basin depocentres.

Changes in base level drive catchments incision and produce variations in the amount and calibre of sediment entering the basin, particularly if the incision rate is sufficient to drive a transition from diffusive to landslide-dominated hill-slopes. Consequently, the timing of linkage and the relative uplift rate across the relay breaching fault is of crucial importance in understanding how sediment supply from these catchments varies through time. Recent work (Faure Walker et al., 2009) showed that the vertical component of slip rate (throw rate) on the relay breaching fault depends on the 3D structural geometry. We use this information to drive a landscape evolution model (CHILD) that includes a catchment uplifted and back-tilted by an active normal fault (e.g. Attal et al.2008).

An increase in relative uplift rate occurs at the time of segment linkage and results in a transient response within the catchment. We model landscape response to a low, moderate and high increase in uplift rate, using typical hydraulic scaling relationships in conjunction with the commonly used stream power law.

We compare this response to the one predicted when dynamic channel adjustment is included, based on field observations in catchments in the Apennines, Italy. We quantify differences in erosion rate in space and time and total volumes of eroded material for each model. Compared to cases where the typical hydraulic scaling is assumed, catchments respond faster to larger increases in relative uplift rate when dynamic channel adjustment is included in the model. In this latter case, large volumes of coarse sediment are more likely to be supplied to hanging wall basins. Our study suggests that relay zone catchments may exhibit different geomorphologies, and produce different sediment volumes and calibre depending on fault geometry as well as the fluvial incision processes operating in the catchment.

Drainage density and landscape evolution in the Alps

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Glaciers overprinted mountain landscapes and generally increase the relief of landscapes. Alpine basins affected by glacial sculpting have common mean slopes between 25° and 37° except in some extremely high erodible rock settings where mean slopes can be as low as 20°. In these high mean slope basins denudation rates vary substantially. The increase of erosion rates is non-linear and insensitive to basin's mean slope. Detachment-limited hillslope processes are supposed to be the dominant control in such settings (e.g. Binnie et. al, 2007)

In order to investigate factors controlling the erosion rates of glacially sculpted basins in the European Alps we derived geomorphometric data from 30 m DEMs and compiled data on erosion rates obtained from Be10 (Wittmann et al. 2007), furthermore on geology, vegetation and precipitation.

We show that drainage density exhibits a negative, linear correlation with denudation rates in basins with mean slope larger than 25°. It is striking that in such basins high erodible rocks show a generally reduced drainage density in contrast to areas with low erodible rocks. Hillslope processes may counteract fluvial incision by horizontal rock mass advection (Korup and Schlunegger, 2007). In accordance, a lower drainage density reflects lower hillslope stability and higher erosion rates and vice versa. If true, drainages per catchment are a mirror for the hillslope activity. The different slopes of the drainage density/erosion rate regression in different parts of the Alps show that other factors, such as mean precipitation, may play an additional important role.

We also show that resistant rocks are associated with more pronounced glacial features such as steep cirques and hanging valleys in contrast to basins with weak rocks. First is represented by higher mean concavities and steepness indices, the later by lower mean concavities and steepness indices.

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Delayed Morphogeny and focused erosion in the Alps and Himalaya

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Mountain-building processes are so varied and complex that each orogenic belt stands as a case apart. Nevertheless, analogies in erosional evolution may be noted between the Alps and the Himalayas, belonging to the same Tertiary orogenic system (Gansser,1982).

Continental collision between India and Asia began at ~55 Ma, and yet neo-metamorphic Himalayan detritus became widespread only in the early Miocene (Najman and Garzanti, 2000), when rapid un-roofing of Greater Himalayan amphibolite-facies rocks triggered huge long-distance sediment transfer to the Bengal Fan.

The main morphogenic and sediment production phase thus took place ~30 Myr after collision onset. Since the late Neogene, erosion has focused at western and eastern Himalayan syntaxes with rates up to 5 mm/yr, producing detritus with peculiar compositional signatures ("Dissected Axial Belt Provenance"; Garzanti et al., 2007; 2010). Here the Indus and Tsangpo–Brahmaputra Rivers leave Tibetan highlands to turn sharply south and cut deep gorges transverse to the structural grain of growing crustal-scale antiforms, suggesting antecedence relationships. Spatial association between river gorges and metamorphic domes, where high-grade mid-crustal rocks of the Indian indenter are quasi-instantaneously exhumed, has suggested the existence of positive feedback between erosion and uplift of hot weak rocks from depth ("tectonic aneurysms" of Zeitler et al., 2001).

In the Alps, continental collision began at ~44 Ma (Rubatto et al., 1998), but focused erosion of domal culminations and rapid unroofing of recently-emplaced plutons and young amphibolite-facies gneisses started suddenly not earlier than the late Oligocene (~25 Ma; Garzanti and Malusà, 2008). Exhumation of the Lepontine Dome was tectonically driven, and possibly accelerated by positive feedback between erosion and uplift of hot weak rocks from depth. The huge volumes of resulting detritus (Gonfolite–Macigno clastic wedge) were transported southward for hundreds of kilometers along the rapidly subsiding foredeep, formed since middle Eocene times in front of the Alpine retrobelt and nascent Apennine forebelt. Such massive sediment influx followed a 15 – 20 Myr-long stage of starved foredeep sedimentation, and testifies to rapid formation of mountain relief in the Central Alps, synchronous to dextral activity along the Insubric Fault. Positive feedback between fluvial incision and exhumation may have thus favoured focused erosion of Lepontine gneisses, as suggested by antecedent transverse drainage cutting straight across tectonic subdomes (paleo-Ticino, paleo-Toce).

Another curious geomorphological analogy is that major Himalayan Rivers (Indus, Tsangpo–Brahmaputra, Ganga– Karnali, Sutlej), as major Alpine Rivers (Rhône, Rhein, Ticino–Toce), are sourced from the same site within the central part of the orogen, at the northern side of the belt. Contrary to the Indus and Tsangpo Rivers, originating in the retro-side of the Himalaya and cutting across young syntaxes toward the Indo–Gangetic pro-side, the Ticino–Toce River flows across Lepontine subdomes towards the Southalpine retro-side. South-directed since the onset of the morphogenic stage because of strong subsidence of the Adriatic foredeep, Lepontine drainage was definitively fixed by Messinian overincision.

Keynote speaker

Lessons from Rapidly Changing Landscapes

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Our understanding of how landscapes turn into rock, and *vice versa,* relies in part on process models that describe the erosion, transport, deposition, and physical-chemical alteration of mass near the earth's surface. Rapidly evolving landscapes offer the opportunity to test and refine such models, on time scales short enough to yield substantial change in the Holocene but long enough to be relevant to the rock cycle. Here we present two case studies in rapid Holocene landscape evolution, and discuss their implications for models of landscape evolution. The first case comes from the active fold-and-thrust belt of western Taiwan.

The Peikangshi, a powerful transverse river, cuts across a series of mapped thrusts en route to the foreland. Optically stimulated luminescence (OSL) dating of sediments on strath terraces reveals systematic variations in Holocene incision rate along the channel. Zones of high incision rate correspond to mapped thrust faults, which are interpreted to be active (Yanites et al. 2010a).
The incision-rate pattern correlates with characteristic stream power and shear stress. Electrical resistivity surveys of channel sediments indicate that much of today's riverbed is blanketed by alluvium, and hence protected from incision (Hsu et al., 2010). This implies that an important aspect of long-term bedrock river incision is temporal variability in sediment cover. This is linked, in part, to the seismic cycle: earthquakes liberate debris that can bury the channel network and switch off incision. Close to the faults, however, propagation of co-seismic knickpoints can drive relatively brief periods of extremely rapid incision. Along the Peikangshi, much of the along-stream variation in river power reflects variations in channel width rather than gradient, which motivates a simple theoretical model for channel-width adjustment in bedrock rivers. Collectively, data from the Peikangshi illuminate the contributions of hydraulic power, sediment flux, and the seismic cycle to bedrock river incision.

A second case study provides a means of testing whole-landscape models. In the Buttermilk Creek drainage basin of western New York, USA, preserved remnants of a glacially formed depositional surface allow reconstruction of topography as it existed shortly after the retreat of the Laurentide ice sheet. Rapid post-glacial incision of this surface generated a system of canyons up to 60m deep. OSL dating of fluvial terrace deposits constrains the tempo of post-glacial incision, and provides a target for calibrating numerical models. A Monte Carlo approach is used to calibrate CHILD, a process-based model of drainage basin evolution. Using a combination of elevation and drainage-network-based metrics as goodness-of-fit measures, the calibrated model can account for the main features of the present-day topography. This finding provides support for current process laws as well as constraints on rate constants, but it also indicates potential for non-uniqueness among parameter combinations.

Together, the two case studies demonstrate the value of Holocene-scale natural experiments for continually challenging and refining mathematical models of the earth's dynamic landscapes.

Uplift and Subsidence by Subduction Dynamics: A Driving Mechanism for the Late Cretaceous and Cenozoic Evolution of Continental SE Asia

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Zircons derived from Paleogene sedimentary rocks exposed in West Java record the timing of an important micro-continental collision at the Java margin (~85 Ma).

The collision halted Cretaceous subduction and appears to be related to the formation of a Cretaceous-Paleocene unconformity that extends across Sundaland, from Vietnam to Java, covering an area in excess of 5,600,000 km^2 (10 times the size of mainland France).

It is difficult to see how creation of such an unconformity could result directly from collisional tectonics given the disparity in size between the accreted continental fragments and area of the unconformity, as well as the lack of evidence for the requisite crustal shortening and thickening. Instead, simple mapping of the spatial extent of the Mid-Late Cretaceous subduction zone and the Cretaceous-Paleocene unconformity, and an assessment of exhumation trends throughout the region suggests that the unconformity might be a consequence of subduction dynamics. Cessation of subduction, descent of a northward dipping slab into the mantle, and consequent uplift of an early Cretaceous dynamic topographic low explain the extent and timing of the unconformity. Sediments started to accumulate above the unconformity from the Early Eocene, which is when subduction recommenced beneath Sundaland.

Onshore-offshore sediment dispersal in the Golo source-to-sink system during the late Quaternary

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The spatial and temporal relationships between tectonics, climate, eustasy and intrinsic system processes control patterns of sediment partitioning along the down-dip transect of sediment routing systems, from the catchment source to the deep-sea sink. This study attempts to link preserved alluvial terraces in the catchment segment with shallow-marine sedimentary wedges on the shelf, and deep-sea fan lobes of the Golo source-to-sink system on the island of Corsica during the last ~60 ky. The study suggests that timing of alluvial aggradation was controlled by climatic related factors such as changing vegetation and river transport capacity, and that significant channel aggradation occurred both during periods of eustatic lowstands when the Golo River was directly connected to slope canyon systems, as well as during short highstands when the onshore-offshore link was disconnected and less coarse-grained sediment reached the deep-sea basin.

Age relationships between the various terraces (obtained by OSL dating) also suggests that the alluvial sediment covering strath terraces may significantly post-date the time of initial terrace formation, and that these terraces may be diachronous along the river depending on the balance between local flood levels and incision rates. During the last ~60 ky, large volumes of sandy sediment were supplied to the deep part of the basin whenever the Golo River reached within a couple of kilometers from the shelf rollover and linked up with slope canyon systems.

First-order estimates on paleo sediment supply rates from the Golo River show relatively good correlations with volume calculations derived from the shallow and deep-marine deposition units, indicating alternating periods of “storage and release” between the various segments. Studies of the Golo system suggest that sediment partitioning between different source-to-sink segments may be controlled by internal “thresholds” which dictate the system response to external forcing on 10^3-10^4 year time-scales. Such internal variability may result in difficulties correlating stratigraphic units within and between systems. In summary, the Golo system can be described as a small, “reactive” source-to-sink system which is capable of “buffering” sediment supply signals induced by climatic fluctuations on millennial time-scales.

Sediment buffering, reworking and drainage evolution in the Holocene Indus River

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The only complete and potentially well-dated record of erosion in the western Himalaya lies in the Indus submarine fan of the Arabian Sea. However, if we are to use this repository then we need to understand how sediment is transported from source to sink. We have examined how the Indus has responded to changing base level and monsoon intensity since the LGM (~20 ka). The onset of the Holocene around 10 ka appears to be linked to a shift in erosion from the high, glaciated peaks of the Karakoram to the frontal Lesser Himalayan ranges, presumably caused by stronger rainfall in those regions (Clift *et al.* 2008). Coring at the delta shows that while clays and micas show the change in provenance effectively coincident with the climate change the signal from detrital U-Pb zircon ages lags that by 5–10 k.y. (Clift *et al.* 2010), probably because zircon is a dense, heavy mineral with slow transport compared to clay and mica that are transported by suspended flow.

Indeed the modern water discharge from the major Indus tributaries predicts a much different zircon age population at the delta than what is presently found there. This we believe reflects the long zircon transport time, so that zircon sand grains now reaching the river mouth would originally have been eroded in the Early Holocene under the influence of a much strong summer monsoon (Alizai *et al.* 2010).

Curiously, while monsoon strengthening causes a strong change in isotopic ratios the weakening of the summer rains after ~6 ka does not seem to result in a return to LGM values. This likely reflects the onset of a period of strong reworking on the flood plain. While sedimentation has continued unabated in southern Pakistan, close to the delta, the northern half of the flood plain shows incision of the rivers into valleys 10–20 m deep and 15–30 km across. This incision has removed a large amount of temporarily stored material, largely deposited in the Early Holocene, and may account for 80% of more of the sedimentation close to the delta since 5 ka. At the same time Holocene sediment cored around the western edge of the Thar Desert shows significant differences in terms of its zircon age spectrum compared to either the closest river, the Sutlej, or the sands of the Thar Desert. This suggests that the western tributaries of the Indus have experienced large-scale reorganization and headwater capture as recently as 4–5 ka. Most dramatically we suggest that the Yamuna, now flowing east into the Ganges, used to flow west into the Indus. At the same time the Sutlej and Beas Rivers used to flow further south than they do now and may have even formed a separated river to the Indus, as far as the Arabian Sea. The capture of the Yamuna headwaters explains much of the provenance mis-match in zircon populatioons between what is eroding now and what is reaching the river mouth today.

We conclude that over millennial timescales the Indus is an unstable river whose sediment load is controlled by changes in the summer monsoon intensity that drive reworking on the plains and changes in erosion pattern. As a result the sediment reaching the sea at any one time may have taken 5–10 k.y. to reach that point after leaving the Himalaya and even then its passage to the deep ocean is not direct because of a cessation of sediment flux through the Indus Canyon after 7 ka.

Numerical modelling of morphodynamics and stratigraphy of river deltas

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Representing the interface of terrestrial and marine basins, river deltas are first-order elements of source-to-sink systems; while acting as a sink for sediments delivered from upstream drainage basins, deltas act as a sediment source for submarine environments. Based on inferences from field observations, several river delta classification schemes have been suggested throughout the past few decades. The well-known scheme of Galloway (1975, Houston Geological Society) addresses prime hydraulic controls; river discharge, wind-generated waves and tides. In addition, the extended version by Orton and Reading (1993, Sedimentology) identifies sediment type as an important control for a delta's planform.

Here, we present results from high-resolution physics-based numerical Delft3D-models on morphodynamics and stratigraphy of river deltas under various forcing conditions. Examples include river-dominated delta progradation under steady upstream water discharge and steady downstream water level, for two sediment fractions (fines and sand) and river delta formation for unsteady, cyclic downstream water levels due to propagation of wind-generated waves (normally-incident to the undisturbed shoreline) or tidal motion (single harmonic constituent). It is shown that river, windwaves and tides govern morphometrics and stratal patterns of river deltas. Moreover, analogous to the concept of morphological conditioning, we suggest the concept of stratigraphic conditioning in that different schematized antecedent subsurface sedimentary compositions result in different river-delta patterns.

