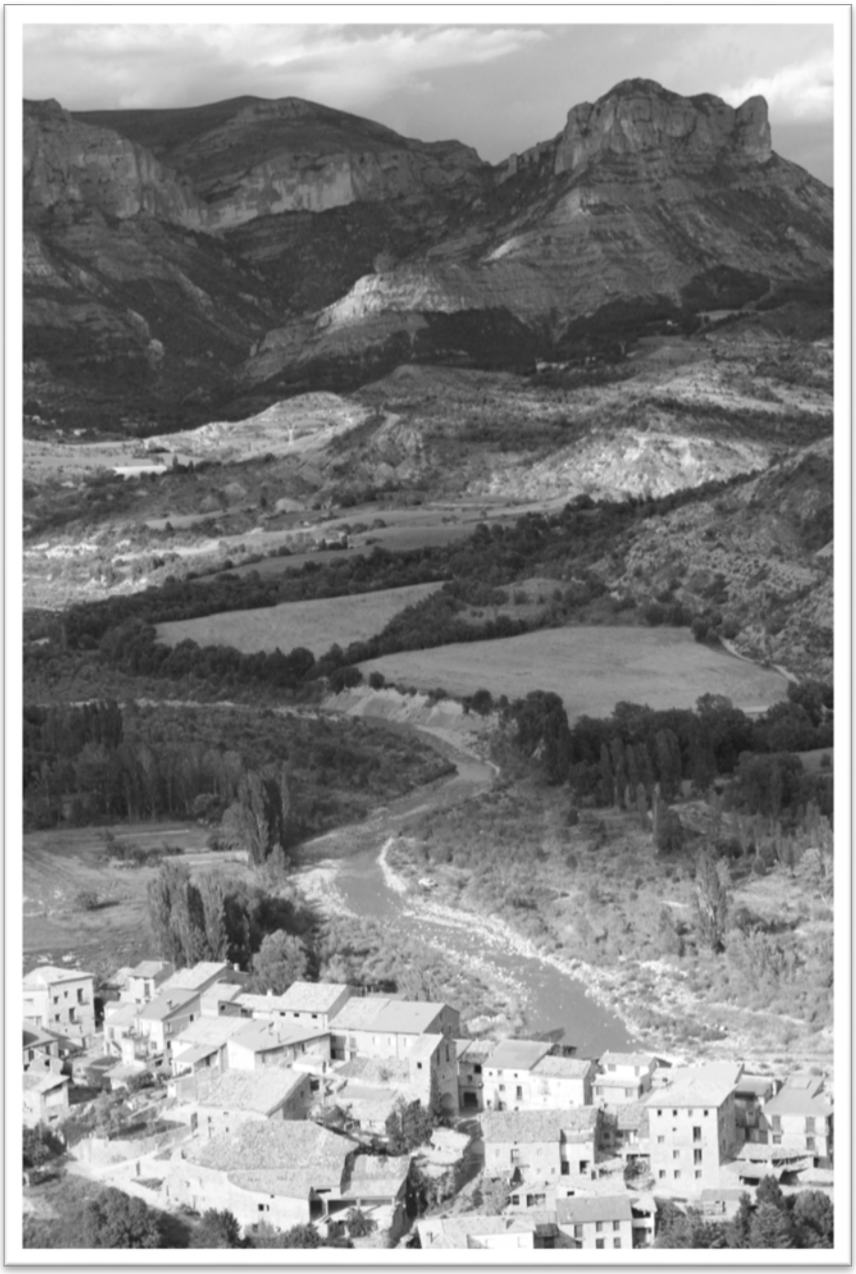
SEPM Research Conference

Propagation of Environmental Signals in Source-to-Sink Stratigraphy

June 5th – 9th 2017

CONFERENCE ABSTRACTS



SEPM S2S Conference

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Conveners: Sébastien Castelltort, Julian Clark,

Andrea Fildani & Cai Puigdefàbregas

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The focus of this SEPM Research Conference is on controls on clastic sedimentation at different geologic time-scales and the propagation of sediment-flux signals in the stratigraphic record of correlative segments of source-to-sink sedimentary systems. The field-based conference will aim to bring together scientists from Academia and Industry interested in the stratigraphic "signals" spawned by sedimentary landscape response to tectonic, climate and sea-level changes, how these 'signals' are defined, how they propagate or attenuate along the depositional profile, and how they end up preserved in stratigraphic archives of sedimentary basins.

The 5-day meeting will be an integrated conference and field excursion, with approximately half the time spent in the field. The Pyrenean foreland basin offers a great opportunity to visit world-class exposures of outcrops that, through decades of geologic study, permit the investigation of cyclicity in correlative stratigraphy from alluvial, fluvial, shallow marine, slope and deep marine environments. Recent source-to-sink research results from this basin will be shared by the conference conveners and other researchers active in the area or in similar settings in other basins. Talks and posters presented at the conference include:

- Studies from outcrop, subsurface and modern sedimentary systems showing long-range signal propagation along the sedimentary routing system
- Numerical and physical laboratory models of stratigraphic signal generation, propagation and attenuation
- Sediment flux vs accommodation and controlling effects on sediment partitioning
- Advances in tectonic geomorphology and application to understanding the stratigraphic record
- Thermochronometric methods applied to provenance controls
- Detection of climatic and tectonic signals and their timescales through use of multi-proxies

The conveners are very grateful to SEPM for their support and assistance in making this event possible, and to Statoil for their generous sponsorship that enabled reduced registration fees for all students and offset of conference expenses.

SEPM Research Conference: Propagation of Environmental Signals in Source to Sink Stratigraphy

Key-Note Presentations

Reconstructing Continental-Scale Paleodrainage and Sediment Routing from Detrital Zircons: Examples from Mesozoic and Cenozoic North America.
Blum, M *(University of Kansas)*

Strategies for Developing Pre-Holocene Paleo-Environmental Records: Application of Detrital Cosmogenic Data to Paleo-Erosion Rates.
Burbank, D *(University of California, Santa Barbara)*

Source-to-Sink (S2S) analysis and applicability to Earth studies.
Martinsen, O. *(Statoil)*

Tracing a Grain of Sand – Novel Detrital Geo- & Thermochronometric Provenance Tools for Elucidating Source-to-Sink Dynamics and Signal Propagation.
Stockli, D. *(University of Texas at Austin)*

Dynamics of River Networks in Eroding Catchments at the Continental Scale.
Willett, S. *(ETH Zurich)*

Oral Presentations

Response of terrestrial and marine environments to the Paleocene-Eocene Thermal Maximum (PETM), insights from a basin-continent transect, NE and Central Pyrenees, Spain.
Adatte, T. et al. *(University of Lausanne)*

Shelf-edge trajectory analysis; the role of differential compaction.
Beelen, D. *et al. (Utrecht University/Imperial College London)*

Immediate propagation of deglacial environmental change to deep-marine turbidite systems along the Chile convergent margin.
Bernhardt, A. *et al. (Freie Universität Berlin)*

Stratigraphic signals derived from physical modelling applied to outcrop studies.
Bijkerk, J. *et al. (Shell International E&P).*

Sediment dispersal and provenance signal variations in small, tectonically active sediment-routing systems, southern California.
Covault, J. *et al. (Bureau of Economic Geology) presented by* ***Sharman, G.***

Isolating a climatic signature on alluvial deposition during the Paleocene-Eocene Thermal Maximum: Piceance Creek Basin, Colorado, USA.
Foreman, B. *et al. (Western Washington University)*

Sediment distribution in the South-Pyrenean Foreland System through time
Garces, M. *et al. (Universitat de Barcelona)*

Source-to-sink relations along the transform margin of central California and the role of tectonic inheritance.
Graham, S. *et al. (Stanford University)*

Source to sink study at continent-scale (Africa): mantle dynamics controls and implications for the sediment routing system.
Guillocheau, F. *et al. (University of Rennes) presented by* ***Robin, C****.*

Where is my sink? Reconstruction of landscape development in southwestern Africa since the Late Jurassic.
Hodgson, D. *et al. (University of Leeds)*

Tracking large river systems during growth of the northern Andes
Horton, B. *et al. (University of Texas at Austin)*

Unmixing Mixed Arc Provenance Signals Caused By Recycling of Zircon From Foreland Tuffs: A Case Study From the Paleogene of NE Mexico.
Lawton, T. *et al. (Universidad Nacional Autónoma de México)*

Recognition of Shelf-Margin Clinoforms in Outcrops; illustrated from Jurassic Las Lajas - Los Molles Formations, S. Neuquen Basin, Argentina.
Olariu, C. *et al. (University of Texas at Austin)*

Source-to-sink analysis in an active extensional setting: Holocene erosion and deposition in the Sperchios rift, central Greece.
Pechlivanidou, S. *et al. (University of Bergen)*

Significance of river hydrological regime in source to sink analyses
Plink-Bjorklund, P. *et al. (Colorado School of Mines)*

Source to sink of the Miocene Ribe Group, eastern North Sea Basin: the control of climate, tectonism and eustatic sea-level changes on partitioning of lithology.