Keynote speaker

Mass balance effects in depositional systems

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Once sediment leaves the net-erosional part of the sediment system, crossing a boundary that is itself complex and prone to migrate, it begins a process of mass loss to deposition. This mass loss results from the net deposition that compensates for subsidence and creates the stratigraphic record. Although its spatial pattern changes and it can be locally stopped or even reversed, in the long run subsidence-driven depositional mass loss is the single most important driving influence on the sediment dynamics of depositional systems. Mass loss leads directly to facies changes as sediment flux gradually declines; indirectly it leads to downstream sediment fining as deposition preferentially removes coarser particles.

Laboratory experiments are useful in exploring mass-loss effects in stratigraphy because they allow for construction of precise sediment budgets. Experiments to date illustrate the effects of mass extraction on fluvial channel stacking and deposit grain size, and show how a mass-balance framework allows for consistent, quantitative comparison across time intervals, spatial scale, and spatial pattern of deposition.

Theoretical approaches based on mass balance also show promise for predicting overall trends in depositional systems.

These results represent first steps towards a framework for quantitative basin analysis based on mass extraction. Any such theory will likely be able to account only for large-scale and/or generic mass-balance effects, and would thus be complicated by local effects (e.g. local erosion, climatically or biotically mediated changes in transport regime, complex transport paths, etc.) We propose that a first step to using such generalised models effectively is to view the results as reference cases of down-transport change resulting from a simplified spatial mass-extraction pattern and sediment supply. The idea is not so much that such reference cases would provide detailed predictions of specific field cases but rather that they would provide a standard against which field cases could be compared in order to separate local, case-specific features from generic system behaviour.

The idea is analogous to the way the geoid serves as a reference against which to measure gravity anomalies. Reference cases for alluvial basin fills would be constructed from three basic external controls: the spatial mass-extraction profile (the net outcome of total sediment supply, subsidence rate and pattern, and external forcing); the rate and (secondarily) temporal distribution of water supply; and the size distribution of supplied sediment. We explore this idea using laboratory experiments, theory, and field examples.

THEME 3: LANDSCAPES INTO ROCK

Landscapes characterised by uplifted peneplains in Greenland: The onshore expression of unconformities.

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Landscape analysis along the passive continental margins of West and East Greenland, in combination with geological evidence and AFTA (apatite fission track analysis) data, has shown that the presently uplifted peneplains are regional features representing erosional unconformities, which can be correlated with unconformities offshore and episodes of exhumation identified from AFTA.

In central West Greenland three peneplains have been identified (oldest to youngest): 1) A peneplain characterised by hilly relief at low elevations, formed by deep weathering in basement rocks prior to deposition of Cretaceous–Paleocene sediments and extrusion of Paleocene basalt. 2) A regional peneplain at between 1-2 km above sea level (a.s.l), formed across the hilly relief peneplain, basement rocks and across different lava flows. The peneplain therefore represents an erosional unconformity, rather than resistant lithologies. The youngest basalt is Late Eocene in age (39 Ma), which provides the maximum age for the peneplain. 3) A minor peneplain incised into the regional peneplain along systems of palaeo-rivers, formed as a consequence of lowered base level.

In South-East Greenland (c. 68-71°N) two peneplains have been identified: 1) A peneplain characterised by hilly relief in basement rocks is preserved below Palaeogene basalts in the north. 2) A regional peneplain, characterised by an elevated, mainly ice-covered plateau above 2 km a.s.l., with deeply incised fjords. This peneplain cuts across flood basalts extruded at around 55 Ma in the south and across Precambrian basement in the north.
Since these peneplains cut across different lithologies and can be mapped over large distances, they clearly represent erosional unconformities.

The most probable explanation is that the peneplains were graded to a common base level, and in this case most likely the sea. We have correlated the formation of the regional peneplain in West Greenland with the major Oligocene – Lower Miocene unconformity seen in the offshore record.

To explain the present relief, the peneplains must thus have been uplifted after their formation. AFTA results from East and West Greenland reveal cooling phases that postdate formation of the high-lying peneplains, which suggest that their uplift to the present-day altitudes occurred since the Late Miocene. This uplift resulted in formation of the present relief by deep incision of valleys into the raised peneplains.

We conclude that the high level peneplains represent the effects of substantial post-rift erosion followed by late Cenozoic uplift which caused incision and development of the modern relief.

3D Seismic Geomorphology of the Norwegian Channel Ice Stream

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Seismic images from formerly glaciated areas display a variety of features attributable to glacial erosion, deposition and deformation. Recent improvements in the quality and extent of 3D seismic coverage has led to a veritable explosion in our knowledge about the imprints of the Pleistocene glaciations on NW Europe. The most prominent glacial feature in NW Europe is arguably the Norwegian Channel paleo-Ice Stream (NCIS), which is readily observable in the present-day bathymetry of the Northern North Sea (NNS) (Fig. 1). This prominent feature dates back at least to 1.1Ma. The NCIS has been estimated to contain some 5000km^3 of sediment, about 1/3 of the total volume of the North Sea Fan which is located at the NCIS terminus (Sejrup et al. 1996). Legacy 3D seismic analysis has confirmed the potential for 3D seismic imaging of the infill and its mode of deposition (Rise et al. 2004) in a manner akin to other ice stream depressions covered by 3D seismic datasets (e.g. Andreassen & Winsborrow 2009).

This study first utilizes the extensive lateral coverage afforded by the PGS NNS megasurvey to map the very base of the ice stream and its underlying deposits in order to ascertain any substrate control on ice stream behaviour. Then we analyse the infill sediments in terms of depositional environments and any imprints of sediment bypass events and provide thickness maps of each major infill unit in order to constrain the spatio-temporal evolution of deposition and erosion in this major sediment fairway through the mid and late Quaternary. Lithological and chronostratigraphical calibration is provided by released exploration boreholes and the cored Troll borehole (Sejrup et al. 1996; Rise et al. 2004).The results have implications for the understanding of erosion and sediment routing during glacial and interglacial periods and for the understanding of sedimentary facies distribution and resource potential of ice stream depressions.

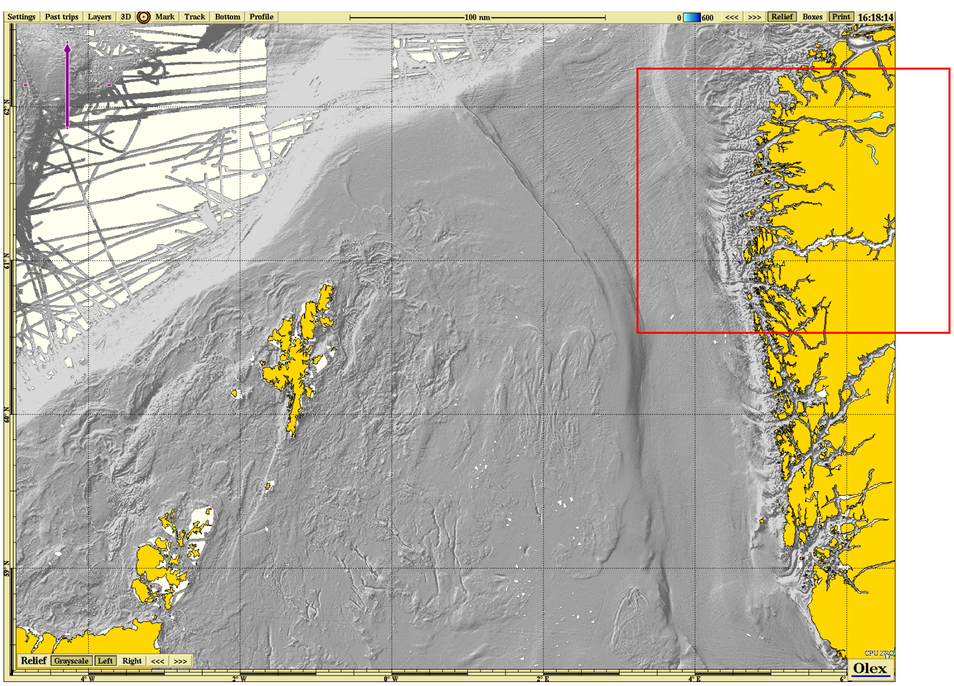

Fig. 1. Location (red box) of the 3D seismic study area of the Norwegian Channel Ice Stream. 3D seismic 'megasurvey' dataset courtesy of PGS Ltd.

Extensional faulting and the long-term evolution of topography at passive margins

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There is a relationship at passive margins between the pattern of crustal necking, inherited from the time when the margin formed, and the onshore distribution of topography and landforms. This hitherto unidentified relationship appears to be independent of the age, magmatic and glacial history of the margin. Thus, there exists a long-term control on drainage evolution, landscape formation and sediment routing patterns at passive margins that becomes set during the main phases of crustal thinning. At present, this control is poorly understood.

Recent studies of passive margins show that reduction in crustal thickness from ±30 km down to c. 10 km can take place over shorter or longer horizontal distances, resulting in different crustal thinning gradients along the margin. Comparing the maximum elevation of the onshore margin escarpment to the distance from that elevation to where the crust becomes thinned to less than 10 km thickness, a clear relationship is identified for a significant number of passive margins worldwide.

At the Norwegian margin, the highest and most asymmetric onshore topography and the most rugged and alpine landscapes are found directly inboard of areas where the continental crust tapers sharply off into the offshore. Conversely, where the taper is less sharp, adjacent landscapes are less dramatic and the topographic crest occurs farther inboard.

Offshore Mid Norway, the necking of crystalline crust is demonstrably related to large-magnitude extensional faults that formed in the Late Jurassic-Early Cretaceous phase of crustal thinning. It is surprising that the above relationship is observed today, 54 Ma after breakup in the North Atlantic and as much as 100-150 Ma after the main phase of faulting.

Reactivation of faults after the main rift phases is documented by apatite fission-track data and appears to be particularly important in areas inboard of sharply tapering continental crust. Linear alpine ranges such as those in the Møre and Lofoten –Vesterålen areas are fault-bounded and flanked by less incised, more subdued landscapes. Thus, whereas deformation migrates basinwards during rifting, it migrates into the continent in the post-rift phase.

Our observations may have profound implications for the long-term formation of landscapes and for the delivery of erosional products from the onshore to the offshore at passive margins.

How important are fault segment linkage points as sediment pathways? : An example from the Jurassic Bremstein Fault Complex, Offshore Mid-Norway

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Studies of modern day fault systems in extensional regimes (e.g. Basin and Range), and in exhumed, ancient rift basins (e.g. Miocene Gulf of Suez) have shown a link between the evolution of fault-related footwall topography and the erosional drainage systems developed on that topography. However, in the vast majority of cases, these drainage systems formed in sub-aerial environments via river incision as a result of footwall uplift; comparatively few examples have been presented from gravity driven fault systems. In such settings, footwall uplift is minimal or absent with hangingwall subsidence accommodating the throw accumulation on the fault system. In this gravity-driven example, the fault footwall erosion has not been influenced by footwall uplift and therefore factors that affect uplifted footwall crests such as antecedent drainage, inherited topography or climatic variations will have had less of an effect. Such a case study therefore provides an excellent opportunity to understand the geomorphological evolution of fault footwall topography in the absence of these factors.

In this study, a normal fault footwall crest erosion system developed in the Jurassic of Halten Terrace, offshore Mid-Norway is exceptionally well-imaged with 3D seismic reflection data. The system is 22 km long and comprises 96 drainage catchments characterised by erosional channels. These erosional channels consist of small, linear systems up to 750 m long located along the front of the fault footwall. Larger, more dendritic channel systems extend further back (up to 3 km normal to fault strike) into the footwall. These channels are up to 7 km long, up to 50 m deep and up to 1 km wide. The axial orientation of the larger catchments varies from fault-parallel in their upper reaches to fault-normal in their lower reaches.

The displacement along the fault shows evidence of three areas of low throw representing the locations of segment linkage points as the fault grew. When the location of the catchments is compared to the throw variations of the fault, the distribution is highly variable. The highest throw variations on the fault may be where the largest catchments are expected but this is not the case. Rather, the segment linkage points do not appear to have been significant sediment pathways in this system in contrast to many published rift models.

This presentation will explore this relationship and its implications for exploration strategies in rift basins.

From grain size to tectonics: Decoding stratigraphic trends in sediment calibre as a function of tectonic subsidence and sediment flux.

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Regional grain size trends in fluvial successions theoretically embed important information on the dynamics of sediment routing systems and their sensitivity to external forcing mechanisms. In simple terms, downstream sediment fining is driven primarily by selective deposition of sediment, and mediated by abrasion of the clasts during transport. However, the relative efficiency of this process is determined by (1) the physical characteristics of the input sediment supply; (2) the spatial distribution of subsidence rate, which generates the accommodation necessary for sediment preservation; (3) the detailed mechanics of sediment transport and deposition.

A key challenge is therefore to determine how these first two factors control the calibre and spatial distribution of deposits over timescales of ~10^4 yrs without incorporating the details of hydraulics and sediment transport which are largely unknowable for time-averaged stratigraphy in the geological past. One method to solve this problem is to assume self similarity between the long-term, longitudinal grain size distribution of the substrate and the dimensionless relative mobility function for gravel, using only the local mean and standard deviation of grain sizes in transport as scaling parameters. In principle, this modelling approach offers a simple, but powerful, means to explore the key controls on downstream grain size fining in fluvial deposits and so understand the temporal evolution of sediment routing systems.

We apply and evaluate this methodology in two complementary ways: Firstly we develop the similarity model to explore the generic sensitivity of stratigraphic fining rates to changes in both sediment supply and tectonic subsidence and secondly we evaluate the model using detailed grain-size data from both the Eocene Pobla Basin, and the Oligocene Antist system, Spanish Pyrenees, where the timing of sediment deposition is known from palaeomagnetic and paleontological dating, and where good exposure enables time-lines within stratigraphy to be picked out unambigously. For successive stratigraphic horizons, we derive downstream trends in coarse-fraction grain-size for three sediment routing systems with maximum lengthscales of 5, 40 and 70 km respectively, using Wolman and photographic point counts, and palaeocurrent data from pebble imbrications and groove casts. Our data show that the rate of grain-size fining varies over time and changes systematically with system length.

Our modelling and field results demonstrate that it is now possible to decode regional grain-size trends in stratigraphy for key controlling variables over geological timescales.

Towards Landscape Evolution Models That Run Much Faster

Scott D. Peckham
University of Colorado at Boulder

Fluvial landscape evolution models may be viewed as a type of nonlinear diffusion, where the diffusion coefficient is a function of slope and area and varies spatially over several orders of magnitude. This fundamental feature of these models means that the timesteps required for stability and accuracy decrease very rapidly with increasing grid size. As a result, these models require prohibitively long run times when applied to large grids.

The purpose of this talk is to present a new algorithm that is tailored to this type of stiff, numerical problem. The key idea is to allow different grid cells to run with different time steps. However, this requires careful attention to conservation of mass and the fluxes between neighboring grid cells. Preliminary results are very promising and we expect a full implementation of our new algorithm to be completed in time to be unveiled at this meeting.

Continental deposits under different climates in Sardinia (Italy): case studies

Luca G. Costamagna,
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The diverse tectonic events in which Sardinia was involved determined the following deposition of continental successions. The good quality of the outcrops makes Sardinia a stimulating place to investigate the alluvial environments and their relationships with climate. As examples, we are recalling selected few of them, related to different climates.

The collapse basins connected with the end of the Variscan deformations gave place to early-molasse-type basins (Late Carboniferous-Early Permian) filled by warm-humid dark “limnic” successions, made of coarse depositional events and lacustrine sediments; they were subsequently covered unconformably by coarse to fine, warm to hot, subarid red-bed deposits pertaining to molasse-type basins (Middle- ?Late Permian). Those successions can be referred to the European Rotliegend and have a maximum thickness of nearly 500 m.

The early Alpine basins related to the opening of the Tethys (Early-Middle Triassic) initiated the deposition of thin, mainly sandy red-bed successions (tens of meters) in a hot arid environment pertaining to the Buntsandstein.

In the Middle Jurassic during the opening of the Alpine Tethys thin clastic wedges deposed around morphostructural highs in Central Sardinia. They were built of coarse to fine, generally quartz-rich siliciclastics (Genna Selole Fm.) under a hot humid climate passing rapidly to carbonate shelf sediments: they are related to ephemeral short depositional systems doomed to a rapid drowning for the close Tethys evolution.

The 400 m-thick molasse deposits (Cixerri Fm.) related to the Pyrenean phase of the Alpine orogenesis are due to the development of a continental long-depositional system connected to the dismantling of the Pyrenees, whose outskirts bordered the Western Sardinia before the Oligo-Miocene rotation of the Corsica-Sardinia block in the Western Mediterranean area. During this rotation, the siliciclastic rift-related succession of Oligo-Miocenic age (Ussana/Flumentepido Fms.) nearly 500 m thick was featured by lined-up fan deltas dipping into the sea gradually invading the Sardinian rift and producing mainly coarse-grained deposits. Those latter successions deposed under warm temperate-subarid climates and are featured by red-bed successions.

The good preservation of these successions allows to try several solutions for the setting of the continental depositional events in climatic, sedimentological, dynamic and architectural frames and to model their paleogeographic context throughout direction and provenance analysis.

Drainage basin morphologies of the Himalaya and southern Tibet

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Catchment morphologies and their associated river networks exert a first-order control on the spatio-temporal distribution of sediment and water flux. Thus, understanding the controls on catchment form constitutes a critical part of understanding the link between erosion and sedimentation. As mountain ranges grow upward and outward, so their catchments evolve, and this signal should be recorded in the stratigraphy of foreland basins.

A morphometric analysis of Himalayan river catchments evaluates the degree to which tectonic displacement versus surface processes determine catchment form. We focus on the relationship between catchment form (planform and mean slope) and catchment orientation with respect to the strike of the mountain belt. Catchment morphology defines four geomorphic zones that run sub-parallel to the trend of the mountain belt; 1) the Ganges/Indus Plains, 2) the front ranges, 3) the High Himalaya and 4) north of the High Himalaya.

Catchments with mean slopes of ~1.5° are confined to the plains and have the highest mean aspect ratio (~3.5). Catchments with mean slopes >25° are largely confined to the High Himalaya (zone 3) and have the lowest mean aspect ratio (~1.8). We suggest these mean slope values correspond to the transition from deposition to erosion, and the onset of pervasive mass-wasting respectively. We show that the geometry of Strahler order 3-5 catchments is strongly coupled to mean catchment slope across all geomorphic zones. Additionally, mean catchment slope in the front ranges (zone 2) is sensitive to orientation, and catchment geometry north of the High Himalaya is sensitive to scale. In contrast, catchments of the High Himalaya (zone 3) show little scale or orientation dependence.

We suggest zone 2 catchments may evolve into zone 3-type catchments through drainage divide migration. In contrast, low erosion rates have inhibited drainage divide migration north of the High Himalaya and enabled larger catchments to record the kinematics of long-term (>10^6 yrs) deformation of the underlying crust. In recognising the zonation of catchment form and process from south to north across the Himalaya, we are able to speculate upon the evolution of catchment form and sediment supply during growth of the range.
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2010 William Smith Lecture

Landscape into rock: a sedimentological view

Mike Leeder
University of East Anglia

Although any observed erosional landscape may contain memory, it is the depositional sedimentary record fed by a given landscape over longer time that must be analysed in order to trace landscape evolution. In fact, many landscape evolutionary models remain essentially untestable since the sedimentary record is not fully utilised.

In the discipline of spatial statistics, quantitative metrics may be used to describe landscape evolution and evaluate patterns and processes. The fundamental unit of analysis is the landpatch, a discrete, relatively homogeneous spatial domain distinguished by properties unique from surrounding patches. Landpatches with similar properties are said to belong to the same class. A landscape is a land area that includes a group of landpatches; whilst in sedimentology a deposcape comprises a group of depopatches, defined as areas with distinct sedimentary properties.

Landscape or deposcape composition refers to the sorts, magnitude and properties of patches whilst configuration specifies spatial location. These measures quantify attributes such as distribution of patch types relative to other patch types across an environmental boundary. These types of measures are important because environments, processes, and organisms are not isolated but are influenced by and linked to adjacent environments.

There are very many physical, chemical and biological controls upon landscape and deposcape composition and configuration. Denudation rates are controlled by altitude, relief, slope, rock type, climate, vegetation and sea level changes: all play some role in determining the course of landscape evolution into rock. But just how many of these concatenated controls may be isolated in the rock record? A key step is to have independent reliably-dated evidence for climate/vegetation change within the eroding landscape. Speleothem and calcisol studies have revolutionized our knowledge in this area over recent years. Another key is an accurate knowledge of the rate of tectonic evolution, in particular the evolution of fault systems that produce major changes to landscape altitude, relief and slope. Finally, there is the recognition of teleconnection, that is the often distant link between eroding landscape and downslope deposcape. The link here is highly complex because it depends on downslope transmission of water and sediment runoff in response to changing climate/vegetation. Consideration of the link through the fundamental equations of motion suggests that previous attempts to define equilibrium, i.e. neither erosion nor deposition, are erroneous.

These various developments will be discussed with reference to recently published work worldwide and from the evidence gained by the author and colleagues from Pliocene-Holocene landscapes and deposcapes in the eastern Mediterranean and SW USA.

Keynote speaker

The Stratigraphy Enigma Machine: Decoding Unique Solutions

Rudy Slingerland, Department of Geosciences, The Pennsylvania State University

It is a basic premise of this conference that a better knowledge of sediment routing systems and their teleconnections will allow us to answer questions like: 1) Does the state of the landscape (drainage networks, topography, relief) exert a fundamental control on rift architecture by modifying thermal/mechanical properties during rifting; 2) Is correlation of Andean volcanism with climate due to increased sediment fluxes to the trench causing increased melt rates; and 3) What fluvial and deltaic stratigraphy should we expect on a planet devoid of vegetation? Answers to many of these questions will come from stratigraphy properly interpreted, but there are many problems to be overcome. The first-order rate laws of sediment liberation, flux, and burial remain scandalously inaccurate. Leads and lags in the sediment routing system preclude using correlation in time to determine causation. To make matter worse the signals of tectonic subsidence, eustatic sea-level, and climate can be substantially overprinted by autogenic processes.

Overcoming these problems so that we can decode the sedimentary record for upstream dynamics is proceeding along two fronts: field analysis of well-controlled systems studied by groups of researchers with complementary expertise (such as the new GeoPrisms initiative at the US National Science Foundation) and modeling studies, both physical and mathematical. These efforts will be reviewed to highlight critical areas in need of concentrated research.

Identifying autogenic organization of surface processes in the stratigraphic record

Elizabeth Hajek, Pennsylvania State University Department of Geosciences
Kyle Straub, Tulane University Department of Earth and Environmental Sciences

Alluvial basins provide important records of climate and tectonic changes on Earth, as well as information about how land surfaces evolve under different boundary conditions. Over basin-filling time scales internally generated (autogenic) processes are typically assumed to be random, producing stratigraphic “noise” via relatively small-scale spatial and temporal variability. However, recent work has shown that autogenic dynamics in sedimentary systems can be structured over relatively long timescales, generating stratigraphy that mimics patterns produced by tectonics, climate, and eustatic change. The evenness or unsteadiness with which depositional systems move across and fill basins can impart fundamental structure into the stratigraphic record, which may be recognizable in some sedimentary deposits.

Here we present statistical analyses of natural and experimental basins that suggest autogenic signals from depositional systems can be identified in preserved stratigraphy. In physical experiments conducted at Tulane University’s Sediment Dynamics Laboratory and the St. Anthony Falls Laboratory, University of Minnesota, sedimentary systems exhibit autogenic organization under constant boundary conditions. In these examples, both the evolution of the deposit surface and resultant stratigraphy show nonrandom spatial/temporal structure. Using only stratigraphic patterns from the experimental deposits, it is possible to infer some aspects of characteristic surface process behavior in each run. The well-exposed Ferris Formation (Cretaceous/Paleogene, Hanna Basin, Wyoming, USA) also shows strong stratigraphic organization. Detailed sedimentologic analysis of this unit indicates that the observed stratigraphic patterns dominantly reflect autogenic depositional processes, despite having accumulated in an active Laramide Basin. Analysis of this deposit provides insight into long timescale landscape dynamics in an ancient basin.

The influence of uplift and rainfall on the sedimentary architecture of alluvial fans in physical models

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We present the results of an experimental investigation for the stratigraphic record characterization of a climatic and tectonic induced perturbation of a feeder drainage basin. Following the results of Bonnet and Crave (2003) which suggest that it is theoretically possible to differentiate between the climatic or tectonic causes of surface uplift from records of output sediment fluxes, we design an experimental device to test this proposition in the sedimentary signal.

The experimental device allows the study of a coupled erosion-sedimentation system at laboratory-scale under different rates of uplift and rainfall forcings, and throughout a perturbation of these controlling factors.

Results from our experiments demonstrate that fan architecture is a good archive for characterizing controlling factor forcing. A decrease in the rainfall rate (or an increase in the uplift rate) is recorded by an increase in the fan slope and the occurrence of some downlap geometries. An increase in rainfall rate (or a decrease in uplift rate) is recorded by a decrease of the fan slope and the development of some onlap, and possible toplap geometries. While this first distinction between onlap and downlap geometry has been performed, the bed and facies stacking pattern allows a discrimination of the forcing nature. While an increase in the uplift rate is characterized by a thickening and coarsening upward package, a decrease in the rainfall rate is characterized first by a thickening and fining upward package followed by a thinning and coarsening upward package.

In these experiments, the erosional perturbation induces a typical dynamic of the sediment supply (Qs) and thus of the ratio between the sediment supply and the water supply. It has a direct impact on the transport capacity resulting in a unique dynamic of the fan slope, apex aggradation, grain size distribution, bed’s thickness, frequency and facies stacking.

THEME 4: INTEGRATIVE STUDIES OF SEDIMENT ROUTING SYSTEMS AND THE PETROLEUM SYSTEMS

From sediment routing to fluid flow: turning doodles into digits

Mihaela Ryer, Dave McGee, Sam Hudson, Anton Wroblewski, Jeff Allwardt, Govert Buijs, Dominic Armitage

Successful hydrocarbon exploration and production depends on the ability to be predictive. Prediction must transcend qualitative description by utilizing quantitative tools, workflows, and approaches that allow us to maximize and apply all available data.

This presentation illustrates how process-based modeling tools predict sediment routing systems, the resulting three-dimensional sedimentary architecture, and facies distribution. A process-based, quantitative approach is used for predicting sedimentary environments by integrating data and knowledge pertaining to modern depositional systems, subsurface, outcrops, laboratory experiments, and numerical modeling tools.

A more quantitative and rigorous data collection and analytical approach is required to facilitate the building of data-constrained predictive models based on first principles. Appropriate sensitivity and uncertainty analysis that captures the complexity of the predicted systems is crucial. A set of case studies demonstrate workflows that integrate diffusion-based forward stratigraphic prediction with petroleum systems prediction. Two of the case studies, one at basin scale and one at prospect scale, are from a deep-water system with a mobile substrate, and a third case study is from a basin with very high rates of subsidence and sedimentation.

These case studies show the influence of accommodation, basin geometry and topography, sediment supply on the sediment routing, and impact of a high resolution, three-dimensional sedimentary model on petroleum systems prediction.

Keynote speaker

Analytical methods and interpretation of ancient landscapes in onshore-offshore correlation of source-to-sink systems: implications for prediction of basin fill

Ole J. Martinsen, Tor O. Sømme**, Allison K. Thurmond*, Jakob Skogseid**, Les Leith*** & Ian Lunt**
**Statoil Research, Norway*
***University of Bergen, Norway*

A new trend in earth sciences is integration between previously disparate fields in geology and geophysics into composite models that hinge on input from various data types. A common denominator in the outcome from the various fields and techniques is topography, a critical factor in understanding Earth Systems and for prediction of resulting deposition.

Ancient onshore catchments is a derivative of topography, and a major challenge in interpreting and predicting the fill of sedimentary basins is to understand the role of landscapes through time, and their size and ability to deliver sediments to offshore sedimentary basins. Recently, numerous authors have attempted to develop semi-quantitative and quantitative relationships that address this issue, both based on flume studies, numerical and experimental modelling and natural examples on various margins. A key issue in the challenge in natural systems is the degree to which ancient topography has been preserved because obviously, the higher the preservation, the more confident the assessment of offshore sedimentation. In the perfect case, major parts or all of an antecedent catchment is preserved, but in general, the older the source-to-sink systems, fewer parts of the system are preserved and this is particularly a challenge with the onshore catchments that is either eroded or only partly preserved. Several examples from onshore Norway (ancient Scandes) will be shown.

In the case where only the offshore stratigraphic record is preserved, modelling of antecedent topography can be performed through a proprietary process called *Predictive Earth Systems Modelling*. This process involves a rigorous and complicated procedure of creating a plate tectonic model, involves paleo-climate analysis and provides sediment yield calculations that eventually lead to a prediction of both the location of sediment entry points and volumes.
An alternative procedure is to perform inversion analysis of for example the volume and size of deepwater submarine fans using recently established 1st order, semi-quantitative relationship from a series of complete source-to-sink systems. Using this method, various characteristic features of the catchment can be modelled, such as its area, and thus provide a proxy understanding of the topography of the catchment. Building such empirical relationships is extremely important because many ancient landscapes are poorly preserved and yield highly uncertain interpretations of sediment yield to offshore basins.

The talk discusses the uncertainty of the various methods and forwards the view that previously disparate geological processes and methods now can be integrated in order to fully understand complete geological systems, their processes and products.

Role of Incised-Valley Systems in Source-to-Sink Sediment Routing and Storage: Examples from the Late Quaternary Northern Gulf of Mexico Margin

Mike Blum
ExxonMobil Upstream Research Company, Houston, Texas

Incised-valley systems form as fluvial systems extend across newly subaerial shelves to the shelf margin in response to sea-level fall. Recent work on Quaternary systems of the Gulf of Mexico margin illustrate how sediment supply might change over the course of a glacio-eustatic cycle, and how the evolution of incised-valley systems modulates source-to-sink sediment routing to deepwater environments.

First, empirical data that links sediment supply to climate suggests supply from the hinterlands should decrease during glacio-eustatic sea-level fall and lowstand due to temperature depression. Hence, supply from the hinterland may be (a) at a maximum when river mouths reside in highstand positions, and sediment storage takes place on the coastal plain and inner shelf, and (b) at a minimum when river systems are extended to the shelf margin lowstand shoreline and directly feeding the slope and basin floor.

Second, studies of Quaternary systems, where deposits can be mapped and dated independent of sea-level change, make it clear that incised valleys form in a step-wise manner in response to sea-level fall, with short periods of incision punctuated by extended periods of lateral channel migration, valley widening, and deposition of channel-belt sands. Step-wise incision and lateral channel migration is the process that both creates the basal valley-fill surface, as well as controls the dimensions of the incised valley, but the timing of incision and channel-belt deposition on the evolving valley-fill surface varies between river systems due to a variety of controls. The total volume of sediment exported during the period of incised-valley formation is a relatively small value compared to the ongoing flux from the hinterlands, and short periods of incision likely produce an insignificant amount. However, periods of lateral channel migration and valley widening significantly increase the export of sediment, perhaps by 25% over background rates, such that periods of fluvial deposition during sea-level fall and lowstand corresponds to increased sediment delivery to the shelf margin.

Finally, for low-gradient continental margins with broad shelves, like those of the Late Quaternary Gulf of Mexico, drainage basins merge as channels extend across the shelf, which in turn increases drainage areas that contribute to single point sources at the shelf margin. Apparent signals of increased or decreased flux of sediment to the shelf margin and beyond may reflect geomorphic response to sea-level change – the merging of drainages as they transit the shelf – rather than changes in supply from the hinterland.