Rasmussen, E. *et al. (Geological Survey of Denmark & Greenland)*

Millennial-scale storage and release in small mountain-to-deep-sea sediment routing systems, southern California.

Romans, B. *et al. (Virginia Tech)*

Climatically controlled increase in Quaternary erosion rates: Real and perceived biases from thermochronology data.

Schildgen, T. & van der Beek, P. *(GFZ German Research Centre for Geosciences)*

Protracted sedimentary signals of slab breakoff beneath the European Alps recorded in Oligo/Miocene Molasse deposits.

Schlunegger, F. *et al. (Univerity of Bern)*

Untangling Provenance Signals in Fluvio-Deltaic-Lacustrine Facies, Gale Crater, Mars.

Siebach, K. *et al. (Stony Brook University)*

The role of climatic and physiographic setting in controlling how environmental signals are propagated within coastal systems: Lessons from the Quaternary Gulf of Mexico.

Sims, A. *et al. (UC Santa Barbara)*

Integrating field observations and numerical models to explain complex fluvial system behavior in Sylhet basin, NE Bangladesh.

Sincavage, R. *et al. (Vanderbilt University)*

The impact of variable sedimentation on reconstructing climate signals in deltaic and shelf deposits: Models and examples from the Paleocene-Eocene Thermal Maximum.

Trampush, S. & Hajek, E. *(Pennsylvania State University)*

A Tale of Two Megafans: Controls on the formation and abandonment of the Tista (West Bengal, India) and Lannemezan (northern Pyrenean foreland, France) megafans, and their role as transient sediment traps in source to sink systems.

van der Beek, P. *et al. (Université Grenoble Alpes)*

Source-to-sink sedimentation of the Waipaoa River, New Zealand.

Walsh, J.P. *et al. (East Carolina University)*

Are landscapes buffered to high-frequency climate change? A comparison of sediment fluxes and depositional volumes in the Corinth rift, central Greece, over the past 130 kyrs.

Watkins, S. *et al. (Imperial College London)*

Fine-sediment mineralogy of the Gulf of Papua shelf deposits: Implications for fluvial storage and sediment dispersal to the clinoform.

Wei, E. *et al. (UC San Diego)*

Controls on the behaviour of sediment routing systems using a mass balance approach.

Whittaker, A. *et al. (Imperial College London)*

Poster Presentations

(* Also Presenting as Field Poster)

*Response of an ephemeral fluvial system to varying tectonic, eustatic and climatic conditions: "Upper Red Garumnian", Central South Pyrenees, Spain.

Arevalo, O. *et al. (University of Leeds)*

Indentation of the Pamirs with respect to the northern margin of Tibet: Constraints from the SW Tarim basin sedimentary record.

Blayney, T. *et al. (Lancaster University) presented by* ***Sobel, E.***

Decoding sediment transport dynamics on alluvial fans from spatial changes in grain size, Death Valley, California.

Brooke, S. *et al. (Imperial College London)*

Quantifying alluvial fan sensitivity to climate in Death Valley, California from field observations and numerical models.

Brooke, S. *et al. (Imperial College London)*

*Impact of tectonics, climate and eustasy on stratigraphic architecture and depositional profile evolution in the Graus-Tremp-Ainsa Basin during Lower Eocene times.

Chanvry, E. *et al. (IFP)*

*Mineralogical distributions and their controlling factors in the Graus-Tremp-Ainsa Basin during Lower Eocene times.

Chanvry, E. *et al. (IFP)*

*Fluvial signatures in depositional system during Paleocene-Eocene Thermal Maximum (PETM) in Tremp formation, Spain.

Chen, C. *et al. (Geneva University) presented by* ***Castelltort, S.***

*Heavy-mineral assemblages as a provenance indicator in the Jaca basin (Middle-Late Eocene, southern Pyrenees)

Coll, X. *et al. (Universitat Autònoma de Barcelona)*

The continental shelf: a conveyor and/or filter of sediment to deep water?
Cosgrove, G. *et al (University of Leeds)*

Thermochronological signal from the Western Axial Zone to the Aquitaine basin: unravelling a late Miocene exhumation.
Fillon, C. *et al. (Université Paul Sabatier, Toulouse)*

*Climatic and tectonic record of the early Eocene Pyrenean foreland basin, a continental-marine correlation model based on a multi-proxy approach
Honegger, L*. et al. (Geneva University) presented by* ***Castelltort, S.***

Channel-Forming Discharge in Source-to-Sink Analysis.
Jones, E. & Plink-Bjorklund, P. *(Colorado School of Mines) presented by* ***Plink-Bjorklund, P.***

*Multiproxy approach to climate signals in the middle upper Eocene deposits of the Ainsa Basin, Spain
Läuchli, C*. et al. (Geneva University) presented by* ***Castelltort, S.***

The Application of Open System Theory to Sedimentary Systems: The Concept of Environmental Signal and Noise Revisited.
Li, H. & Plink-Bjorklund, P. *(Colorado School of Mines)*

*Paleobathymetry, paleomorphology and sediment partitioning during early stage foreland basin thrusting: The Ypresian Roda Sequence, South Pyrenean Foreland Basin (Spain).
Martinius, A. & Puigdefàbregas, C. *(Statoil)*

Signal propagation in a natural catchment-fan system: Pleistocene paleo-erosion rates in the Great Basin, U.S.A.
Mason, C. & Romans, B. *(Virginia Tech)*

*Long lived isolated Southern Pyrenean foreland source to sink systems: Constrains from detrital zircon double-dating and detrital rutile U-Pb geochronology
Odlum, M*. et al. (University of Texas at Austin) presented by* ***Stockli, D.***

*Sediment Routing and Fluvial Architecture in the Ypresian-Lutetian Corçà Fm. (Àger sub-basin, south-central Pyrenees, Spain).
Poyatos-More, M. *et al. (University of Manchester)*

Spatial-Temporal Evolution of Sedimentary Transition Zones and Stratigraphic Sequences in an Exhumed Basin Margin Succession.
Poyatos-More, M. *et al. (University of Manchester)*

*Facies Analysis and Sequence Stratigraphic Implications of a Mixed (Clastic-Carbonate) Depositional System: lower Eocene Castigaleu Fm. (south-central Pyrenees, Spain).
Poyatos-More, M. *et al. (University of Manchester)*

*Structure-Stratigraphy Interactions, Landscape Evolution, and Internal vs. External Sediment Sourcing—Implications to S2S systems: Integrated outcrop study of the Ainsa Basin, Spain.
Pyles, D. *et al. (EOG Resources) presented by* ***Clark, J.***

*Evolution of the sediment routing systems in the south-central Pyrenean Basin: Unravelling the interplay between northern (hinterland) and southern (craton) provenance.
Roige, M. *et al. (Universitat Autònoma de Barcelona)*

*Foreland basin emersion and cannibalization: a case study of integrated sandstone petrography and detrital zircon geochronology in the Jaca basin (Middle Eocene-Oligocene, South Pyrenean basin).
Roige, M. *et al. (Universitat Autònoma de Barcelona)*

Cosmogenic-isotope tracking of sediment cycling and erosion-rate changes in the northwestern Himalaya
Scherler, D. *et al. (GFZ German Research Centre for Geosciences)*

*Provenance Evolution and Detrital Zircon Double Dating Signal Propagation from Fluvial to Deep Marine in the South Central Pyrenean Foreland Basin During the Eocene.
Thomson, K. *et al. (University of Texas at Austin) presented by* ***Stockli, D.***

Transfer of cyclic sediment supply signals to stratigraphy: experimental test of a theoretical framework for channelized systems.
Toby, S. *et al. (University of Liverpool)*

100-kyr fluvial fill terrace cycles since the Middle Pleistocene in the southern Central Andes, Toro Basin, NW Argentina.
Tofelde, S. *et al. (University of Potsdam)*

*A magnetostratigraphy-based correlation of the middle-late Eocene fluvial to shallow marine units of the Aínsa and Jaca Basins.
Vinyoles, A. *et al. (Universitat de Barcelona)*

Straight from the source's mouth; a quantitative study of grain-size export for an entire rift, the Corinth rift, central Greece.
Watkins, S. *et al. (Imperial College London)*

Core Workshop.
Abreu, V. *(Abreu Consulting and Training)*

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Response of terrestrial and marine environments to the Paleocene-Eocene Thermal Maximum (PETM), insights from a basin-continent transect, NE and Central Pyrenees, Spain

Thierry Adatte[1], Hassan Khozyem[1, 2], Jorge Spangenberg[3], Yoann Chevalier[1], Gerta Keller[4]

[1]Institute of Earth Sciences, University of Lausanne, Lausanne, Switzerland
[2]Departement of Geology, Faculty of Sciences, Aswan University, Aswan, Egypt
[3]Institute of Earth Surface Dynamics, University of Lausanne, Switzerland
[4]Department of Geosciences, Princeton University, Guyot Hall, Princeton, NJ 08544, USA

Geochemical and mineralogical proxies of terrestrial and marine clay-rich sediments are an excellent tool to understand paleoenvironmental and climatic changes that occurred during the Paleocene-Eocene Thermal Maximum (PETM). Two sections, Zumaia and Esplugafreda, respectively located in the Basque Basin and South Central Pyrenees preserve a remarkably continuous record of the PETM events, which allows high-resolution correlations between continental and marine settings.

The Esplugafreda section shows an excellent terrestrial record of the early Eocene warm events. High-resolution $\delta^{13}C$ and $\delta^{18}O$ analyses of two types of calcareous paleosoil nodules reveal two distinct negative excursions: a Pre-Onset Excursion (POE) and the Paleocene Eocene Thermal Maximum (PETM). The POE is located above an unconformity between red soil and calcarenitic fluvial to lacustrine sediments and corresponds to a sea-level rise and a rapid temperature increase (8°C). A second gradual warming from 6 to 8°C is observed in the upper part of the section and appears to be linked to the PETM. The Paleocene Eocene boundary is located four meters below the Claret conglomerate, which was previously thought to represent an extreme climatic event in the Pyrenees linked with the PETM. The Claret conglomerate was therefore deposited between these two climatic events and about 10m above the top of the POE and is therefore not directly related to the PETM-onset. A prominent increase in kaolinite content during the POE implies intensified runoff and/or weathering of adjacent soils. In the marine section of Zumaia, the PETM interval is marked by an abrupt change from turbidites to clay-rich sediments with dominant kaolinite. The presence of several peaks of mercury coincident with both POE and PETM intervals supports the role of volcanism (North Atlantic Igneous Province) to initiate the concomitant warming and sea-level rise characterizing the POE and PETM.

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Response of an ephemeral fluvial system to varying tectonic, eustatic and climatic conditions: "Upper Red Garumnian", Central South Pyrenees, Spain

Oscar J. Arévalo, Nigel Mountney, and Luca Colombera

Fluvial & Eolian Research Group, School of Earth and Environment, University of Leeds, Leeds, West Yorkshire, United Kingdom

The late Paleocene to earliest Eocene sedimentary succession exposed in the Arén–Esplugafreda sector, informally known as "Upper Red Garumnian", is interpreted as the accumulated deposits of an ephemeral fluvial system that developed in the marginal part of the Central South-Pyrenean Foreland Basin under the influence of a semiarid climate. At the time of accumulation of the Upper Red Garumnian, the developing foreland basin was open to the Atlantic Ocean; thus, the depositional evolution of its sedimentary fill reflects the interplay between eustatic and tectonic controls, on which climatic factors were superposed.

The regional and local geological background is well constrained by data accumulated since the 1990s from across the Central South-Pyrenean Foreland Basin, including a biostratigraphic and magnetostratigraphic framework, palaeoclimatic interpretations from clay mineralogy and stable isotopic geochemistry analyses, and structural reconstructions supported by geochronology and thermochronology. Based on this understanding, a detailed depositional model has been developed to explain the response of this fluvial system to a set of varying allogenic drivers which include: i) changes in structural basin configuration in response to different thrust emplacement stages and uplifting rates of the Pyrenean chain; ii) transgressive-regressive pulses and associated base-level changes; and iii) seasonal climatic patterns and an extreme global warming event corresponding to the Paleocene-Eocene Thermal Maximum (PETM).

To obtain a detailed characterization of the Upper Red Garumnian succession, quantitative sedimentological and stratigraphic data have been acquired through remote sensing and field-based analyses. The photointerpretation of LiDAR-derived DEMs and high-resolution orthophotographs has enabled the detailed mapping of channelized and floodplain elements over an area of 3 km^2. Field-based analysis has involved the measurement of 15 regional stratigraphic sections (882 m cumulative thickness). Analysis of architectural elements entailed GPS mapping to establish lateral continuity and extent, detailed graphic logging (255 logs) to record internal lithofacies composition, determination of paleocurrent directions (330 measurements), and establishment of the external geometry and connectivity of the bodies. One-hundred-and-eighty sand-prone and conglomeratic channelized elements have been assigned to 4 distinctive genetic origins: i) mass flow deposits, ii) simple and iii) compound channelized deposits and iv) amalgamated complexes.

Based on lateral and vertical changes in the overall arrangement of architectural elements of the Upper Red Garumnian, four unconformity-bounded, fining-upward stratigraphic intervals (1 to 4 from base to top) have been defined. Each of these records distinct conditions in terms of relative influence of allogenic drivers. Intervals 1 (~100 m thick) and 2 (~40 m thick) were accumulated during an initial phase of tectonic quiescence following an episode of non-deposition characterized by the region-wide formation of paleosols. Fluvial sedimentation occurred on a low-gradient fluvial plain, where numerous laterally disconnected, channelized elements associated with avulsive rivers were developed. Occurrence of calcrete horizons, calcareous nodules and gypsum accumulations in Interval 2 suggests a change to more arid conditions in the fluvial system. Interval 3 (~165 m thick) records an increase in the mean grain size of conglomeratic deposits and is characterized by the occurrence of compound channelized deposits and conglomeratic amalgamated complexes, which are spatially grouped in paleo-valleys surrounded by wide (> 1 km) interfluves. In contrast to underlying deposits of Interval 1, the proximal overbank deposits within these paleo-valleys are only slightly bio- and pedoturbated. This interval likely records an increase in the rates of sediment supply and subsidence associated with tectonic movements related to the reactivation of the Pyrenean uplift. Interval 4 (~50 m thick) records mainly a transgressive episode with superposed climatic influence related to the PETM event; deposits formed previous to the negative isotope excursion which characterizes the PETM comprise the fill of local incised valleys formed as part of a relative sea-level fall and the onset of the subsequent rise; syn-PETM deposits occur as conglomeratic amalgamated complexes that possess considerable lateral continuity (500 m to 2,000 m); these complexes are locally associated with grey mudrocks containing coaly fragments. Post-PETM deposits are mainly composed of multicolored mudrocks and represent fluvial-to-coastal deposits accumulated as part of a transgressive episode which culminated in the establishment of a carbonate platform over the former fluvial succession.

The studied Upper Red Garumnian succession represents an example of the complex evolution of a fluvial system, where independent eustatic, tectonic or climatic controls cannot be invoked. Instead the resultant sedimentary record reflects the varying influence over time of a combination of these drivers, whose relative roles can be interpreted only by considering the significance of the succession from the regional perspective of the entire depositional system.

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Shelf-edge trajectory analysis; the role of differential compaction

Daan Beelen, Christopher A.L. Jackson, David Hodgson,
João Trabucho Alexandre, and Stefano Patruno

[1] Department of Earth Sciences, Universiteit Utrecht, P.O. Box 80115, 3508 TC Utrecht, The Netherlands
[2]Basins Research Group, Department of Earth Sciences and Engineering, Imperial College, London SW7 2AZ, U.K.
[3] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, U.K.
[4] PGS, London

Shelf-edge trajectory analysis of clinoformal strata on continental margins is used to 1) describe the architecture of sedimentary prisms, 2) complement conventional sequence stratigraphic interpretations by deducing the interplay of controls on sediment dispersal, and 3) support prediction of the timing and extensiveness of coarse-grained sediment bypass from shelf to deep basin e.g. the formation of basin-floor fans. Because of this, Shelf-edge trajectory analysis bears relevance to hydrocarbon exploration and geohazard assessment. The strong dip variability in lithology across clinoformal strata on continental margins means that significant post-depositional differential compaction is anticipated. Despite this, the role of differential compaction in modifying the primary stratal architecture of continental margin clinoforms and its impact on shelf-edge trajectories remains poorly constrained.

This study aims to determine the extent to which differential compaction modifies primary, near-surface trajectories, and to understand how this impacts the assessment of the controls on basin filling and deep-water sandstone prediction. Backstripping and decompaction was applied to outcrop, seismic and borehole data from a range of sedimentary basins including: Exmouth Plateau (NW Australia), van Keulenfjord (Spitsbergen, Norway), Karoo Basin (South Africa) and Washakie Basin (USA). Afterwards, shelf-edge trajectories were recalculated and compared to the original interpretations. Mud-rich bottomsets compact more than sand-rich topsets and flat-to-slightly-rising initial trajectories rotate basinward to appear as falling trajectories: hence the counterintuitive 'preservation' of topsets in flat and falling trajectories. Differential compaction also causes an apparent change in topset to foreset volume ratios (T/F) which have been linked to fluvial and basinal conditions on the shelf-edge and differences in the method of channel incision. Substantial changes in T/F ratios and the overall character of the trajectories imply that according to current models of sediment bypass and deep-water sand deposition, predictions made through shoreline trajectory interpretations may be inaccurate.