Keynote speaker

Stratigraphic Forward Modelling in Hydrocarbon Exploration: Visualization, Scenarios and Numerical Experiments

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The earliest stratigraphic forward models (SFMs) applied to hydrocarbon exploration were developed during the 1980s and formed an important element in developing the early sequence stratigraphic conceptual models (e.g. Jervey et al., 1988). Since then models have increased in sophistication, and debatably also increased in realism. The latest generation of 3D models are moving closer to being process-based representations of depositional systems and span siliciclastic and carbonate deposystems formed in environments ranging from terrestrial to deep-marine.

Three basic approaches now exist for application of these latest generation SFMs to hydrocarbon exploration; best fit models, preferably generated using a quantitative inversion process (e.g. Charvin et al., 2009), scenario 46odeled46 (e.g. Burgess et al., 2006) and experimental 46odeled46. In general and despite this development, SFM methods and models remain an immature technology, with only very limited predictive power. Their most useful contributions are still in the realm of numerical experiments illustrating how sedimentary systems might work and helping to develop new depositional and play concepts.In this context, numerical experiments conducted with SFMs have made some useful contributions to hydrocarbon exploration.

In terms of sediment routing in siliciclastic systems and the impact this has on development of reservoir, seal and source rock elements of petroleum systems, stratigraphic forward models have made an important contribution by demonstrating how variable sediment supply may arise and is likely a significant control. Related to this, recent 46odeled46 has demonstrated potentially significant relationships between accommodation and supply and siliciclastic shelf or topset width (Burgess and Steel, 2008), with some important implications for sediment bypass and development of deep-marine siliciclastic systems.

In understanding the large scale controls on carbonate platform type and petroleum system elements, recent numerical experiment work (Williams et al., in review) has shown how sediment transport is a more dominant control on carbonate platform architecture than is the type of water-depth production profile. Mapping of 46odeled platform geometry in a multidimensional parameter space suggests a continuum of platform geometries rather than discrete classes, and raises the challenge for quantitative carbonate facies prediction from a next generation of carbonate SFM. On a smaller scale in carbonate strata, numerical experiments are making progress in understanding and explaining how lithofacies thickness distributions observed in outcrop and subsurface strata may link to planform lithofacies distributions. Model experiment are also providing insight into what the influence of various controlling factors such as relative sea-level oscillations and sediment production rate variations might be.

Poster presentation abstracts

THEME 1: THE EROSIONAL ENGINE

Hydrogeological hazards and their consequences in the area south of East African Rift Albertine Rift, Eastern R.D.Congo, North Kivu.

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The East African Rift extends over 6000km from the Afar Triple 119 Junction in Ethiopia to offshore Mozambique, forming the divergent boundary 120 between the Nubian and Somalian plates (Maasha et al., 1972; Ebinger, 1989; Stamps 121 & al., 2008; d'Oreye Nicolas, 2010). Since May 1997, we witness the intense development of hydrogeological risks in the southern East African Rift (Rift Albertin). These risks include soil erosion and landslides accompanied by a high sedimentation in the shallows of uplands.

The main soil erosion and landslides best known in this region are:
- The landslide in Municipality of Cimpunda Kadutu, Institute Kasali, Bukavu, South Kivu, in 1965.
- The landslide of Mumosho on 1972, an entire village slid into the Ruzizi river
- The landslide of Uvira on1986.
- The Landslide in Municipality of Bagira, Bukavu, South Kivu on 31st May 1997
- The landslide of Murhala Katana in Kabare region, Southern Kivu on 1997.
- The landslide of Muhungu, in Bukavu town, South Kivu, 28th April 1998.
- The landslide of Mweha Nyabibwe, in Kalehe region, South Kivu in 2000.
- The landslide of Uvira and Minova, South Kivu on 2005.
- The landslide Kibiriga-Kibumba, in Rutchuru region, North Kivu, on 15th May 2010.

All these risks are classified hydrogeological major natural disasters experienced in the region, following the enormous materials and human health risk they cause. The investigations made that their main issue in this area is the recent seismic activity observed in this part of the East African Rift (Munyololo Wa Yemba & al, 1997).

This fact was also confirmed by the local people because they usually felt the earthquakes and a few days later, during heavy rainfall, there are consequently significant erosion and landslides of earth. All the earthquakes associated with the hydrogeological risks were recorded at the seismographic stations of Lwiro and them of Goma Volcano Observatory.

On 15th May 2010, three earthquakes preceded the landslide of Kibiriga Kibumba. The first earthquake took place at 16 hours 35 minutes 53.4 seconds and the second at 21 hours 11 minutes 13.7 seconds and the third at 10 hours 34 minutes 12.09 second. These earthquakes are recorded by five functional seismograph stations of Goma Volcano Observatory. These stations are Rusayo, Bulengo, Goma, Luboga and Kibumba. These stations are not very far from Kibiriga where the landslide took place.

This intense seismic activity is in turn due to the reactivation of faults in this part of the East African Rift. Earthquakes associated with the recent landslide of Kibiriga, are observed on the seismograms of tectonic origin. The rate and magnitude of landslides in the southern East African Rift depend on the following factors. the intensity of rainfall, runoff, susceptibility to erosion, gradient and slope length, vegetation and human activities on the environment such as deforestation and intensive subdivision on steep slopes.

For these hydrogeological risks, it must:
-Estimation of risk of erosion and landslides based on a multidisciplinary approach: geodesy, geology, hydrogeology, mechanical and geotechnical engineering.
-Establishment of hazard maps and risk in the area of ground movement.
-Prevention of natural hazards from monitoring systems (with geodetic) and assist in the decision on the plans and evacuation of people.

Landscape resistance: using drainage networks as deformation markers

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Fluvial networks determine to a large extent the structure and geometry of erosive landscapes in mountain ranges. As a consequence it is fundamental to understand how they develop and evolve in order to reconstruct and predict landscape evolution. A particularly important issue is the degree to which fluvial networks evolve and change through their existence.

Two end members can be invoked:
On one hand, river networks are very dynamic, changing and reorganizing frequently during orogen evolution. In this view, landscapes mostly reflect the present state of the tectonic forcing, with a minor component of “memory”. This has found support in a variety of observations like wind gaps, hanging valleys, sinuous shape of water divides, inferred changes of detrital sources that all evoke river captures and drainage network changes, and are reproduced in some analogue and numerical models.

On the other hand, river network can be viewed as largely resistant to deformation and change, thus potentially acting as useful passive markers of the crustal strain.

Some notorious examples are antecedent rivers and drainage systems cutting through lithological and geological structures (folds and faults), drainage systems extending behind the main drainage divide in large mountain ranges, and preservation of superficial cover rocks adjacent to valleys deeply incised into the basement. Spectacular plane deformation of large river basins also points to the large resistance of river networks to deformation and their difficulty to reorganize, especially when relief is high and / or increases [*Hallet and Molnar*, 2001]

Based on natural examples of tectonically deformed drainage network in the European Alps and Southern Alps of New Zealand we address two fundamental questions:

What are the required conditions for a drainage network to be used as a marker of the deformation?

How much deformation can record a given drainage network? Does this depends and strain rate and potential erosion rates?

It appears that drainage network can be used as strain marker if i) the initial shape of a drainage network can be constrained, and ii) the ratio between erosion and deformation allows the strain to be recorded without dramatic change (e.g. piracy). Large rivers can record more deformation than small ones, for similar strain rates. Finally, this shows that incision of the rivers (i.e. increase of the relief) makes the network more stable (and therefore more suitable to record deformation).

Hallet, B., and P. Molnar (2001), Distorted drainage basins as markers of crustal strain east of the Himalaya Journal of Geophysical Research B: Solid Earth, 106(B7), 13697-13709.

Alpine glacial topography and the rate of rock column uplift: a global perspective

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The study presented here investigates the influence of alpine glacial erosion on the morphology and relief distribution of mountain regions associated with varying rock column uplift rates. We have taken a global approach by analysing the surface area distribution of all mountain regions affected by glacial erosion between latitudes 60^o S and 60^o N.

Most surface area in glaciated mountain ranges is concentrated below the modern snowline as predicted by the glacial buzzsaw hypothesis. Above the modern snowline, the analysed mountain regions all exhibit an exponential decay in their topographic distribution. On the basis of this decay, the analysed mountain regions fall within three distinct groups, which we suggest primarily reflects variations in average values of rock column uplift rates. Mountain ranges affected by rapid rock column uplift display high above-snowline relief and large decay lengths, whereas inactive orogens with only isostatically driven rock column uplift have little relief above the modern snowline. We find a surprisingly simple relation between the hypsometry of glacial landscapes and regional tectonic activity.

Erosion dynamics modelling in a coupled catchment- fan system with constant external forcing

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Recent alluvial fan models have suggested that deep alluvial fan entrenchment could occur without any change in sediment and water influx. Moreover, other studies have shown that the evolution of a fan could strongly depend on feedback between the fan and the mountain catchment. We evaluate if natural entrenchment still occurs in a coupled catchment-fan system, and we evaluate its possible impact on the evolution of mountain erosion. We use a landscape evolution model where the mountain corresponds to an uplifting block and where fans form over an initial horizontal surface. Our experiments confirm that deep entrenchment at the fan apex can occur without a change in climate or in uplift rate under two conditions: (1) the transport threshold (critical shear stress) is significant and (2) the downstream boundary condition corresponds to an open boundary with fixed elevation, which stops the progradation of alluvial fans.

A stable entrenchment occurs when sediments reach this limit. The entrenchment can be explained by a strong dependence of the transport law on the slope when the shear stress is close to critical. A fan slope increase occurs when sediments reach the model limit, and this drives entrenchment. Fan entrenchment drives a strong erosion in the mountain with an intensity and a response time similar to those observed for the initial mountain uplift. These results indicate that determining how much of natural erosion is from autogenic mechanisms is essential in order to link landscape entrenchment with past external changes.

Comparing long term deformations and short term fluvial response at the hanging-wall of an active low angle normal fault in the Northern Apennines of Italy.

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The Northern Apennines of Italy are characterized by the interaction of three main morphogenetic processes which affect the rivers incision: a regional uplift in the order of 0.5 mm/yr; climatic/eustatic changes and active tectonics. While the first two can be considered quite uniform at a local scale, the tectonics effects change depending on whether we observe an uplifted or a lowered block.

We investigate the inteference between uplift and extensional tectonics along the hanging-wall of a low-angle NE-dipping normal fault (the Altotiberina fault -ATF) in the Northern Apennines of Italy. The fault is active since the lower Quaternary. Microseismic surveys and geodetic measures have higlighted that the fault is presently active at 2.5 mm/yr rates. The long-term offset distribution indicates that the fault is continuous for 60 km and it is the detachment of smaller splays the youngest of which border the Quaternary Tiber valley. The ATF splays have driven the Quaternary evolution of three thresholds-separated continental basins (1000 m of infill). Within these basins we identify three depositional cycles from early to late Pleistocene evolving from clay-dominated sediments to conglomerates and sands, up to heterogenic deposits. The Quaternary deposits distributed along the Tiber valley are deformed by the ATF splays and are deeply incised by the Tiber river.

To evaluate the incision distribution, we made a geological/geomorphological mapping of the river terraces through aerial-photo interpretation and field investigations.

We find that the Tiber river behaviour is not homogenous and the rates of incision varies downstream. The northwestern basin is pretty flat with little or no incision, while the southeastern basins are characterized by two orders of well-recognizable fluvial terraces resting on top of the Quaternary deposits up to 250 m of elevation. One of these surfaces, containing a travertine has been dated through U/Th yielding an incision rate of 0.4 mm/yr.

We interpret the along strike changes of Tiber river incision as the result of the interference between the regional uplift and the local extensional tectonics. Within the competence between these factors, the northwestern sub-basin appears to be dominated by local subsidence. This is due to the fact that the basin bounding normal faults are vigorously active and the hanging-wall subsidence overcomes the regional uplift.

On the other hand within the southeastern sub-basins, uplift dominates on the foot-wall subsidence promoting river incision.

Erosion in the semiarid Chilean Andes over 10 yr, 10 k.y. and 10 m.y. time scales

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We compare the erosion rate at different time scales in the Huasco watershed basin, located in the semiarid Andes of Northern Chile (29°S). We calculate decadal erosion rates from modern sediment yield, millennial erosion rates (k.y.) from ^{10}Be concentration in fluvial sediments, and long-term erosion rates (m.y.) through geomorphological quantification of valley incision and pediment diffusion (Figure 1). Decadal erosion rates range 4 - 11 m/m.y. is small in relation with range of millennial and million-year time scales. Millennial erosion rates range 12 – 44 m/m.y. (mean 27 m/m.y.). Two erosion rate clusters can be interpreted as two different velocities and mechanisms in the watershed dynamic: valley incision (30 - 44 m/m.y.) and diffusion on pediments (12 - 14 m/m.y.). Long-term erosion rates show two different periods. Valley incision during the last 6 m.y. yields larger erosion rates (34 – 57 m/m.y.) than the former pedimentation period from 17 to 6 m.y. (5 – 30 m/m.y.).

Millennial erosion rates in incising valleys are similar to erosion rates calculated for the valley incision during the last 6 m.y., while millennial erosion rates in pediments under diffusion processes are more consistent with decadal erosion rates and erosion rates calculated for the pedimentation period. These similarities in erosion rates for different time scales suggest a relatively constant erosion rate during the last 6 m.y., and the geomorphological disconnection between valley and pediment evolution. In fact, pediments preserved on interfluves indicate a transient stage of landscape evolution resulting from differential velocities and mechanisms of erosion in the Huasco watershed.

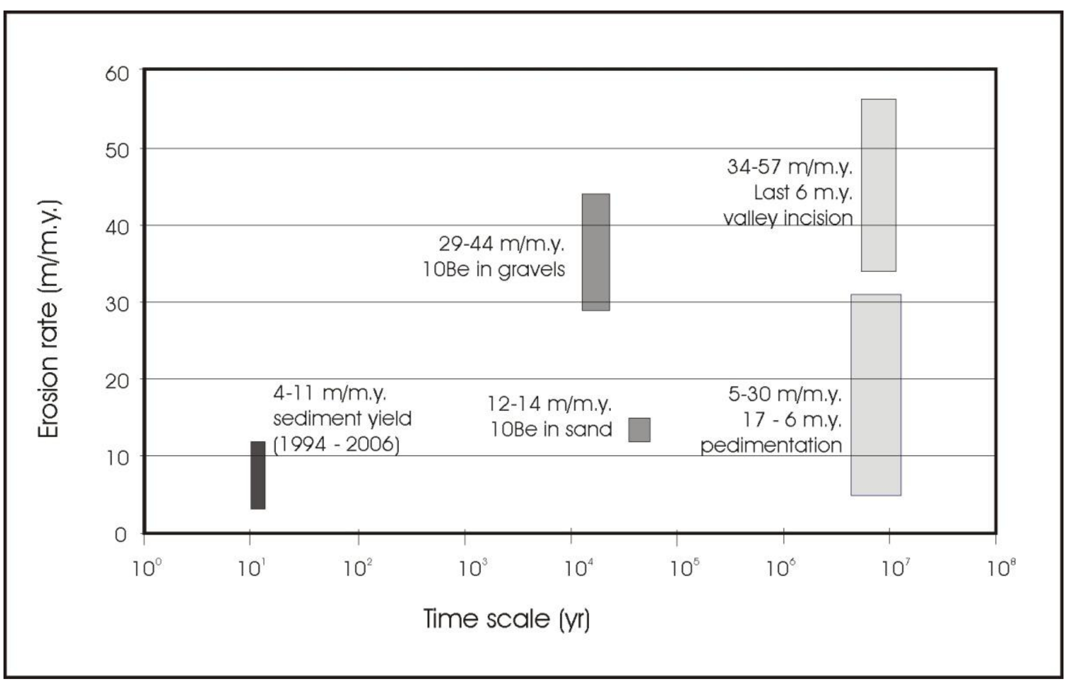

Figure 1: Erosion rate at different time scales in the Huasco watershed basin. Rectangles delimit ranges of erosion rates and time scales. Decadal erosion rates consider different areas of watershed basin and sediment yield calculated by Pepin et al. (accepted). Millennial erosion rates were calculated from the ^{10}Be concentration in gravels (4 samples) and sand (2 samples). The calculus considered production rate of 4.5 $at*g^{-1}*a^{-1}$ to sea level and high latitude, half-age of 1.36 m.y. (Nishiizumi et al., 2007), rock density of 2.700 $kg*m^{-3}$, and the equations of Braucher et al., (2003). Million-year erosion rates were calculated from quantification of valley incision with the Black Top Hat function (Riquelme et al., 2008) and Ar-Ar ages of volcanic rock (Bissig et al., 2002).