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Immediate propagation of deglacial environmental change to deep-marine turbidite systems along the Chile convergent margin

Bernhardt, Anne [1], Schwanghart, Wolfgang[2], Hebbeln, Dierk[3], Stuut, Jan-Berend[3,4], Strecker, Manfred R.[2]

[1]Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany
[2]Institute of Earth and Environmental Science, Potsdam University, Potsdam, Germany
[3]MARUM – Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany
[4]NIOZ – Royal Netherlands Institute for Sea Research, Department of Ocean Systems, and Utrecht University, Texel, The Netherlands

Understanding how Earth-surface processes respond to past climatic perturbations is crucial for making informed predictions about future impacts of climate change on sediment fluxes. Sedimentary records provide the archives for inferring these processes but their interpretation is compromised by our incomplete understanding of how landscapes and sediment-routing systems respond to millennial-scale climate cycles and how these signals propagate into the sedimentary sink.

Tracing the impact of climatic perturbations in deep-marine archives in regions with well documented climatic changes will improve our understanding of how environmental signals can be deconvolved in these ultimate sinks. In this study, we test how a pronounced, deglacial humidity decrease propagates into clastic deposits along the Chile continental margin (Fig. 1). In particular, we are interested in how the southward migration of the moisture-laden Southern Hemisphere Westerly Winds is reflected in the turbidite record of three study sites at 30°S, 32.5°S and 38-40°S. Therefore, we analyzed seven sediment cores recovered from marine turbidite depositional sites (Fig. 1A). The sites span a pronounced arid-to-humid gradient with variable topographic gradients and related connectivity of terrestrial and marine landscapes (Fig. 1A, B). These settings allowed us to study event-related depositional processes from the Last Glacial Maximum to present in different climatic and geomorphic settings. The turbidite record was quantified in terms of turbidite thickness and frequency. The three studied sites show a steep decline of turbidite deposition during deglaciation. High rates of sea-level rise significantly lag the decline in turbidite deposition by 3-6.5 kyrs. However, comparison to paleoclimate proxies shows that this spatio-temporal sedimentary pattern mirrors the deglacial humidity decrease and concomitant warming with little to no lag times.

Our results suggest that the deglacial humidity decrease resulted in a decrease of fluvial sediment supply, which propagated rapidly through the highly connected systems into the marine sink in north-central Chile. In contrast, in south-central Chilean systems, connectivity between the Andean erosional zone and the fluvial transfer zone probably decreased abruptly by the deglaciation of piedmont lakes, resulting in a significant and rapid decrease of sediment supply to the ocean. Additionally, reduced moisture supply may have also contributed to the rapid decline of turbidite deposition.

These different causes result in similar depositional patterns in the marine sinks. We conclude that turbiditic strata can act as reliable recorders of climate change across a wide range of climatic zones and geomorphic conditions. However, the underlying causes for similar signal manifestations in the sinks may differ, ranging from maintained high system connectivity to abrupt connectivity loss.

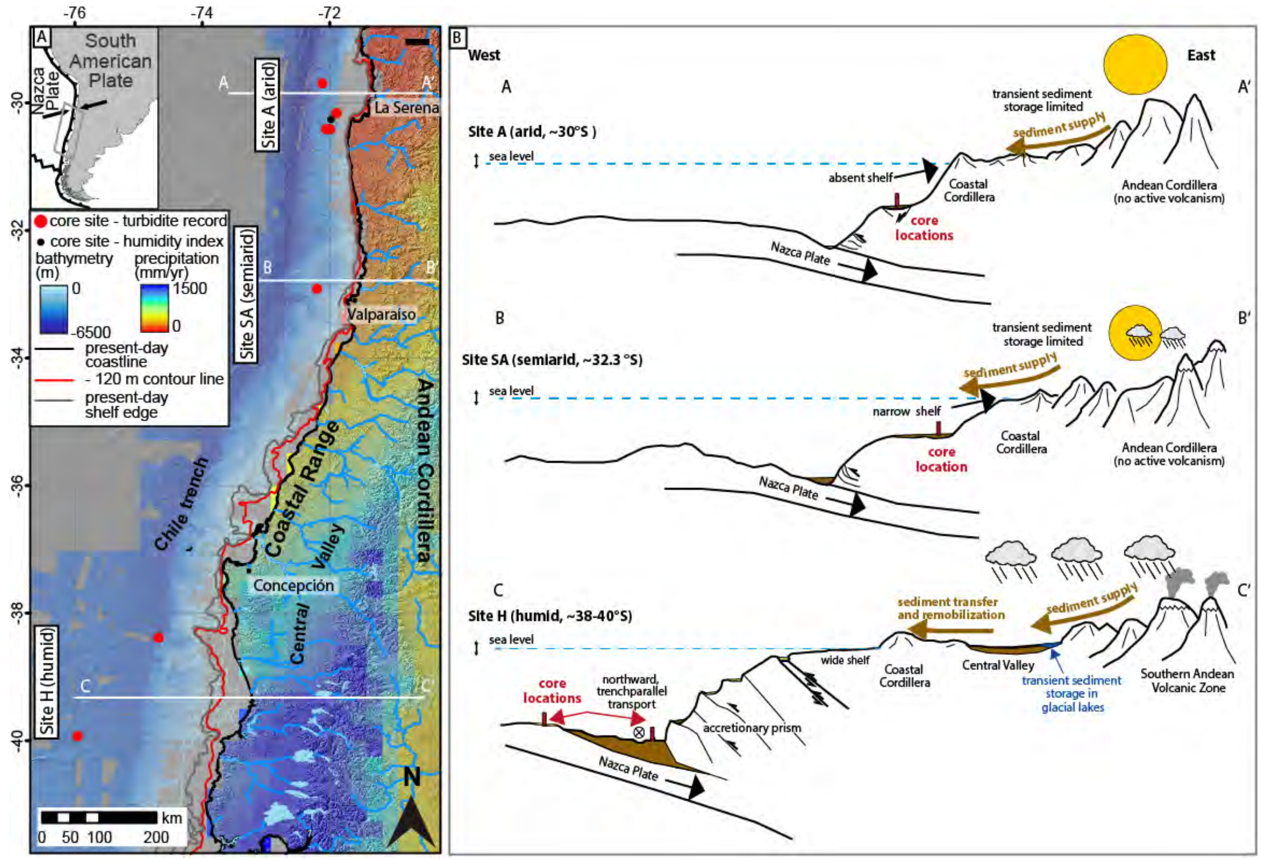

Figure 1. Overview of the three study sites. (A) Overview map of the Chile margin section showing draped with the mean annual rainfall distribution derived from the Tropical Rainfall Measurement Mission (TRMM) satellite (courtesy of B. Bookhagen, Potsdam University). Bathymetry is compiled from several RV Sonne research cruises and is underlain by a the hillslope-shade map derived from the Etopo1 database (http://maps.ngdc.noaa.gov). B) Schematic profiles illustrating the geomorphic differences of the hinterland gradients, transient sediment sinks, shelf width, and the continental slope of the three study sites. See Figure 1A for profile locations.

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Stratigraphic signals derived from physical modelling applied to outcrop studies

Jochem Bijkerk[1], Joris Eggenhuisen[2], Ian Kane[3], Paul Wignall[4], Colin Waters[5], Bill McCaffrey[4]

[1]Shell International E&P, The Hague, The Netherlands
[2]Utrecht University, Utrecht, The Netherlands
[3]University of Manchester, Manchester, England
[4]University of Leeds, Leeds, England
[5]British Geological Survey, Keyworth, England

Physical laboratory models bridge a gap between modern analogues and outcrop or subsurface data because the controlling input parameters, the temporal evolution of the sedimentary system, and the final stratigraphy are typically known at high temporal and spatial resolution. Therefore, such models enable insight to be developed into allo- and autogenic controls and the timescales at which these controls influence sedimentary systems to create the stratigraphic record. Here, results from several physical laboratory models exploring allogenic controls are described, and subsequently compared to the fluvial to marine deposits of the Millstone Grit sedimentary system, that infilled the equatorial Carboniferous Central Pennine Basin of Northern England, a series of passively subsiding, interconnected, sub-basins separated by tilt-block highs.

The equilibrium profile for fluvio-deltaic systems has been defined as the surface of full bypass, and provides a starting point for the study of source to sink sediment transport on geological time scales. Equilibrium is only achieved when the system does not prograde, or it progrades while relative sea level falls such that the prograding system forms a continuation of the equilibrium profile (Fig 1a); in this bypass state the system is fully efficient in sediment transport. When not at equilibrium, downstream mass extraction will typically occur along the transport system. Physical laboratory models, following the analogue scaling method, are used to explore the factors affecting how closely fluvio-deltaic systems can approach equilibrium. In scenarios with constant sea level, the greater the basin depth (i.e. the height of the water column at the toe of the slope) the lower the rate of progradation, allowing the system to reach closer to equilibrium and to transport a larger and coarser fraction of its sediment load to the shoreline (Fig 1b-d). This implies that in systems close to equilibrium the along-slope grainsize partitioning is limited, which promotes delivery of coarser-grained sediment fraction to the shelf and deeper marine sedimentary environments as well. Sea-level fall also pushes the system towards equilibrium conditions by inducing erosion of the low-gradient segment of the coastal fluvial system, with stronger erosion generated in deeper basins (Fig 1e-g). In extremely shallow basins, high rates of progradation can annul the effect of sea-level fall.