Origin of martian valleys: some highlights by geomorphic and hydraulic properties.

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The Mars valleys analysis is a crucial point for arguing the presence of liquid water on Early Mars (~ 3.5 Gy). Many studies indicate a strong analogy between earth and mars networks (dendritic organization, drainage density Strahler ordering).

Here, we study the downstream convergence of flows in rivers suggesting a stability of liquid water in the drainage network. This method lies on the relationship between the increase of width (W) versus the discharge of the river or the upstream drainage area (A) such as $W= bA^{0.5}$ (e.g Leopold and Maddock, 1953; Montgomery and Gran, 2001). On Mars, the extraction of the drainage area is problematic, so we have derived this relationship with the length of the river (L) in order to test a width-length relationship. With this approach, on Earth, by using the Hack relation $L=cA^{0.5\text{-}0.6}$, the previous relation becomes $W=\beta L^{\alpha}$ with $\alpha \sim 1$.

On Mars, we have plotted at the outlet of 150 valleys their lengths (between 10-1000 km) and widths (between 0.5-80 km) which indicates a global increase of the width-length ratio but with a very high dispersion of data. This dispersion is mainly correlated with the depth of the valleys and their topographic localization. The valleys are divided into two categories of depth (1) an uniform maximum depth of 250 m (2) varying depths but still above 300 m.

The first categories of valleys show no particular width-length relationship and represent flow that are established on roughly rectilinear slopes. Absence of enlargement with length suggests a process of non convergence of downstream flows. The global maximum depth of 250 m suggests either (1) a global paleo base-level that constrained this depth or (2) a threshold in erodible thickness due to particular erosive processes.

The second categories of valleys are in good agreement with the width-length relationship and represent flows that are established on non-rectilinear slopes with a clear escarpment near the outlet. Their width-length relationship such as $W=\beta L^{\alpha}$ with $\alpha \sim 0.3$ suggest a convergence of downstream flows (but with a lower exponent compared to Earth) combined with regressive erosion due to association of runoff and groundwater processes.

To conclude, we propose that shallow valleys correspond to non-permanent runoff processes while deep valleys correspond to more permanent groundwater processes.

Leopold, L. B. and T. Maddock (1953). "The hydraulic geometry of stream channels and some physiographic implications." United States Geological Survey Professional Paper 252: 1-57.
Montgomery, D. R. and K. B. Gran (2001). "Downstream Variations in the Width of Bedrock Channels." Water Resour. Res. 37(6): 1841-1846.

Depositional response of the Rhône dispersal system to accelerated Pliocene erosion of the Alps

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A combination of sediment volumes, bedrock thermochronology, and foreland basin inversion, have been used to demonstrate that the western Alps experienced accelerated erosion rates from Pliocene times onward. This project uses detrital thermochronology, provenance techniques and seismic analysis to test the sediment response of the Rhone dispersal system to the proposed changes in source area erosion rates.

Heavy mineral analysis combined with U-Pb dating of detrital zircons indicates that the source areas of the Rhône system since Miocene times have been dominated by the external Hercynian Massifs of the Alps as well as the more internal high grade terrains such as the Lepontine Dome; there is a dominance of reworked sedimentary cover as opposed to directly sourced basement Massifs as exposed today. Detrital apatite fission track analysis from Lower Miocene through to mid-Pliocene successions show a progressive increase in lag time between the depositional and the thermochronological ages. This suggests a slowing in long-term exhumation, and hence erosion rates that is typical of late to post-orogenic mountain ranges. However, the transience in the lag times between a forcing and the recorded signal is given by the depth to closure divided by the new exhumation rate; hence, early Pliocene forcings won't be recorded in the stratigraphic record until mid to late Pliocene times at the earliest. New data that compares modern river apatite ages with the stratigraphic record will test these predictions.

The sedimentological record from the Rhone valley indicates an increase in coarse conglomeratic sediment released from the western Alps from approximately 20 Ma into Pliocene times. Additionally, isopach data from the deep-sea fan indicate a post-Messinian pulse of high sediment accumulation rates that are then sustained at high levels to the present-day. Overall, the results suggest accelerated unroofing of the western Alps from Miocene into Pliocene times with sediment sourced from the erosion of the sedimentary cover as opposed to basement massifs that are presently exposed. Importantly, the transience in detrital thermochronological lag times must be taken into account when attempting to define a particular change in erosion rates.

Temporal calibration of fluvial sequences in the Makran Range, SE-Iran

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A relatively high sediment flux occurs at the offshore Makran active accretionary wedge. Intensified monsoons, associated with higher precipitation and runoff lead to tremendous flash floods, have been suggested to be the most important agent for transmitting sediments from the continent to the sea. This flux – amongst others, such as remobilization and distribution - influences the style and rates of deformation of the accretionary wedge complex.

The Makran Range is located in a critical area of various climate systems (SW- and NE-monsoon, Mediterranean) with profound shifts of the ITZC and associated rainfall systems. Fluvial and alluvial sequences are abundant in the lower Makran Range but little is known on the driving forces, rates and timing of those fluvial processes due to unknown absolute ages.
We focus here on fluvial and alluvial sequences in tectonically separated basins of the lower and higher Makran Range. They have been deposited probably in the Pliocene/Quaternary, based on stratigraphic classification. These sequences provide key information for understanding the climatic (e.g., monsoon) and tectonic processes (e.g., uplift) occurring during the ongoing accretionary wegde formation.

We employed terrestrial cosmogenic nuclides (TCN, ^{10}Be, ^{21}Ne, ^{36}Cl) of amalgamated clast samples to establish terrace abandonment chronologies of strath terraces. Those terraces are deposited onto Oligocene-Pliocene flysch/turbiditc sequences, cut by erosional unconformity and covered by a gravel fill of a only few meters. Age chronologies are biased by large uncertainties in ^{21}Ne ages due to low cosmogenic ^{21}Ne excess over atmospheric neon (a result of low TCN production rates), while ^{10}Be measurements are with sufficient precision acquired (^{36}Cl currently processed). Minimum abandonment ages from terrace and alluvial sequences range from ~250 ky to modern (modern wash as a measure for inheritance). Cluster of ages occur during wet phases, but not exclusively, and do not tend to be specifically located at either the beginning or end of more pluvial phases. Furthermore, our data suggest that events of terrace formation are roughly coeval between basins. Although suggested, a genetical relation and connection of those fluvial sequences to coastal terraces and wave-cut platforms is problematic due to ambiguous ages and obscured stratigraphic linkage.

Preliminary incision rates derived from strath terraces are on the order of 0.5-1 mm/yr with non-steady intervals. This in turn is well in the range of uplift rates deduced from coastal terraces.

The effect of fluvial, glacial or fluvial-glacial landscape imprint on catchment wide denudation rates

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The northern foreland of Switzerland has been occupied by glaciers during the last glacial maximum (LGM) with only a few highs remaining ice free or only covered by local ice (e.g., Napf, Hörnli). Landscape form of this particular regions show evidence of this glaciated and non-glaciated parts, commonly in terms of surface roughness, depth of incision, valley widths, mean slopes or elevations.

We have studied the Hörnli area in detail in order to test the effect of landscape imprint on modern and medium term denudation rates (catchment wide denudation rates by cosmogenic nuclides, TCN). Some topographic parameters separate glacial and non-glacial (fluvial) landscapes, whereby glaciated catchments have usually lower mean slopes, are at lower mean elevations and have a lower hypsometric integral compared to fluvial catchments. Furthermore, non-lithological controlled knickpoints in the glacial or mixed fluvial-glacial catchments are evidencing rejuvenation of the glacial imprint and transition to a modern fluvial regime.

Catchment wide denudation rates by TCN are constantly (2-5 times) lower for glacial or mixed fluvial-glacial catchments compared to sole fluvial catchments. Catchments with a transition from headwater-fluvial to downstream–glacial imprint show decreasing denudation rates, while sole fluvial do not show such a pattern.

Furthermore, variability in TCN-denudation rates of fluvial catchments is much greater than compared to the glacial or mixed fluvial-glacial catchments, a variability typically observed for small sized catchments (<30km^2). On the other hand, in the fluvial catchments, no distinct correlation of topographic parameters with denudation rates is observed. We propose that two mechanisms may cause the heterogeneous pattern of denudation rates between fluvial, glacial or mixed fluvial-glacial catchments. On the one hand, catchments with smoother topographies and accumulated glacial deposits in their lower reaches protect the landscape against faster erosion rates.

Another option would be that glacially sourced sediments of the catchment with relatively higher cosmogenic nuclide concentrations (due to post LGM-exposure) control the lower denudation rates. Additionally, the fluvial catchments, with steeper slopes and exposed at higher elevations are controlled by more active processes (shallow landsliding, rock falls, debris flows, little soil development) which would promote shorter residence time of sediments in the catchment, hence higher denudation rates.

As such, glaciated or mixed fluvial-glacial imprinted catchments seem to buffer TCN-derive catchment wide denudation rates, specifically if the glacial imprint has been a while ago. Little Ice Age imprints may cause the opposite for TCN denudation rates, being higher due TCN-under-saturated sediments produced.

The influence of surface and tectonic processes in Late Miocene-Quaternary landscape evolution of Western Alps: a quantitative geomorphological analysis

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Key words: morphometry, Western Alps, topography, mountain chain evolution

First-order topographic features in a tectonically active landscape including relief, drainage patterns, and stream gradient slope represent ways to quantitatively characterize the interaction between tectonics and geomorphology, providing a basis for modelling landscape evolution. We analyzed the topographic features of the Western Alps, a double vergent mountain chain, thought to be a post-orogenic collapsing belt as neotectonic, seismotectonic and geodetic data suggest.

Moreover, AFT data show high cooling rates during latest Miocene-Pliocene final synchronous exhumation of the External Crystalline Massifs, but also provide evidence for diachronous Neogene evolution along and across the internal arc. In this work we show the morphometric analysis that has been carried out in the Western Alps, focussing on local relief, swath profiles, drainage pattern, and stream longitudinal profiles. Our main data source is a ca. 1 km pixel size DEM (GTOPO30), whereas bedrock erodibility and denudation rates are taken from literature. Our results reveal that both lithology and tectonic structure are the main factors ruling the topography and drainage pattern of the study area. Nevertheless the high values of concavity and steepness indices of the stream long profiles suggest a strong influence of glacial erosion as well as uplift rates. The regional water divide tends to migrate W-wards.

Such a migration is consistent with the faster uplift occurring in the external arc prevents the regressive erosion of French rivers. The axial sector of Western Alps is characterized by a low local relief that is interpreted as a record of a previous gentle topography now almost completely eroded and testified by the position of peaks at about the same elevation. This smoothed landscape may be related to different processes and genetic environments occurred before the post-Miocene uplift of the chain.

Finally, an integrated geological, morphological and morphometric study of the lower Sesia R. valley (Piemonte, Italy) allowed to reconstruct the 0.8 Ma stream long profile, and to calculate an incision rate of 0.2 mm/yr for the Middle Pleistocene-Present interval. This value is compatible with the sedimentation and erosion rates inferred from the surrounding areas.

THEME 2: DYNAMICS OF SEDIMENT ROUTING SYSTEM

The role of climate dependent regolith production rate on fluvial evolution

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Streams on the Andean margin in western Peru flow from a high elevation plateau, locally known as the Meseta, over a knickzone and down through a system of ca. 1000 m-deep gorges and >100 m-high cut-and-fill river terraces to the Pacific Ocean. A distinct orographic precipitation gradient with annual rates of more than 800 mm/yr on the Meseta decreasing rapidly to near 0 mm/yr at the coast over a distance of ~80 km length is reflected by a general downstream decrease in soil thickness ranging from several meters on the Meseta, to bare bedrock beneath the knickzone. The strong precipitaiton gradient also makes the sediment transport and delivery system in the Western Andes in general and the Pisco River in particular extremely sensitive to climate variables. Multiple cut-and-fill terrace sequences have been identified and dated in the Pisco Valley (Steffen et al., 2009). The age of the valley-fill shows that wet climates result in debris flow derived-sediment pulses from the hillslopes, leading to accumulation of sediment on the valley floor. Steffen et al. (2009) suggested that the change from accumulation to incision was associated with a nearly complete stripping of soil and regolith from the hillslopes as opposed to a return to dryer conditions.

We develop a coupled 1D sediment reservoir-transport model in which sediment production on hillslopes scales with physical (soil depth and erosion rate) and climatic (ambient temperature and precipitation rate) parameters and is calculated using a combination of established soil weathering and production functions (White and Blum, 1995; Heimsath, 1997).

Fluvial transport capacity is modeled using bed shear stress and is related to precipitation patterns through the discharge (e.g. Tucker & Slingerland, 1994). Model results suggest that differences in climate-controlled regolith thickness and soil production on hillslopes can explain the fluvial evolution of streams in western Peru. Zones of thick regolith cover related to high precipitation rates act as sediment sources, while further downstream, where precipitation rates are lower, regolith cover is thin to absent. The stream adjusts to these changes by exhibiting enhanced erosive power where sediment supply is reduced while shear stress continues to increase, resulting in parallel knickzone retreat. The model also implies that climate-driven shifts in soil production and hillslope sediment transport results in strong variations in ratios between sediment loads and transport capacity. This explains the accumulation of sediment and subsequent incision, leading to the formation of cut-and-fill terraces.

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Source-to-sink analysis and submarine landscape evolution across the Strait of Messina, Italy

Rajasmita Goswami, N. C. Mitchell and S. H. Brocklehurst (University of Manchester) and A. Argnani (Council of National Research, Bologna, Italy)

Submarine continental slopes are characterised by a variety of scales of landforms, from rills and gullies to large canyon systems, but how these features develop is still not well understood. The coasts of NE Sicily and SW Calabria are uplifting moderately rapidly resulting in narrow shelves. Some obvious connections between the rivers and their adjacent submarine counterparts avoid the complexities of sediment transport across broad shelves in other settings.

The long term fluxes of sediment carried by streams to the sea are assessed from uplift rates and from landslide occurrences. A marine geophysical dataset, including multibeam bathymetry and chirp data, was collected reaching to within 100m water depth around the coasts. Local relative sea level during the Last Glacial Maximum is estimated to have been depressed by 120m, so the marine data includes areas that were exposed at this time.

This allows an assessment of sediment transport paths during glacial times. Spectacular underwater landscapes are observed in the geophysical data, including rills, gullies and deeply incised canyons. Topographic analyses reveal that submarine channels lying offshore of large rivers are characterised by canyons with broad channels and graded-like longitudinal profiles.

Channels that lie offshore small rivers have small relief with steep longitudinal profiles. The rugged topography that may have been dissected during low stands appears to be maintained in present high-stand conditions. Only a few patchy deposits are observed on the inter-channel ridges, which are controlled by channel location through its influence on turbidity current pathways. Some of these turbidite deposits have been reworked by contour currents during the present high stand stage. Entrenchment by down slope sediment flows causes undermining of and slumping in the canyon walls. Gravitational processes may also be triggered by earthquakes, given the neo-tectonic setting. Our findings suggest that sediments delivered from the adjacent land might be the ultimate driver for these landscapes by supplying erosive sedimentary flows.

Landscape Evolution and Geodynamic Reconstruction of the NeoTethys Region from Cretaceous to Recent.

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The landscape evolution of the Mediterranean has been reconstructed through the geodynamic and palaeoenvironmental mapping of the NeoTethys for the 32 stages of the Cretaceous to Recent. This time interval marks the closure of the NeoTethys and subsequent Alpide orogeny. The geodynamics of NeoTethys is very complex with numerous small plates and blocks and several phases of rifting and compression.