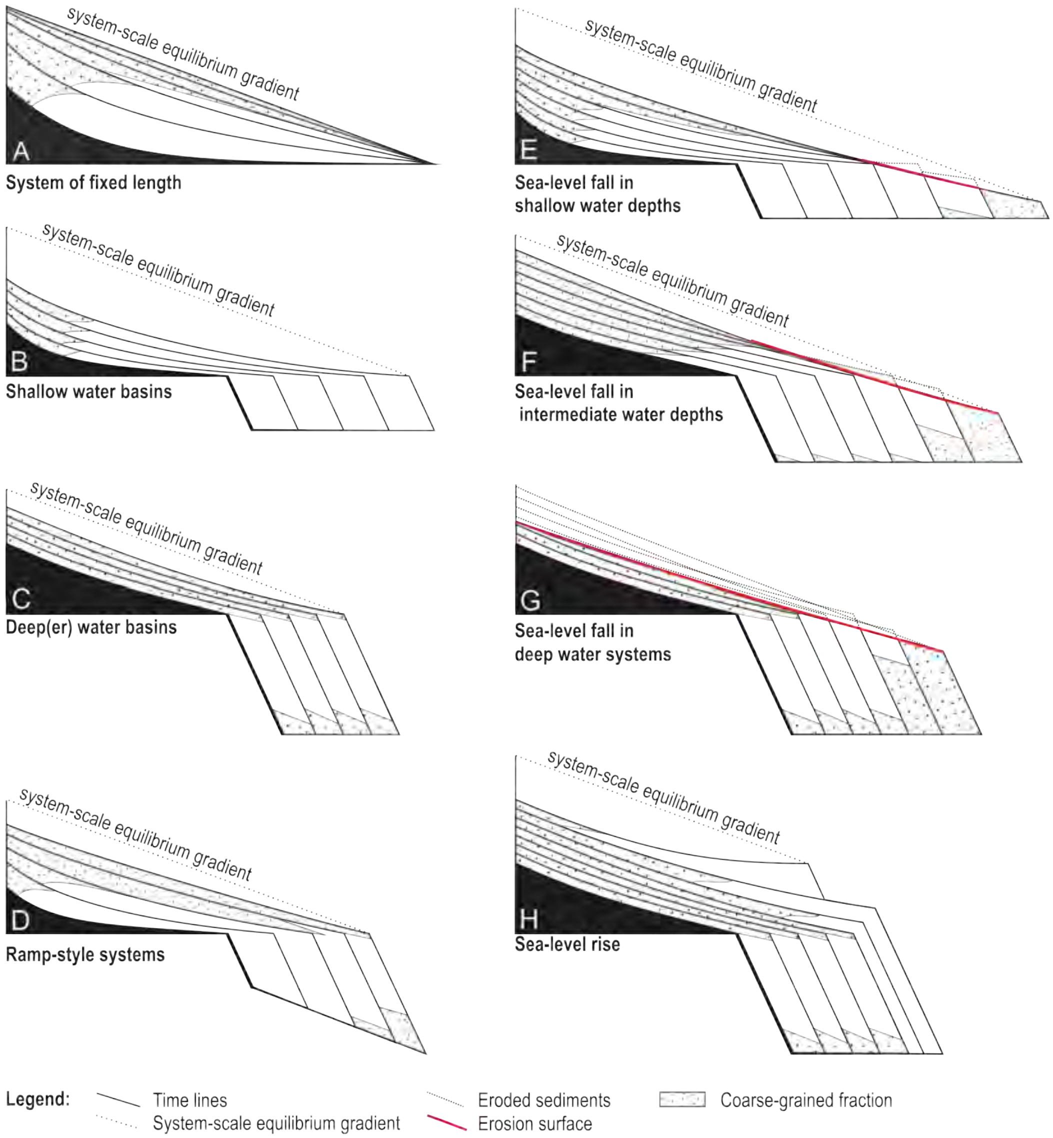

Figure 1) Influence of water depth on the longitudinal grade of sedimentary systems. Gradients and curvature are exaggerated.

Experiments examining sediment discharge pulses in the source area have found these to be transmitted inefficiently to the depositional domain. By way of contrast, increases in water discharge result in increased efficiency of sediment transfer from the source area to the sink, because it decreases the equilibrium slope along the entire system. Multiple experiments with water discharge variations at equal periodicity as the sea-level fluctuations, but shifted in phase, all indicate more prominent erosion during sea-level fall compared to a control experiment with constant discharge: increases in water discharge during sea-level fall lead to high sediment supply to the delta front and the development of well-developed incised valleys that are connected to the trunk river. Decreases in discharge during sea-level fall result in a decreased sediment supply, and the subsequent development of disconnected erosional shelf edge gullies. Discharge variations therefore alter the morphology of the delta, and the timing of high sediment supply from the transfer system to the sink. Discharge variations at significant higher frequency than sea-level variations did not influence the experimental stratigraphy, but might be expressed in sedimentary facies variability within deposits.

The overview of the stratigraphic effects of allogenic-forcing is used to interpret stratigraphic patterns in the Millstone Grit Group. The Millstone Grit forms a cyclical progradational succession characterized by ~47 discrete flooding events marking eustatic sea-level highstands at ~100 ky periodicity. During sea-level fall, coarse-grained fluvio-deltaic systems prograded into the Central Pennine Basin and over ~10 million years progressively infilled successive sub-basins. Typically, the deepest incised valleys occur where fluvial systems incised into the highest shelf margins; such scenarios are associated with the transfer of substantially larger sediment volumes into associated deeper water depositional systems (Fig 2). When the system prograded into shallower basins or across a drowned shelf, shallower incised valleys were typically formed, or no erosion occurred. Lateral variations in shelf-margin height appear to have steered the positions of fluvial systems, increasing the likelihood of valley incision in specific locations. In particular, basin depocenters seem to act as attractors to incised valleys, possibly due to more efficient headward erosion of shelf edge gullies connecting to the trunk river system. The underlying control on these observations is inferred to be that of basin depth on the bypass efficiency of the Millstone Grit fluvial system, and hence the ability for valley incision. Based on literature review other systems exhibit similar features, suggesting that basin depth or shelf height has significant implications for the efficiency of sediment transport and the possibility of clastic reservoir development in e.g. turbidite systems.

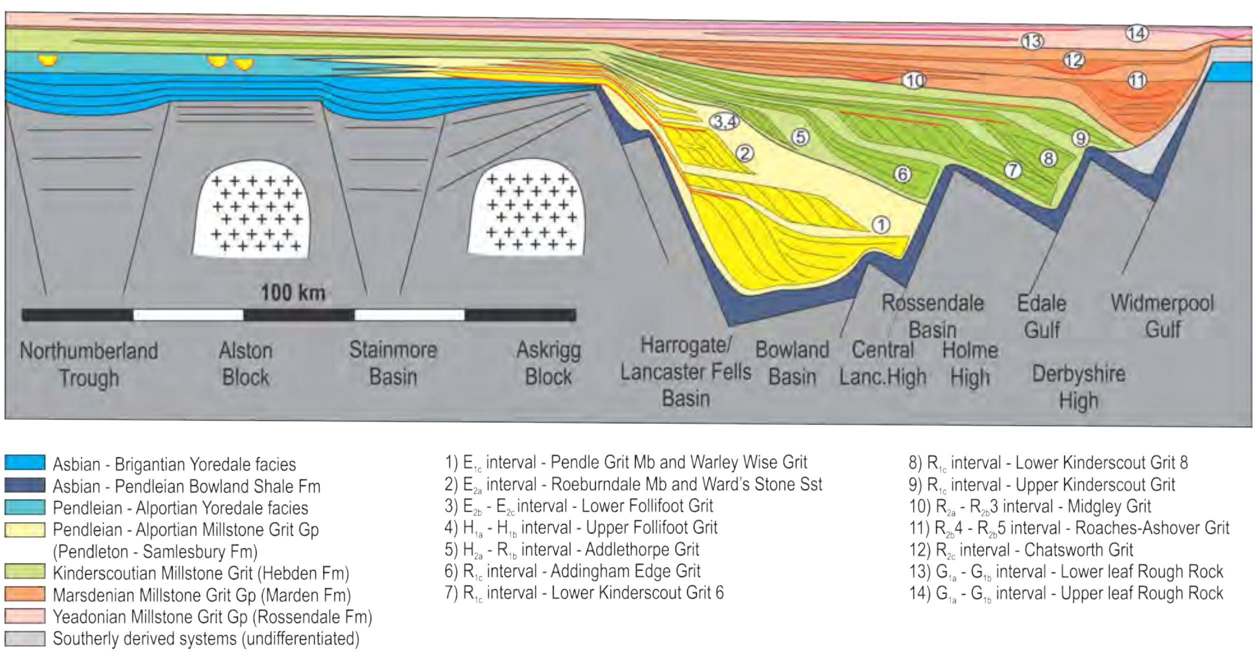

Figure 2) Cross section through the Pennine Basin, indicating the major depositional units of the Millstone Grit depositional system. Units 1, 7 and 11 build out into deeper basins and are characterized by their deeper incised valleys and large sediment volumes.