The results have major implications for understanding depositional systems and source-to-sink relationships across the NeoTethys region. In addition, these maps are designed to be the boundary conditions for climate and oceanographic modelling.

Our initial baseline model was that of Stampfli et al., (1998, 2001), which is one of the most commonly cited plate models for this region. Geological data was then added on to the basemaps based on a thorough survey of the literature. This data is used to develop the palaeoenvironmental reconstructions which represent the contemporary base-level with areas of deposition (below base-level), and areas subjected to erosion (tectonophysiographic terranes). An iterative process of mapping and plate modelling was undertaken to make changes to the plate model to fit observed geology, this is because the NeoTethys is a complicated region with overprinting from repeated extension and compression. The use of a rigid plate solution adds further spatial complications. GETECH's updated model now shows similarities to that of Schettino & Scotese, (2002).

Palaeo-DEMs were then reconstructed for each stage together with the large scale palaeo-drainage. This is based on an analysis of the link between elevation and tectonics using the generated base-level maps. All calculations were made in ArcGIS. The grids created can be quantitatively manipulated, which allows the user to account for geological history.
In this presentation we show six key time-slice maps using the GETECH plate model from the Cretaceous and Tertiary periods. The stages shown have been selected as they show important changes in the structural regime, palaeoenvironments and basin evolution. These times therefore reflect the major changes seen in the regional landscape and provide a unique opportunity to quantitatively calculate source to sink relationships due to the changes in topography, drainage, and denudation rates.

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A Rift-scale Analysis of Present-day Sediment Routing Systems and Their Evolution Through Time, Gulf of Suez, Egypt

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The Oligocene-Miocene Suez Rift is well studied in terms of syn-rift stratigraphy and petroleum systems, yet relatively overlooked in terms of geomorphic analysis. The excellent exposure in the region is ideal for both the remote sensing and Digital Elevation Model (DEM) analysis utilized in this study. By identifying weathering style, regional drainage and palaeodrainage, this study assesses the first-order controls on the location and size of sediment sources and the evolution of sediment transport pathways in the Gulf of Suez.

The Suez rift consists of large-scale half-grabens which alternate in polarity along strike. Within these classic half-graben geometries is a complex pattern of smaller tilted fault blocks which display variable throws and dimensions. Where uplifted footwalls expose the heterolithic pre-rift stratigraphy, a characteristic drainage pattern is observed. Preferential erosion of the weak Cambrian-Cretaceous Nubian sandstone forms a linear, fault parallel depression between the more competent Precambrian basement and Eocene limestone. Due to the angle of bedding this 'intra-footwall trough' adopts the geometry of a half-graben and displays both transverse and axial drainage. In terms of sediment routing, this is significant because firstly, the 'weathered out' footwall provides an additional sediment source, and secondly, sediment sourced from the centre of a fault segment may be delivered axially to the fault tip, or where a cross-cutting structure or antecedent river provides a more proximal route to the basin.

Regional-scale drainage analysis identify the dominant control of syn-rift structures on the orientation of present-day sediment transport pathways and highlight the influence of pre-rift structural features, such as basement shear zones and the Wadi Araba anticline, in the formation of anomalous orientation and large drainage basins. Finally, the mapping of geomorphological features such as windgaps and misfit valleys give indications of drainage reorganisation through time and allow reconstruction of palaeodrainage. The combination of fault-block weathering style, regional drainage patterns and palaeodrainage shown by this study, provide valuable insights into both structural and lithological controls on the present-day sediment routing systems as well as their evolution through time.

Morphometric parameters and catchment wide denudation rates in catchments affected by crustal bending.

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We analyzed morphological parameters of catchments (e.g. Rio La Paz system), which incise the virtually flat Altiplano with its Mio-Pliocene fluvio-lacustrine deposits and volcanics, and drain into the Subandean zone by cutting transversely the Eastern Cordillera. Subbasins with high erosion rates in the Rio La Paz system are located close to the Cordillera, whereas subbasins with low erosion rates are located in immediate vicinity of the Altiplano.

However, we do not recognize a correlation of mean slopes and mean relief in the subbasins and their respective erosion rates.

To investigate the feedback mechanism between erosion rates and surface morphology in more detail we conducted a study on the subbasins. The higher erosion rates correlate unexpectedly with a lower Hypsometric integral, widely used to infer the stage of maturity of a basin. Further analysis concentrates on parameters derived from the channel network. Particularly parameters like Steepness index (k_s) and Specific Stream Power (SSP) reveal the focus of erosion within the studied catchments. These spots of enhanced erosion coincide in general with the parts of the rivers, where mixed channel or bedrock incision is observed, mainly where the channel length profile show knick points. A spatial analysis of the geological properties detects those knick points induced by structures (faults and folds) and changes in lithology.

We will demonstrate that the TCN results from the interior parts of the Rio La Paz catchments correlate only to certain extend with the surface morphology within the catchment. However, including the erosion rates and morphometric parameters from the catchments on the Altiplano, the correlation spanning data from both landscapes is obvious. This implies that the effects of feedback mechanisms between erosion and lithospheric deformation are substantial at the scale of individual structures where the morphometry of catchments and channel morphologies are modified. Which erosion processes (e.g. headwater expansion by landsliding and / or fluvial incision) is dominant might be influenced here by tectonics and consequently cause the spatially variable erosion rates and different surface morphologies and therefore the partly inconclusive correlations.

Sediment budget of a synorogenic sediment routing system, the Escanilla Formation, South Central Pyrenees

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The Escanilla Formation is the depositional product of a middle-late Eocene to Oligocene sediment routing system that was sourced primarily from the Axial Zone of the Spanish Pyrenees and was deposited on top of the active fold-thrust belt of the Southern Pyrenean pro-wedge. The sediment routing system from source to sink is 300 km long and extends from the Tremp-Graus and Ainsa basins and stretches all the way to the outer Jaca basin [1-2]. The sediment routing system includes a wide variety of sedimentary facies and depositional environments from proximal palaeovalley fanglomerates, which acted as the main tributaries and provided the main sedimentary input in the system, to braided river deposits and meandering channels of the Graus and eastern Ainsa basins [3] and deltaic, shallow marine and deep-marine deposits of the western Ainsa and Jaca basins [4-7].

We present a reconstruction of the sediment routing system by identifying sediment source regions using light fraction petrography, heavy minerals, and U-Pb zircon geochronology. Using available biostratigraphic and palaeomagnetic correlation schemes [8-10] we identify a number of time-lines that can be traced from proximal regions downstream through the fluvial segment. Using these time-lines we assess down-system changes in grain size within the fluvial segment of the routing system, and document the volumetric partitioning of gravel, sand and fine fraction. The impact of spatial and temporal variations in tectonically generated accommodation is evident from downstream variations in sediment accumulation and rates of granulometric downstream fining.

The compilation of volumes and calibre of depositional products from source to sink allows the inversion of both the pdf of sediment supply from mountain catchments and the sediment discharge Q_s for each time-line, facilitating an assessment of how active tectonics determined the time-history of sediment supply from the erosional engine.

A record of continental collision and regional sediment flux for the Cretaceous and Paleogene core of SE Asia

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Paleogene sedimentary rocks exposed in West Java were derived from local volcanic sources and central Sundaland, the core of SE Asia. Common age distributions of seven detrital zircon samples include 40–80 Ma, 85–125 Ma, 200–300 Ma, 480–650 Ma and 900–1200 Ma. Late Cretaceous and Paleogene zircons in Middle Eocene forearc sandstones were derived from two spatially and temporally discrete volcanic arcs. Permian-Triassic zircons in Middle Eocene quartz-rich sandstones and all other formations were derived from granites of this age in the SE Asian Tin Belt.

Mid Cretaceous zircons in all Late Eocene and Early Oligocene formations were derived from the Schwaner Mountains of SW Borneo. The differences in zircon populations thus reflect changing Sundaland sources with time. In the Middle Eocene, sediment was derived mainly from the Tin Belt. From the Late Eocene onwards a Borneo source became more important. Older zircon ages are from basement that once formed part of Gondwana. Zircons also record the timing of an important micro-continental collision at the Java margin (~85 Ma) that halted Cretaceous subduction and probably resulted in the elevation of large parts of SE Asia.

The morphology of elevated passive continental margins is not related to rifting, break-up or continental separation

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Many passive continental margins are bordered by elevated areas whose altitudes commonly exceed 2 km above sea level in places. It is commonly assumed that these elevated passive continental margins (EPCMs) have survived since the time of rifting and continental break-up. The elevated plateaux on such margins are commonly assumed to represent either a pre- or syn-break-up surface or a surface that has remained high despite significant erosion.

The absence of a post-rift section from many EPCMs is taken as evidence that it was never deposited. EPCMs around the world have similar morphology: elevated plateaux separated from a low-lying coastal area by one or more escarpments. Sediments offshore dip away from the EPCM and are truncated by a shallow unconformity.

Recent studies in West Greenland (Japsen et al. 2006) have shown that typical EPCM morphology, with a high-level plateau, deeply incised valleys and offshore sediments dipping away from the EPCM, formed c. 50 Myr after continental break-up and that the present-day plateau is the remnant of a post-rift erosion surface that was uplifted in the late Neogene.
The similarity of West Greenland to other EPCMs suggests that their development may also have taken place long after rifting and break-up. We present a conceptual model that accounts for EPCM morphology by post-rift burial followed by episodes of km-scale uplift and erosion.

At least two episodes of uplift are required to form an EPCM, one to provide the relief to be eroded to form a peneplain near the level of the adjacent sea and a second to lift it to its present elevation to form the high-level plateau (Japsen et al. 2009).

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Modelling sediment transfer through mountain basins

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We have developed a conceptual model, based on a linear reservoir model (Lu et al., 2005, 2006), that will be used to investigate and compare the interactions between sediment production, storage, transfer, and yield at a number of mountain basins covering a range of climatic and geomorphic settings (figure 1).

The model addresses several key aspects of basin sediment dynamics in its structure. Firstly, the model explicitly accounts for sediment residence times in different morphological elements of a basin system. It is on the basis of residence times that the discrepancies between short and long-term sediment yields observed in many studies can be reconciled (e.g., Clapp et al., 2000; Kirchner et al., 2001). The model also includes stochastic forcing in the form of extreme rainfall events and stochastic sediment supply in the form of mass movements triggered by these events, as well as bank erosion. This is important because time series of sediment yield carry signatures of events at all frequencies and because this stochastic forcing may be able to explain complex response of a system that is not obvious from observations of sediment yield alone (e.g., Philips, 2006; Slaymaker, 2006).

Finally, the key questions of space and time scales in sediment delivery (Walling, 1983) and the role of landscape connectivity (Harvey, 2001) are addressed in the model structure.

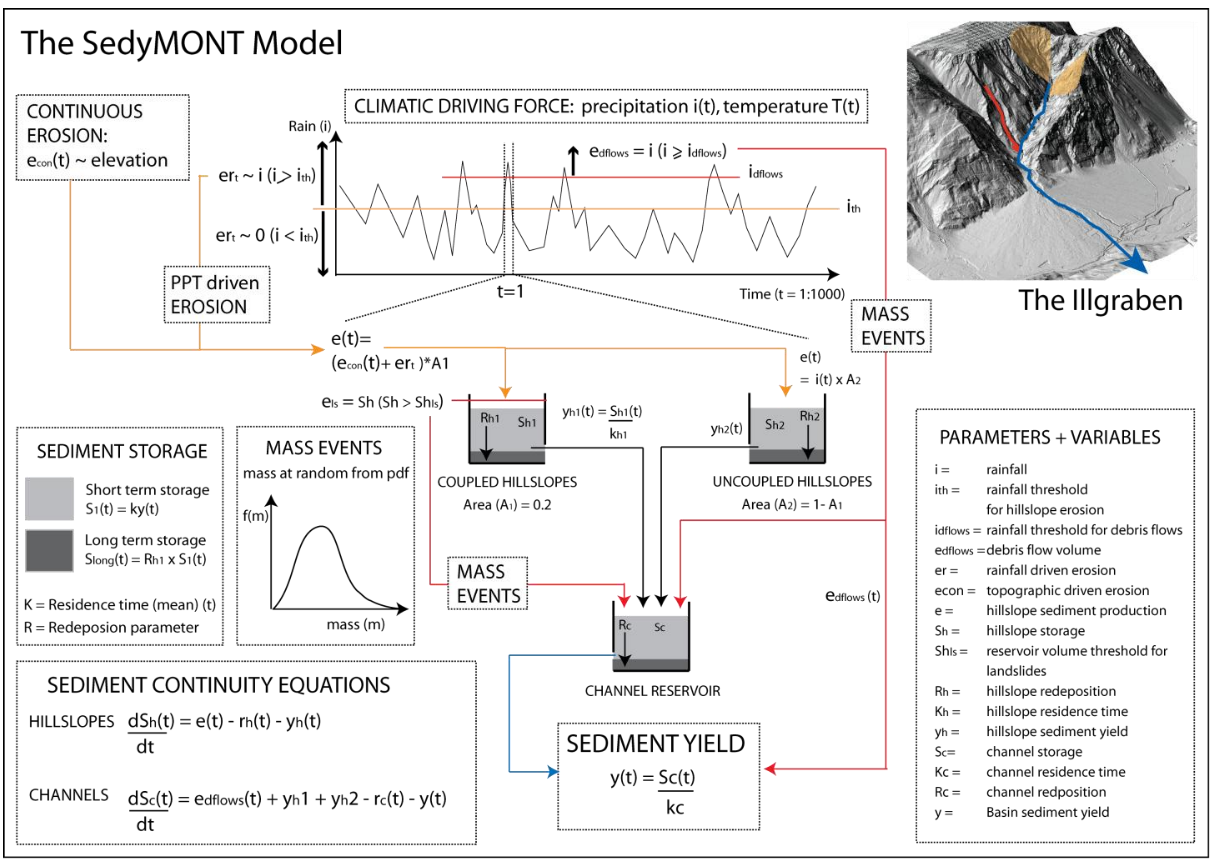

Figure 1 – Schematic of the SedyMONT model framework for a hypothetical basin and precipitation time series. Only 3 reservoirs are shown for simplicity. The zones highlighted in the Illgraben are similarly simplistic.

Experiments based on a 'toy' model have given significant insights into basin sediment dynamics. The effects of increasing reservoir residence time and redeposition, changing model structure, and introducing transport and supply limiting thresholds on the evolution of sediment yield are presented. The model is currently being applied to the Illgraben, Switzerland. A reservoir scheme has been developed based on geomorphic mapping. Sediment storage volumes, residence times, redeposition rates within reservoirs and transfer processes between reservoirs are being calculated from available data and from photogrammetric processing of historical aerial photographs of the Illgraben. Reservoir schemes will also be constructed for the Pasterze basin, Austria, and the Erdalen basin, Norway, over the following months. Progress on the application of the model to these basins is presented.

Diver Shoal – A Managed Dynamic System

Alex Mortley, Port of London Authority

The River Thames is a major sediment transport pathway in southern England. From a river which once transported sediments from the mountains of Snowdonia to a river which enabled London to develop as a major trading port and ultimately as the capital, is a system which today still presents many challenges.

Diver Shoal in Gravesend Reach is a significant controlling depth to vessels transiting in to the Port of London. Since large scale dredging of the shoal ceased in the 1960's, the natural limiting depth was 7.6m below chart datum or better (Greenland, 1996). With commercial pressures increasing, the Port of London Authority undertook a series of investigations and finally the construction of six groynes along the north shore in 1995 with the aim of increasing the ruling depth to 9.1m below chart datum.

Numerous scientific studies have been carried out on the shoal and associated sediment transport of the tidal Thames, e.g. Prentice (1972). These identified two distinct sedimentary regimes; a seasonal movement of fine silts between the "Mud Reaches" and Gravesend Reach and an upstream migration of coarser bedload. An empirical study in 2007 analysed bathymetric surveys since 1998 and supported the earlier theories that the seasonal accretion of fine silts was linked to the rate of freshwater flow (Mortley, 2007).

Until 2007 the fine grained central and northern parts of the shoal had maintained at the 9.1m design level, with the more dynamic, coarser bedforms to the south being the controlling depth. High freshwater flows since 2007 have resulted in a notable shallowing and consolidation of the main shoal to 8.7m. How will the shoal respond to recent below average rainfall and will intervention be required? Depths are now monitored at monthly intervals with high resolution multibeam surveys to assist in the management of this critical shoal.

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The Aleutian Trench

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Oceanic trenches commonly are under nourished with sediment receiving only pelagic and volcaniclastic material, however, the mainly open ocean Aleutian trench is different because it contains vast volumes of clastic sediment. Alaska is the primary source for the Aleutian trench clastic sediment fill a supply predicated on the dynamic process of glacial erosion. Sediment delivery to the trench, therefore, is dominated by allocyclic influences.

Milankovitch-induced climatic cycles cause the episodic release of sediment that is transported as both unconfined and confined turbid flows, the latter routed along submarine channels that cross the abyssal plain of the Gulf of Alaska and finally discharge into the trench at several points. Small volumes of sediment enter the trench directly from glacier snouts at the transform trough-end of the trench. GLORIA and multi-channel seismic surveys conducted by the USGS have revealed details of both the geometry and distribution of the trench sediments and their associated supply systems. From analysis of the records it can be shown that a major channel system extends along the trench axis and reworks and redistributes the supplied material. Even so subduction of seamount chains coupled with the westward-increasing obliquity of plate collision and accretionary prism-sourced slumps serve to compartmentalise the trench depositional environment. This means that the axial channel system is divided into several separate flow patterns.

This complex trench redistribution regime, when seen against the primary supply mechanisms and when coupled with the effect of compartmentalisation, has the potential to create discrete segments of fill that may be distinctive. Moreover, it should be possible to correlate each compartment of fill along the trench because every major supply episode has the potential to be recognised using as a regional time frame the undiluted pelagic sediment horizons that accumulate during episodes of glacial minima. Furthermore, the identity and actual position of each segment along the arc may be additionally confirmed through tectonic fabric analysis associated with subduction obliquity. This simple model expressed as compartments of sediment with potentially identifiable characteristics may be extended to the accretionary prism complex. The form and content of the prism should reflect the present trench fill sequences with their compartment-based distinctiveness.

A theoretical model of grain mobility in bedrock rivers

Rebecca Hodge and Trevor Hoey, University of Glasgow; Leonard Sklar, San Francisco State University

Bedrock rivers are important conduits of sediment in erosional landscapes. Furthermore, the rate of sediment flux and the resulting spatial and temporal patterns of sediment cover are key components of bedrock river incision (Gilbert, 1877; Sklar and Dietrich, 2004). It is therefore necessary to be able to predict both the rate and spatial pattern of sediment transport in bedrock systems. However, current understanding of bedrock river processes is surprisingly limited.
Models of sediment transport in alluvial systems have recently advanced from measuring and predicting averaged bulk fluxes towards a greater consideration of grain-scale processes. Such models of sediment transport (e.g. Ferguson and Hoey, 2002; Wong *et al.*, 2008) include an active sediment layer from which grains are entrained, allow grains to be buried thus reproducing the exchange of grains between layers in the bed, and incorporate the effects of shear stress magnitude on grain transport. These models have been parameterised and tested with field and flume data.

These current alluvial models are not directly applicable to bedrock rivers. This is because bedrock rivers have discontinuous sediment cover of varying thickness, which may not have the same distinction between active and inactive layers. Furthermore, our research has shown that sediment grains in bedrock rivers appear to display different dynamics to those in alluvial rivers. Figure 1 shows the distances travelled by grains of different size classes (a) in a bedrock river under events with different maximum shear stress and (b) in different reaches of an alluvial river over 2 years (Ferguson *et al.*, 2002). The alluvial grains show strong size dependence, with smaller grains travelling further. In contrast, the distance travelled in the bedrock case is independent of grain size. Under comparable conditions, grains display higher virtual velocities in bedrock rivers.

We have therefore developed a new theoretical model of grain mobility in bedrock rivers that incorporates the effect of discontinuous sediment cover and the dynamics of grains in a bedrock setting. This model is tested with field data from two bedrock rivers with contrasting extents of sediment cover: River Calder, Scotland, D_{50} = 50 mm, sediment cover = 10 %, average distance moved by tracer grains = 0.8 m per day; South Fork Eel River, California, D_{50} = 60 mm, sediment cover = 80 %, average distance moved by tracer grains = 0.4 m per day. The model reproduces short-term travel distances, and enables longer-term behaviour to be predicted.

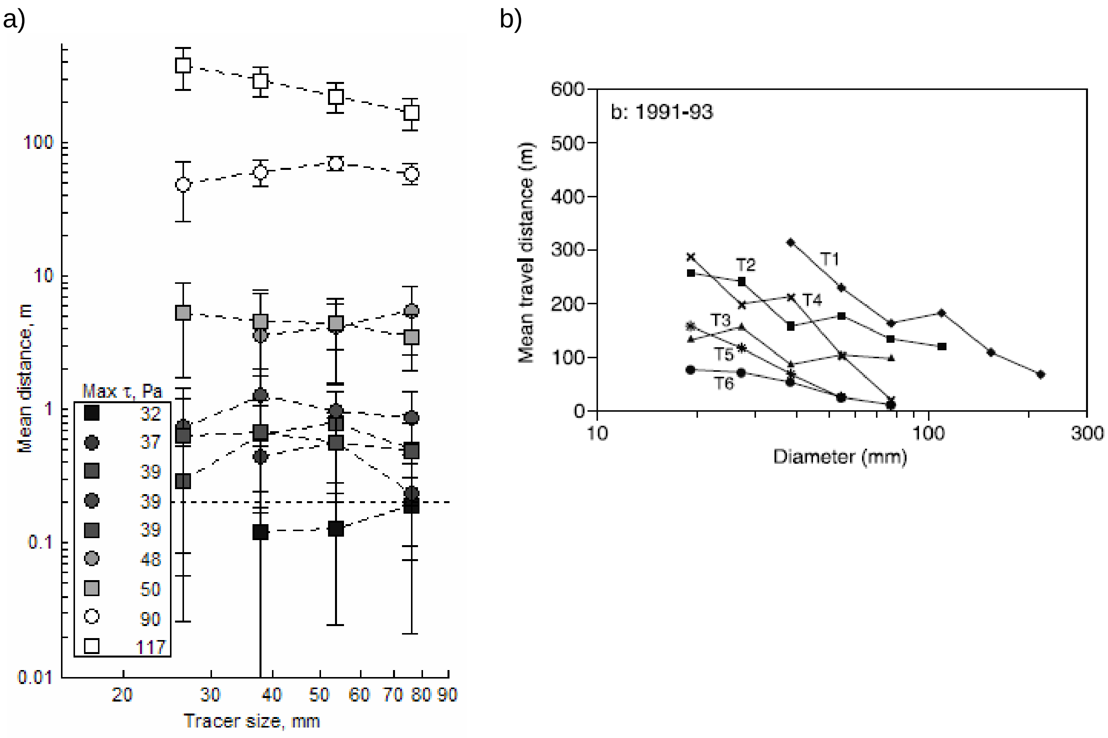

Figure 1: a) Mean distances travelled by different sized tracer grains under different shear stress conditions in the bedrock River Calder, Scotland, b) mean distance travelled by different sized tracer grains in reaches T1 to T6 of the alluvial Allt Dubhaig (from Ferguson *et al.*, 2002)

The detrital heavy mineral record of river behaviour in the eastern Himalayan syntaxis

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Six of the large Asian river systems, the Tsangpo, Brahmaputra, Irrawaddy, Salween, Mekong, and Yangtze, flow through the syntaxis region of the eastern Himalayas. The evolution of these rivers through capture and river piracy has been discussed by many authors. Using detrital zircon geochronology, we have established that the Tsangpo River was connected to the Irrawaddy River in Myanmar from at least 43 Ma until sometime shortly after 18 Ma, and that one of the tributaries of the Brahmaputra captured the Tsangpo drainage between 17-18 Ma.

The present day circuitous route that the Tsangpo follows around the Namche Barwa before draining into the Brahmaputra is here constrained to have established after 18 Ma. Isotopic and geochemical tools now allow finer and finer resolution of provenance areas and the potential exists for detrital mineral records to provide erosional histories that are more spatially constrained. Combined U/Pb dating and □Hf analyses of detrital zircons extracted from Eocene, Oligocene, and a suite of Miocene deposits in the Central Myanmar have been compared to the published □Hf data for the Transhimalayan batholiths in Tibet and Myanmar.

The provenance of the Eocene and Oligocene detrital zircons is predominantly the Gangdese batholith in Tibet within the present day Tsangpo catchment. Significantly, the □Hf signature of detrital zircons changes in the Miocene deposits and negative □Hf values similar to those of the Dianxi-Burma batholith within the Irrawaddy catchment are the dominant signature, with positive □Hf values becoming less common for younger Miocene samples.

We interpret this change in provenance to signal the disconnection of the Tsangpo-Irrawaddy river system, and that river capture by one of the tributaries of the Brahmaputra occurred between 17-18 Ma. The timing of this event is coincident with major re-organisation in the orogen, faulting in the syntaxis, and the onset of strike-slip movement on the Sagaing Fault in central Myanmar. Our results explain why Transhimalayan detritus arrives in the Bay of Bengal in the Early Miocene, and provides new palaeogeographic reconstructions and chronology which can be used to address tectonic-erosion coupling questions.

THEME 3: LANDSCAPES INTO ROCK

Further data on the NW Sardinia continental Permo-Triassic basin (Italy)

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Investigations have been performed on the post-Variscan rocks cropping out along the Northwestern Sardinian coastline southward to Alghero. Stratigraphic sections have been scrutinized at Il Cantaro Rock and Cala Bona localities: they have been dated and correlated using some well-defined lithostratigraphic horizons, as the Early Triassic Conglomerato del Porticciolo and the early Middle Triassic Buntsandstein-Muschelkalk transition.

A nearly 85 m thick succession resulted from the Permian Rotliegend via the Early - Middle Triassic Buntsandstein up to the Middle Triassic Muschelkalk carbonates. The sections show the unconformity between the Permian Rotliegend and the Triassic Buntsandstein deposits and the Buntsandstein/Muschelkalk gradual passage. Those features are evidenced for the first time south of Alghero. Besides, in the Rotliegend a further, marked unconformity has been evidenced: it could be identified as the Saalian unconformity, aged 270 MA and related to the tectono-magmatic Mid-Permian Episode, which evidences are spread all over the European continent.
The Rotliegendes, whose age is supposed to be Mid to ?Late Permian, are related to the Porto Ferro and Cala del Vino Fms., pertaining to the Sardinian Rotliegend Group: they deposed in a molasse-type basin where developed braided stream environments featured by ephemeral rivers under a warm to hot, subarid climate.

The Buntsandstein deposits, aged late Early to early Middle Triassic, belong to the Verrucano Sardo Fm., related to the Sardinian Buntsandstein Group: they are connected to an early Alpine basin where alluvial lobes to braided stream environments developed and ephemeral waterways run under a hot-arid climate.

The transition to the inner ramp peritidal cycles of the Middle Triassic Muschelkalk carbonates of the Punta del Lavatoio Fm. of the Sardinian Muschelkalk Group takes place through a gradual growing of the carbonate content and the development of evaporitic minerals: those latter are present as nodules (chikenwire structure) in the supratidal part of the carbonate sequences, suggesting a sabkha environment.

The depositional characters of the investigated sections along with comparisons with other well-known Permian-Triassic succession located from 20 to 40 km northward allowed a better reconstruction of the Nurra post-Variscan basin. This basin had a EW graben structure and a multi-phase history. Its main tectonic lines were revived several times: they probably originated from reactivated Variscan thrust surfaces.

Evolution of depositional systems in extensional continental basins : A chimera of climate change?

Stéphane Pochat / LPG Nantes, UMR-CNRS 6112 / Université de Nantes

Climatologic reconstruction from sedimentary deposits in active tectonic basin always consider that climate changes are global whereas tectonic is local. However, extensional continental basins shows a very similar pattern independently of the climatic context i.e. the deposits evolve from (1) fluvial deposits in the opening rift, (2) deep-water lacustrine sediments in a deep elongate basin (anoxic condition, grey and black shale, turbidites), as tectonic subsidence exceeds sedimentary fill, (3) lacustrine sediments deposited in a shallowing environment (shallow playa lake, red shales, evaporites), as sedimentation rates equal and then exceed tectonic subsidence, and (4) deltaic and fluvial sediments, as the rift basin is overfilled (e.g. Johnson, T. C., 1984; Lambiase, J. J., 1990; Schlische, R. W., 1991; Gawthorpe, R. L. & Leeder, M. R., 2000; Miall, A. D., 2000).

Such an evolution is entirely controlled by basin enlargement due to two concomitant processes (1) the progressive filling of the basin and (2) the transition from tectonic driven subsidence to thermally driven subsidence. However this sequence is also interpreted in Late Paleozoic basin to be significant of a evolution from wet to arid climate. Here we show, in a sedimentary basin characteristic of this period, by reconstruction of lacustrine configuration, lacustrine depth and lacustrine water volume that the volume of the water lake, between 20-35 km^3, remained constant during 50 My and that the sedimentological indicators of shallowing and episodic drying inside Late Paleozoic Variscan Belt result from tectonic basin enlargement due to the Variscan belt collapse rather than from climate change.

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Climatic versus tectonic controls on the Neogene succession of the northern Great Plains, Nebraska, U.S.A.

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The Miocene to recent fluvial succession of the Great Plains, Nebraska, records a time-integrated history of denudation of the Rocky Mountains. The base of the Miocene succession is defined by a major unconformity that is overlain by fluvial deposits of the Ogallala Group. The Ogallala succession consists of sands and gravels and extends laterally for several hundred kilometres east of the Rockies Front Range.

These sediments are incised by a base-Pliocene palaeovalley that has 80 m of relief, filled with coarse cobble-grade fluvial deposits of the Remsburg Ranch Beds, overlain by gravel dominated deposits of the capping Broadwater Formation (Swinehart et al., 1985). In particular the distinctive Remsburg Ranch Beds unit can be traced down-system for over 600 km, and represents the coarsest sediment to have been exported into the Great Plains in the last 60 million years. The construction of these major incisional surfaces and the coarse sediment discharge over the Great Plains during Mio-Pliocene times have been variably interpreted in terms of regional tectonic tilting (McMillan et al., 2002), temporal variability in sediment and water discharge from the Rocky Mountains resulting from a fluctuating Neogene climate (Anderson et al., 2006), and to increasing snowmelt driven by the growth of glaciers (Pelletier, 2009).

We present data on sediment thickness, incisional depths, sediment calibre and down-system grain size fining rates for four key time-surfaces within the Neogene succession. This data demonstrates that the transition from the upper Miocene to the basal Pliocene is associated not only with an order of magnitude increase in the grain size of material transported by the fluvial system from the Rockies, but also with an increase in stratigraphic fining rates of at least a factor of two. We use a self-similarity model of grain size fining, specifically developed to interrogate time-averaged grain size patterns in fluvial successions, and a 1D model of river profile evolution to estimate the spatial distribution of deposition, time-averaged water and sediment discharge, and the grain size distribution of the sediment supply that would be necessary to account for the observed data. We compare model outputs with known constraints on the tectonic and climatic evolution of the region in the last 10 My, and critically evaluate the likelihood of a tectonic and/or climatic control on the spatial and temporal evolution of the Neogene stratigraphy of the northern Great Plains.

Factors controlling stratigraphic architecture on short and long time-scales

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Generation of stratigraphy occurs on many spatial and temporal scales, but the fundamental building blocks of any stratigraphic unit are the beds and laminas relating to “every-day” events. The transition from such every-day events to preserved rock stratigraphy typically occurs on time-scales between 10^3 and 10^6 years, depending on the return interval of the dominating processes in a given depositional environment, the amplitude-frequency distribution of climatic and eustatic forcings, subsidence rates, and autogenic processes. It is the interplay between these factors which control the geometry and stacking of depositional units in the stratigraphic record.