Sedimentological observations of the Millstone Grit succession suggest water discharge variations form an important additional control. Gilbert deltas that formed within the incised valleys during sea-level rise are thought to be affected by river floods, based on deposits interpreted as generated by prolonged hyperpycnal flows. Such deposits are not present in Gilbert deltas deposited during early sea-level fall. When considered in combination with further climate indicators, these observations suggest variations in water discharge that would fit with a monsoonal climate.

Physical models provide a means of understanding the effects and timescales of different types of allogenic forcing on sediment transport and mass extraction from source areas to the depositional sink. Based on this understanding, more detailed hypotheses can be formulated compared to a regular sequence stratigraphic framework that aid the interpretation of sedimentary systems for which the allogenic controls are unknown.

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Indentation of the Pamirs with respect to the northern margin of Tibet: Constraints from the SW Tarim basin sedimentary record

Tamsin Blayney[1], Yani Najman[1], Guillaume Dupont-Nivet[2, 3, 4], Andrew Carter[5], Ian Millar[6], Eduardo Garzanti[7], Edward R. Sobel[3 *], Martin Rittner[8], Sergio Andò[7], Zhaojie Guo[4], and Giovanni Vezzoli[7]

[1]Lancaster Environment Centre, Lancaster University, Bailrigg, UK
[2]Géosciences Rennes, Université de Rennes 1, Rennes, France,
[3]Institut für Erd- und Umweltwissenschaften, Universitaet Potsdam, Potsdam, Germany
[4]Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, Beijing, China
[5]Department of Earth and Planetary Sciences, Birkbeck College, London, UK
[6]NERC Isotope Geosciences Laboratory, BGS Keyworth, Nottingham, UK
[7]Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, Milano, Italy
[8]Department of Earth Sciences, University College London, London, UK
[*]Presenting author

The Pamirs represent the indented westward continuation of the northern margin of the Tibetan Plateau, dividing the Tarim and Tajik basins. Although their evolution may be a key factor influencing aridification of the Asian interior, the tectonics of the Pamir Salient are poorly understood. In particular, when and how the northern margin of Tibet evolved and the Pamir range indented and uplifted are poorly documented. We present a provenance study of the Aertashi section, a Paleogene to late Neogene clastic succession deposited in the SW Tarim basin to the north of the NW margin of Tibet (the West Kunlun) and to the east of the Pamirs.

Our detrital zircon U-Pb ages coupled with zircon fission track, bulk rock Sm-Nd, and petrography data document changes in contributing source terranes during the Oligocene to Miocene, which can be correlated to regional tectonics. We propose a model for the evolution of the Pamir and West Kunlun (WKL), in which the WKL formed topography since at least ~200 Ma. By ~25 Ma, movement along the Pamir-bounding faults such as the Kashgar-Yecheng Transfer System had commenced, marking the onset of Pamir indentation into the Tarim-Tajik basin. This is coincident with basinward expansion of the northern WKL margin, which changed the palaeodrainage pattern within the Kunlun, progressively cutting off the more southerly WKL sources from the Tarim basin. An abrupt change in the provenance and facies of sediments at Aertashi has a maximum age of 14 Ma; this change records when the Pamir indenter had propagated sufficiently far north that the North Pamir was now located proximal to the Aertashi region.

At <11 Ma, petrography and heavy minerals show dominant influx from a penecontemporaneous volcanic unit. The sample at <11 Ma shows an increased resemblance to the modern Yarkand River, in terms of the first sparse occurrence of Cretaceous aged zircons, yet the petrography remains distinct. The Yarkand River in its current form, with a drainage basin encompassing an extensive area of the southern Pamirs, was primarily established after deposition of our youngest,

<11 Ma old sample. This suggests that the evolution of the Kongur Extensional System and the Mustagh Ata gneiss dome, presently lying to the west of Aertashi, significantly altered the regional fluvial network.

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Reconstructing continental-scale paleodrainage and sediment routing from detrital zircons: examples from Mesozoic and Cenozoic North America

M. Blum

Department of Geology, University of Kansas. Lawrence, Kansas 66045 USA

The source-to-sink approach explicitly considers the rate and unsteadiness of sediment production and routing to depositional basin. Accordingly, source-to-sink studies require quantitative to semi-quantitative insight about source terrain, including parameters like contributing drainage area and relief, which can lead to estimates of sediment flux. This presentation discusses changes in North American Mesozoic and Cenozoic paleodrainage and sediment routing, based largely on the rapidly increasing numbers of detrital zircon studies.

At the regional to continental scale, patterns of Mesozoic and Cenozoic paleodrainage and sediment routing in North America are directly coupled to major long-lived tectonic and physiographic features, including: (a) the Paleozoic Appalachian-Ouachita Cordillerra of the eastern US and Canada, (b) the Mesozoic Western Cordillera of Mexico, the US and Canada, (c) the Mesozoic evolution of western North America from a passive margin to a retroarc foreland-basin system, and (d) the Mesozoic opening and subsequent Cenozoic evolution of the Gulf of Mexico passive margin sedimentary basin.

Assembly of the Appalachian-Ouachita Cordillera along eastern and southern Laurentia had a profound impact on Mesozoic and Cenozoic sediment routing. Detrital zircon records from Wyoming and the Grand Canyon in Arizona first show large-scale east-to-west transfer of Appalachian-Ouachita derived sediment beginning in the late Paleozoic. However, the actual routing systems remain difficult to identify and may not be preserved. The Triassic Chinle Formation in the southwestern US represents the first well-documented trans-continental fluvial system that is preserved in the stratigraphic record: detrital zircon records show the Chinle drained the southern Appalachian-Ouachita cordillera in Oklahoma, Texas and Mexico, and routed sediments to the western US margin in what is now Nevada. Estimated Chinle paleodrainage is ~$1.5*10^6$ km^2, with an estimated length scale of 1500 km: for comparison sake, a drainage basin of this scale would rank in the top 20 of Earth's modern-day river systems. The Chinle therefore represents a large system in its own right, but represents only a small part of the drainage of Laurentia for this time, and the rest remains poorly known. At this time, the Gulf of Mexico was in its early rift stage, and received detritus from the rifted margins only, likely through a series of short and relatively steep fluvial systems.

The general pattern of transcontinental, east-to-west sediment dispersal continued until the middle Jurassic, by which time the Western Cordillera had evolved to the point where proximal foredeeps were filled and marine conditions were no longer present, and sediments from the advancing fold and thrust belt were routed back to the east. This change in routing is recorded by the Late Jurassic Morrison Formation, interpreted to have been deposited in the Western

Cordillera backbulge depozone. The Morrison is the first large-scale routing system to have a detrital zircon record that features reworked Appalachian-Ouachita populations, derived from passive margin sediments that were then entrained in the advancing Western Cordillera fold and thrust belt, coupled with primary signals from the Western Cordillera magmatic arc. The continental-scale context for the Morrison is unclear, and a Morrison terminal sink has not been clearly identified, but the west-derived Morrison may have been part of an integrated drainage network that merged in the continental interior with Appalachian-derived systems, and flowed to the north towards an early Western Interior Seaway.

The pattern of convergence between west-to-east flowing river systems from the Western Cordillera, and east-to-west flowing river systems from the Appalachians, with northward sediment transport thereafter, characterized the early to middle Cretaceous, and produced the Aptian-Albian Mannville Group of the Alberta foreland basin. The Mannville routing system represents the Mississippi or Amazon of its time, with paleodrainage areas estimated to have been $3\text{-}6*10^6$ km^2. Here again, the routing system is well preserved, but the terminal sink is not well understood, and was perhaps eroded away by late Cenozoic glaciation: a back-of-the-envelope estimate suggests ~6-700,000 cubic kilometers of sediment from this paleodrainage is unaccounted for. At this time, the Gulf of Mexico was fully developed, but total contributing drainage area was $<1*10^6$ km^2, south of the Appalachian-Ouachita cordillera, and individual fluvial systems were modest in scale. Nevertheless, the mid Cretaceous represents the first time that significant volumes of fluvial sediment were routed to the Gulf of Mexico, and formed an integrated fluvial-deltaic to shelf margin to basin-floor fan sediment dispersal system.

Development of a continuous late Cretaceous Western Interior Seaway, from the Arctic to the Gulf of Mexico, likely played a major role in disruption of this continental-scale drainage pattern. The east-to-west and west-to-east dichotomy for sediment routing, forced by the Appalachian-Ouachita and Western Cordilleras, respectively, remained in place for the southern half of North America, but withdrawal of the seaway during the early Paleocene led to rerouting of fluvial systems to the Gulf of Mexico, which set up the general continental-scale template that persists today. In the Paleocene and early Eocene, much of the western US drained to the western Gulf of Mexico, and the ancestral Mississippi was a secondary system: this western fluvial system had headwaters in the Cordilleran arc from southern California to Idaho, as well as the Laramide Rocky Mountains, and an estimated drainage area of $1.5\text{-}2.8*10^6$ km^2. This fluvial system produced the laterally-extensive and thick Paleocene-early Eocene Wilcox fluvial-deltaic strata of the Texas coastal plain, plus basin-floor fans that extend >500 km basinward from the contemporaneous shelf margin into the deep Gulf of Mexico, which contain >750,000 km^3 of sediment. Contemporaneous late Cretaceous and younger drainage of Canada is unclear, but it seems likely that, following seaway withdrawal, the foreland basin system filled with sediment, and river systems were routed from the Canadian Rocky Mountains to the Atlantic margin.

Western US tectonics and active volcanism in the Eocene resulted in eastward migration of the Gulf of Mexico vs. Pacific drainage divide, such that the Cordilleran arc and the Sevier fold and thrust belt no longer contributed sediment to the Gulf, and instead drained to the Pacific margin or to closed lacustrine basins within the Laramide province. By the Oligocene and early Miocene, the ancestral Mississippi system, with east-derived Appalachian and west-derived Rocky Mountain tributaries, had emerged as the largest sediment routing system for the Gulf of

Mexico, a pattern that continues to today. However, it did not reach its present configuration until Quaternary ice sheets diverted rivers that flowed from the northern US towards Canada and the Atlantic margin, to the south and the Gulf of Mexico. The pinnacle, or zenith, of the Quaternary Mississippi system actually occurs during glacial periods, when the Mississippi and its tributaries drain the continental ice sheet, and almost 50% of Canada is routed to the Gulf of Mexico as well. Indeed, the entire source-to-sink Mississippi system is "turned on" only during glacial periods, with sediment routing through the drainage network to the shelf margin, slope canyons, and the basin-floor fan. The interglacial drainage area of $>3.4*10^6$ km^2 is modest by comparison, with reduced water and sediment flux, and storage of all sediment on the shelf, such that the basin-floor fan system is effectively "turned off".

Decoding sediment transport dynamics on alluvial fans from spatial changes in grain size, Death Valley, California

Sam Brooke[1]; Alexander Whittaker[1]; Stephen Watkins[1]; John Armitage[2]

[1]Department of Earth Science and Engineering, Royal School of Mines, Imperial College, London, SW7 2AZ, United Kingdom
[2]Institut de Physique du Globe de Paris, Dynamique des Fluides Geologiques, 1 rue Jussieu, 75238 Paris, Cedex 05, France

How fluvial sediment transport processes are transmitted to the sedimentary record remains a complex problem for the interpretation of fluvial stratigraphy. Alluvial fans represent the condensed sedimentary archive of upstream fluvial processes, controlled by the interplay between tectonics and climate over time, infused with the complex signal of internal autogenic processes. With high sedimentation rates and near complete preservation, alluvial fans present a unique opportunity to tackle the problem of landscape sensitivity to external boundary conditions such as climate.

For three coupled catchments-fan systems in the tectonically well-constrained northern Death Valley, we measure grain size trends across well-preserved Holocene and Late-Pleistocene deposits, which we have mapped in detail. Our results show that fan surfaces from the Late-Pleistocene are, on average, 50% coarser than counterpart active or Holocene fan surfaces, with clear variations in input grain sizes observed between surfaces of differing age. Furthermore, the change in ratio between mean grain size and standard deviation is stable downstream for all surfaces, satisfying the statistical definition of self-similarity.

Applying a self-similarity model of selective deposition, we derive a relative mobility function directly from our grain size distributions, and we evaluate for each fan surface the grain size for which the ratio of the probability of transport to deposition is 1. We show that the "equally mobile" grain size lies in the range of 20 to 35 mm, varies over time, and is clearly lower in the Holocene than in the Pleistocene. Our results indicate that coarser grain sizes on alluvial fans are much less mobile than in river systems where such an analysis has been previously applied.

These results support recent findings that alluvial fan sediment characteristics can be used as an archive of past environmental change and that landscapes are sensitive to environmental change over a glacial-interglacial cycle. Significantly, the self-similarity methodology offers a means to constrain relative mobility of grain sizes from field measurements where hydrological information is lost or irretrievable.

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Quantifying alluvial fan sensitivity to climate in Death Valley, California from field observations and numerical models

Sam Brooke[1]; Alexander Whittaker[1]; John Armitage[2]; Mitch D'Arcy[3]; Stephen Watkins[1]

[1]Department of Earth Science and Engineering, Royal School of Mines, Imperial College, London, SW7 2AZ, United Kingdom
[2]Institut de Physique du Globe de Paris, Dynamique des Fluides Geologiques, 1 rue Jussieu, 75238 Paris, Cedex 05, France
[3]Institute of Earth and Environmental Science, University of Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam-Golm, Germany

A quantitative understanding of landscape sensitivity to climate change remains a key challenge in the Earth Sciences. The stream-flow deposits of coupled catchment-fan systems offer one way to decode past changes in external boundary conditions as they comprise simple, closed systems that can be represented effectively by numerical models. Here we combine the collection and analysis of grain size data on well-dated alluvial fan surfaces in Death Valley, USA, with numerical modelling to address the extent to which sediment routing systems record high-frequency, high-magnitude climate change.

We compile a new database of Holocene and Late-Pleistocene grain size trends from 11 alluvial fans in Death Valley, capturing high-resolution grain size data ranging from the Recent to 100 kyr in age. We hypothesise the observed changes in average surface grain size and fining rate over time are a record of landscape response to glacial-interglacial climatic forcing. With this data we are in a unique position to test the predictions of landscape evolution models and evaluate the extent to which climate change has influenced the volume and calibre of sediment deposited on alluvial fans.

To gain insight into our field data and study area, we employ an appropriately scaled catchment-fan model that calculates an eroded volumetric sediment budget to be deposited in a subsiding basin according to mass balance where grain size trends are predicted by a self-similarity fining model.

We use the model to compare predicted trends in alluvial fan stratigraphy as a function of boundary condition change for a range of model parameters and input grain size distributions. Subsequently, we perturb our model with a plausible glacial-interglacial magnitude precipitation change to estimate the requisite sediment flux needed to generate observed field grain size trends in Death Valley. Modelled fluxes are then compared with independent measurements of sediment supply over time. Our results constitute one of the first attempts to combine the detailed collection of alluvial fan grain size data in time and space with coupled catchment-fan models, affording us the means to evaluate how well field and model data can be reconciled for simple sediment routing systems.

Strategies for developing pre-Holocene paleo-environmental records: application of detrital cosmogenic data to paleo-erosion rates

Douglas W. Burbank

Dept. of Earth Science, University of California, Santa Barbara, CA 93106, USA

In any attempt to interpret the environmental significance of a detrital "signal" within the sedimentary record, several questions should be addressed: how does the signal reflect the geomorphic, climatic, and/or tectonic processes that created it; from where in the hinterland did the sediment of interest come and what happened to it on its pathway to the basin where it now resides; under what conditions did the signal get preserved; how has the signal been modified since deposition; and what is the temporal framework within which the signal should be interpreted? Here I focus primarily on applications of detrital cosmogenic raidonuclides, but these questions are relevant to most paleo-environmental records preserved in sedimentary successions.

Over the past several decades, the proliferation of digital elevation models (DEMs) and the expanded use of concentrations of cosmogenic radionuclides (CRNs) in rocks and sediments has re-invigorated and revolutionized many facets of geomorphology by providing a level of quantification that was previously absent. In the past, modern catchment erosion rates were commonly calculated using approaches such as stream gauging or measured reservoir volumes. For steep rivers descending through alpine topography, bedloads were typically unmeasured, but simply estimated as a fraction of the suspended load. Presently, however, thousands of catchment-averaged erosion rates have been estimated from CRN concentrations in detrital sediments. These rates have been shown to correlate with both average hillslope angles (up to a threshold) and normalized channel steepness in catchments, thereby providing some insight on the geomorphic conditions that control erosion rates. The long-standing debate about whether climate or tectonics controls erosion rates is (and will likely remain) unresolved, but in actively deforming mountain belts, it seems that tectonics exerts the dominant control.