In this study we apply Sedflux, a forward process model which allows us to bridge the gap between basic event beds and the stratigraphy observed in outcrops, cores or in seismic data. One important aim is to quantify stratigraphic breaks in different climatic, eustatic and tectonic settings, and investigate how time is distributed and represented in stratigraphic sections covering different geologic time-spans. Changing environmental parameters such as wave climate and fluvial discharge allows us to investigate the effect of short-time controls (millennial and younger). On longer Milankovitch time-scales, the same parameters can also be changed to investigate climatic induced changes in sediment supply rate which may be in or out of phase with eustasy. On even longer, tectonic time-scales, variable subsidence patterns and rates illustrates the generation of long-term preservation space, and the ultimate storage of sediments.

Another focus of this study is to identify the variable importance of different external forcing mechanisms in controlling the geometry and geomorphic expression of depositional units at various geologic time periods.

Other combinations of eustatic amplitudes and frequencies, together with variable sediment supply rates from the fluvial system may have resulted in shelf stratigraphy during greenhouse times that was quite different from what has been observed during the recent icehouse conditions. Such differences have important implications for sequence stratigraphic models which aim to predict sediment distribution between source-to-sink segments.

Climate vs. tectonic induced variations in Cenozoic sediment supply from western Scandinavia

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The rates of sediment input to the North Sea and the Norwegian Shelf varied significantly during the Cenozoic. During Paleocene and Eocene times The Shetland Platform and Scottish Highlands were the main sediment sources, while with the onset of the Oligocene more sediment was coming from the Scandinavian shield. This is believed mainly to be a consequence of varying erosion rates and/or changes in sediment catchments in Western Scandinavia and has previously been interpreted in terms of variable tectonic uplift of the area caused by a hitherto unknown tectonic agent.

During Paleocene to Early Eocene times tectonic activity related to the final stage of opening of the North Atlantic was apparently controlling the sediment input in the North Sea as sediment pulses correlate well with tectonic events. Although there is no signs of Cenozoic tectonic activity onshore Scandinavia (igneous bodies, faulting), tectonic disturbance related to ocean opening could be responsible for deposition of thick Paleocene wedges along the western coast of Norway. During subsequent Cenozoic periods domal structures in the Norwegian shelf are a proof for mild and protracted compression.

However, depositional patterns from offshore Scandinavia have been interpreted as a result of significant tectonic movements. In the absence of proofs for active tectonic agents we attempt to explain these sediment input variations as a result of climate fluctuations. The Eocene-Oligocene greenhouse-icehouse climate transition corresponds to an increase of sediment yield from the Scandinavian shield. Furthermore, several studies show a correlation between climate fluctuations, sequence stratigraphic surfaces and lithological changes in the North Sea.

We suggest that a rapid cooling at the beginning of Oligocene (Oi-1 glaciation) changed the erosional regime in western Scandinavia from fluvial (inefficient in tectonically stable settings, almost regardless of the amount of precipitation) to glacial. Glacial erosion is much more effective and is apparently able to outpace tectonic processes responsible for development of high topography. Therefore, a hypothesis of climate control on erosion and deposition during the Cenozoic history of western Scandinavia and adjacent sedimentary basins emerges. This theory is further supported by higher sediment input and pronounced progradation patterns of the Molo Formation (deposited during Late Miocene-Early Pliocene cooling) and the spectacular prograding wedges of Naust Formation (with onset of deposition at around 2.8 Ma, matching the Pliocene ‘climate crash’)

Multiscale Basin Development in Taiwan: First Results with 3D-Stratigraphic Modelling (DIONISOS)

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The detrital infill of foreland basins provides a record of orogen formation and gives insight into the hinterland development through time. However, by analysing the geometry of the basin and calculating the sediment volume it is possible to estimate the (relative) amount erosion and thereby reconstruct the exhumation history of the growing orogen.

In Taiwan, there are several problems related to this approach. The Neogene foreland basin system of Western Taiwan recorded infill from both the Chinese Mainland as well as from the emerging Taiwan Island, and thus the exact timing and the subsequent change from a passive margin sedimentation to the development of the "active" foreland basin is still not yet well defined. In addition, the oblique collision between the volcanic Luzon arc (Philippine Sea Plate) and the Eurasian Continental Plate lead to a different distribution of sedimentary facies from North (shallow env.) to South (deep marine env.).

Moreover, the sedimentation processes in the Taiwan Strait are strongly influenced by the climate showing today (in average) four typhoons and 2'500 mm precipitation per year. Modern catchment-scale erosion rates of up to 60 mm per year were found on active thrust faults (Dadson 2003), but in average these range between 3 to 6 mm/a. After deposition, seasonal variation in the current pattern within the Taiwan Strait modifies and redistributes the sediments and erodes an uncertain amount of material away into the South China Sea and East China Sea (e.g. Okinawa Through) respectively. To be able to exactly interprete the exhumation history it is essential to know the amount of sediment bypass.

The project will focus on the high-resolution stratigraphic record of the collision in the foreland basin in order to reconstruct paleogeography, depositional environment, and tectonic and sediment-transport controls on depositional patterns. These results will serve as input to stratigraphic and 3D deformation models to constrain the development of the orogen and its southward propagation.

The results of this study will provide important evidence for the space and time evolution of the orogen-related loading of the foreland basin.

Modification of passive margin landscapes by active normal faulting in Troms County, Norway

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In Norway topographic escarpments, creation, preservation and destruction of landforms, and drainage patterns appear to be related to structural templates created during the Jurassic thinning phase. Here we present geological evidence for currently-active tensional deformation, accommodated by release faulting, in uppermost Kåfjordalen and Signaldalen. Such faulting has implications for the destruction of the Norwegian landscape.

Ground observations indicate a large normal fault defines the eastern border of the Lyngen 'Alps' peninsula. A series of exceptionally well-preserved triangular facets adorn a sharp, elevated escarpment.

We interpret the valleys of Signaldalen, Skibotndalen, and Kåfjordalen, located in the hanging wall of the Lyngen Fault, to have formed at least partly under the influence of release faults accommodating flexure and failure. Mineralized surfaces exhibiting dip-slip slickenlines indicate these faults are true tectonic features, not simply gravitationally-driven *'sackung'* planes-of-failure.

Active deformation in the region is evidenced by multiple data. During the late 1990s four small seismic events with epicentres directly along the northernmost trace of the main Lyngen fault were recorded by NORSAR. Satellite Interferometry (InSAR) data indicate ground motion consistent with the accumulation of strain across a large normal fault. Road survey data also suggest the footwall horst is undergoing upward strain relative to the hanging wall. Narrow, deep, structurally-guided canyons have been opened within the gently-sloping uppermost ends of Kåfjordalen and Signaldalen. Many canyons run parallel to hillside slopes for long distances, indicating they do not represent ordinary down-slope drainage. Some drainages appear to crosscut foliation surfaces and are characterized by regular (commonly sinistral) geometric 'steps.' In uppermost Kåfjord, Quaternary deposits are deformed by a graben.

The Lyngen and Kåfjordalen faults can be placed within the context of post-rift normal fault guided reactivation and consequent geomorphic modification of the Norwegian margin. In the Møre og Romsdal region, escarpment topography is fault-controlled and fault-guided large-volume catastrophic failure is well documented. Similar large-volume catastrophic landscape modification occurred, or is in the process of occurring, in the Lyngen 'alps' region. Normal fault processes have also profoundly affected Scandinavia's sedimentation patterns from local to continental scale. Thermochronology and landscape analysis strongly suggests fault reactivation occurred episodically throughout Cenozoic time, with consequent implications for paleo-topography. Offshore data link the preferred localization and magnitude of reactivation to the crustal architecture formed during the thinning phase of continental extension. A holistic interpretation of the landscape evolution of the Norwegian extended margin must encompass at least one-half of the Wilson Cycle.

Episodic exhumation in both basement and sedimentary basins: Is it possible to trace sediment from source to sink?

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Understanding exhumation is important to hydrocarbon exploration, not only through prediction of reservoir horizons resulting from denudation of basin margins but also through implications for generation and preservation of hydrocarbon accumulations in exhumed basins. In numerous regions mass-balance calculations have been attempted, comparing amounts of denudation with corresponding amounts of section preserved in adjacent (usually offshore) basins.

Implicit in this approach is the assumption that elevated onshore regions represent areas of prolonged uplift/exhumation, while adjacent offshore basins have continuously subsided, receiving and retaining all of the eroded detritus. But in many areas, our studies using AFTA and vitrinite reflectance have shown that offshore sedimentary sequences have themselves been exhumed, often (but not always) synchronous with exhumation of neighbouring onshore regions. This is well documented around the Arctic and North Atlantic margin during the Cenozoic. Around the Eocene-Oligocene boundary both the onshore West Greenland margin and the offshore shelf underwent major exhumation, in which up to a kilometre of Eocene to Early Miocene section was removed. This episode is evidenced by a major Eocene to Lower Miocene unconformity around much of West Greenland, the counterpart of which is an peneplain which has been uplifted and dissected to form mountain summits at elevations up to 2 km onshore.

The offshore unconformity shows little evidence of angular truncation over most of the offshore shelf. This is usually taken as evidence that the interval unrepresented by preserved rock represents an interval of stability in which little sediment was deposited. But in West Greenland and in other areas, we commonly observe that large amounts of section must have been deposited and removed on this unconformity, the low-angle nature of which reflects the regional extent of the corresponding uplift and erosion.

Attempts to explain exhumation in these regions have focussed on local mechanisms, but our results suggest broadly synchronous exhumation at the Eocene-Oligocene boundary over wide areas of the Arctic and the North Atlantic margin, implying that the controlling processes act on a plate scale.

Understanding the nature of the processes responsible requires that the true scale of such events should be defined. Reliable mass balance calculations require that the extent of the uplifted and eroded region and the ultimate repository of the eroded detritus are defined. But the possibility of multiple exhumation episodes suggests that even when this is achieved, it is far from straightforward to assume that the sedimentary section has been completely retained.

Non-seismic Discovery of the Delvina Carbonate Gas Condensate Field

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The gas condensate field of Delvina is the last discovery in carbonate reservoir in Albania It represents an anticline structure of Cretaceous-Eocene limestone sealed by the Lower Oligocene flysch. Unlikely the other carbonate fields, the Delvina one is completely masked by a double cover owing to westward thrust of the Mali Gjere anticline eroded from the Eocene down to Upper Triassic carbonates.

Depiction of the Delvina prospect during integrated geological-geophysical synthesis based only on few following data:

1. Location of Delvina prospect between two anticline structures, eroded from Eocene to Lower Cretaceous carbonates.
2. Existence of the Delvina-4 well, which had crossed the microfaunistic boundary between the Middle and the Lower Oligocene flysch deposits at the 2430m and suspended at 3050m depth owing to that time uncertain geological view and technological impossibility of drilling continuation.
3. Presence of the Spontaneous Polarization gradient of 5mv per 100m, at that time bottom interval of 2900-3050m of the Delvina-4 well.
4. Presence of the element of Fe two-valiant in form of sulphide mineralization of pyrite detected in the Lower Oligocene flysch of the Delvina-4 well.

Really, discovery of the Delvina field has been a very difficult undertaking because of the total lack of direct surface geological data and depth seismic information. Also, drilled wells have faced a tight carbonate reservoir of very low porosity and permeability, dependent on very low effective fractures of some 0.2%. So, the Delvina-9, 4, 12 and the Delvina-10 wells, which has penetrated the Cretaceous-Eocene reservoir have produced nothing from the 140m interval of the upper part of the Eocene mudstone. In other words, high cost of exploration and development operations, as well as presence of very low production reservoir classify the Delvina field as a very risky one. Nevertheless, non seismic discovery of the Delvina field in a very complicated geological setting and depiction of some credible similar prospects in south-western Albania are some other clues against the “Peak Oil” explorationists, because the Albanides thrust belts, as well as Hellenides ones are similar with numerous thrust belts developed wherever the tectonic plates collision has taken place. Subsequently, the challenge ahead is looking over all hydrocarbon leads detected so far and finding out high tech exploration methodologies.

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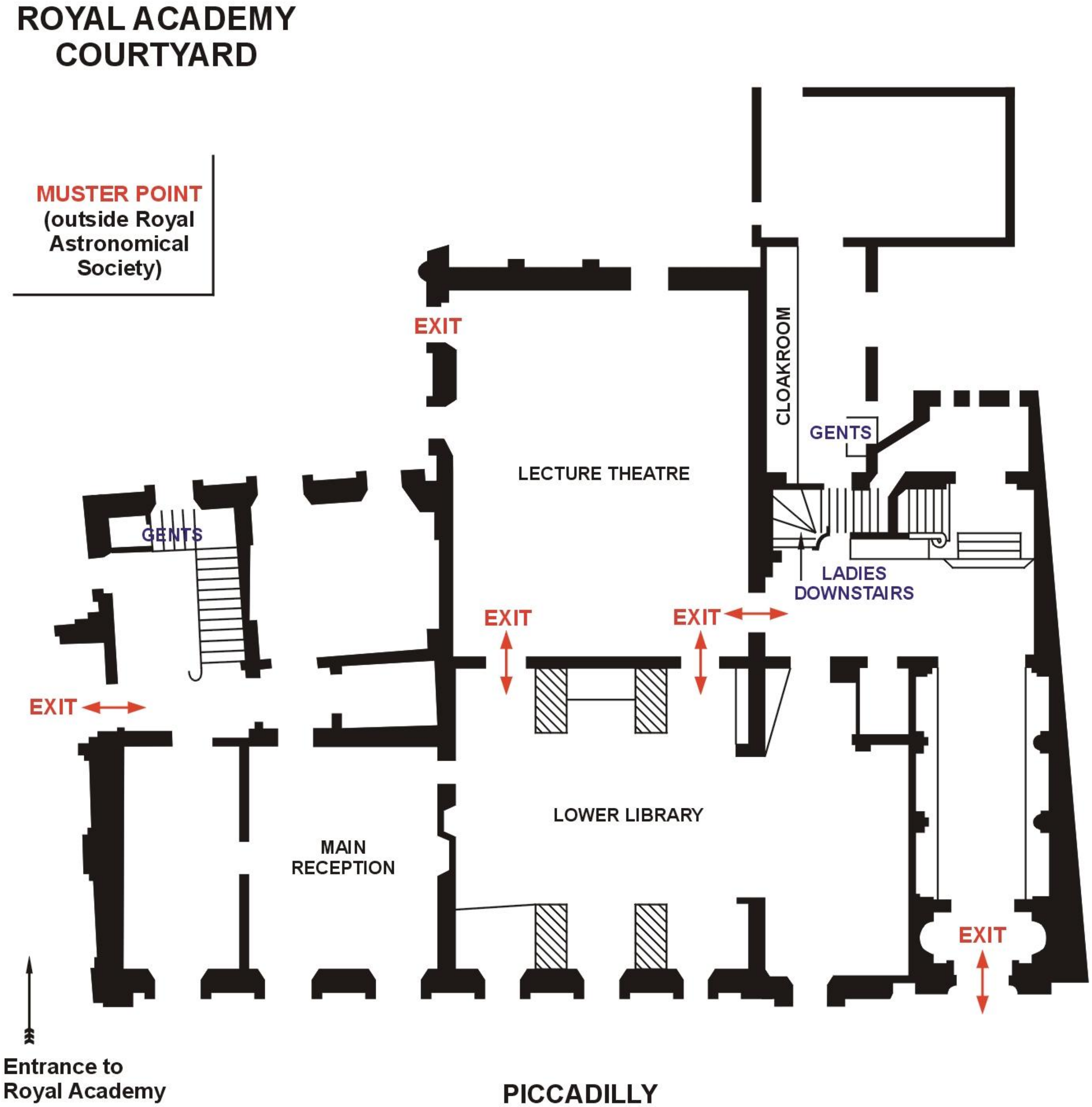
Ground Floor Plan of the Geological Society, Burlington House, Piccadilly



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