Because a handful of sand holds a half million grains that are assumed to represent contributions from throughout a catchment, CRN-derived rates are interpreted to be representative of an entire catchment. CRN results from regional studies comprising multiple catchments are commonly used to infer spatial variations both in erosion rates and in long-term rock-uplift rates. But, the validity of these assumptions critically depends on approximately uniform distributions of quartz throughout a catchment and typically assumes incremental (grain-by-grain) erosion, rather than episodic removal of material by landslides. In addition, because glacial ice both shields the rock beneath it from effective cosmic radiation and contributes sediment by abrading and plucking this un-dosed rock, glaciated basins yield lower CNR concentrations and higher interpreted erosion rates than do nonglacial basins with comparable erosion rates. Nonetheless, many studies assume that impact of recent glaciation is negligible. With sufficient, carefully collected data, numerical modeling studies suggest that both landslide inputs and glacial contributions can be accounted for. For example, except for unusually large landslides, collecting CRN data only for basins larger than ~25 km^2 will common;y integrate sufficient area to substantially mute erosion-rate perturbations due to individual landslides. Similarly, statistical methods can be used to account for the impact of partially glaciated catchments.

For ancient basins where the morphology of the contributing catchments has been largely obliterated, the provenance of the sediments being examined becomes important. Were they derived from a consistent source area or several different ones, and did their source area evolve over time. An array of sediment tracers has been used to try to document changes in provenance through time. Sometimes, sandstone petrology or unique mineral or clast assemblages provide unambiguous evidence for persistent or evolving source areas. With the advent of inexpensive, U-Pb dating of single zircon grains, a potent sediment tracer has become accessible to many basin-analysis studies. Once the age distribution of diverse source areas has been determined (commonly using detrital samples that collect zircons from throughout a source area), systematic sampling and detrital zircon dating (100-200 dates per sample) of a stratigraphic section can be used to test of changes in provenance through time. Typically a few, discrete age clusters within a much larger zircon-age population are shown to characterize specific source areas. Examples from NE Tibet, the Himalaya, and the Andes illustrate how a detrital zircon age signal may evolve downstream, the insights such evolution may give on the relative contributions from tributary catchments, and how the pattern of changing source areas can be reliably determined.

The transit history of sediments commonly remains unknown: to what extent have sediments been recycled; did they sit in sandbars for millennia; or were they swept downstream in a single storm? In theory, the use of three or more cosmogenic isotopes on the same sample could permit calculation of transport times. But, at present, the uncertainties in CRN measurements preclude their use to meaningfully assess transport times. Sediment-accumulation rates in basins may provide some useful clues. For example, rapid subsidence deduced from sediment successions in foreland basins suggests both high rates of sediment delivery and a proximal, growing tectonic load. These interpretations, along with the observed narrow gorges in active orogens and the relatively brief time that sediments are likely to reside in the top 2-3 meters (where they accumulate more CRNs), suggest short transport times from the sites of erosion to depositional basins in many active orogens. Despite such inferences, however, robust documentation of sediment-transport times remains an open question needing innovative techniques and analyses to unravel.

In the absence of abundant, well-constrained biostratigraphic data or numerous interbedded volcanic ashes, reliable time control for sedimentary sections is commonly difficult to attain. Yet, such temporal control is needed not only to guide correlations and pinpoint the timing of events, but also to reconstruct sediment-accumulation and subsidence rates: key attributes and descriptors of most stratigraphic sections. Because fine-grained iron-bearing detrital sediments orient in the ambient magnetic field at the time of deposition, they record past reversals of Earth’s magnetic field and underpin the creation of magnetic polarity stratigraphies through sedimentary sections. In the absence of external time control from fossils or ashes, however, even long records of multiple successive magnetic reversals may resist unambiguous correlation to the magnetic polarity time scale. Given assumptions of nonrandom sediment-accumulation rates, just a few biostratigraphic or radiometric tie points are typically needed to generate a convincing correlation to the magnetic time scale. In some fine-grained sections, cyclic variations in magnetic susceptibility appear to provide temporal resolution at Milankovitch time scales (20-100 kyr). Slow rates of sediment accumulation (<0.1 mm/yr) in terrestrial basins guarantee that newly deposited sediments will spend ≥20 kyr in a CRN "production" zone, during which time their concentrations of CRNs will increase: a process that can obscure the original catchment-derived concentrations, especially in the catchment erosion rates exceed 0.1 mm/yr – more rapid erosion means lower CRN concentrations. Similarly, in the process of exposing a stratigraphic succession, the rapidity of exhumation is inversely proportional to how much additional CRN production occurs as each layer nears the surface. Clearly, rapid exhumation is preferable.

An example of a source-to-sink environmental signal derived from detrital CRN concentrations from the Andes of NW Argentina will be described. There, along the Rio Iruya in the Andean foreland, a magnetic polarity stratigraphy that is punctuated by five, precisely dated volcanic ashes provides a robust chronology from ~5.5 to 1.7 Ma. Sediment-accumulation rates averaged ~1 mm/yr across this interval, thereby suggesting rapid burial. Notably, exhumation rates of ~1 meter/yr indicate essentially no additional CRN production occurred since burial. U-Pb ages of detrital zircons from (i) hinterland source areas, (ii) major stratigraphic groups (Neogene to Precambrian) in the region, and (iii) a dozen stratigraphic levels in the Iruya section allow tracking of provenance changes through time. These data suggest the Altiplano (with abundant Neogene volcanics) was a significant source area between ~4 and 2.2 Ma, whereas that Neogene signal is lost prior to ~4 Ma and after 2.2 Ma. Structural and stratigraphic data in the nearby eastern Andes, along with >50 dates ashes, provide data consistent with this interpretation. Within the dated Iruya strata in the foreland, 28 ^{10}Be and 21 ^{26}Al detrital cosmogenic samples were analyzed. Temproal changes in CRN concentrations reveal intervals prior to 4 Ma and after 2.2 Ma characterized by relatively rapid erosion rates that display irregular, 2- to 4-fold variations through time. Remarkably, the 2.2-to-4 Ma interval shows four distinct, repetitive cycles of erosion that are each ~400-kyr long and are well synchronized with the 400-kyr eccentricity cycles. Each cycle is defined by 4 to 6 data points and show relatively steady, cyclic variation through time. We think that no such well-constrained record of pre-Pleistocene terrestrial erosion rates has been previously described. The drivers for such long-term cyclicity, one that far exceeds the well-documented 20- to 100-kyr climate cycles, remain uncertain, although landscape resonance in response to cyclic forcing[1] is one possibility.

[1]Godard, V., Tucker, G. E., Burch Fisher, G., Burbank, D. W., and Bookhagen, B., 2013, Frequency-dependent landscape response to climatic forcing: Geophys. Res. Lett,, v. 40, 859-863.

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Impact of tectonics, climate and eustasy on stratigraphic architecture and depositional profile evolution in the Graus-Tremp-Ainsa Basin during Lower Eocene times

CHANVRY Emmanuelle[1], DESCHAMPS Rémy[2], JOSEPH Philippe[2], GARCIA Daniel[3] and PUIGDEFABREGAS Cai[4]

[1] TOTAL, Pau, France
[2] IFP Energies nouvelles, Rueil-Malmaison, France
[3] ENSM, St Etienne, France
[4] Barcelona University, Barcelona, Spain

The aim of this contribution is to constrain and hierarchize the impact of the controlling factors (tectonics, climate and eustasy) acting at different time and space scales in the active Graus-Tremp-Ainsa piggyback basin succession. In order to discriminate the influence of the local and the regional controlling factors, especially the tectonic impact proper to the piggyback evolution, we investigate the Lower Eocene times, from the Ilerdian (Claret Conglomerates) to the Cuisian (Castissent Formation). This period corresponds to the development of the Montsec frontal thrust which caused the southward transport of the Graus-Tremp-Ainsa piggyback basin.

The sedimentary succession in the Graus-Tremp-Ainsa basins is exposed along the Tremp syncline from the Figols de Tremp village, to the San Esteban Hermitage near the Charo village, 75 km westward (Fig. 1). Five regional reference sections over a total of twenty sections were used to constrain the correlation of the succession from the Paleocene Garumnian/Navarri Formations to the Cuisian Castissent Formation.

We identify facies associations and reconstruct four successive depositional systems that include all depositional environments, from the alluvial fan to the turbiditic basin. Then we propose a new sequence stratigraphy framework with three levels of hierarchy, allowing us to proceed to a multi-scale analysis. This approach based on a new age model, the computation of accommodation curves and the comparison with eustasy and climate curves lead us to discriminate the dominant controlling factors acting at a regional versus local scale (respectively at the world / orogeny scale and at the scale of the piggy-back thrust sheet). Local tectonic controls are identified by rapid thickness variations, abrupt changes of environments, local or intense erosion, change of sedimentary processes, change of current directions and difference in accommodation rate between sections.

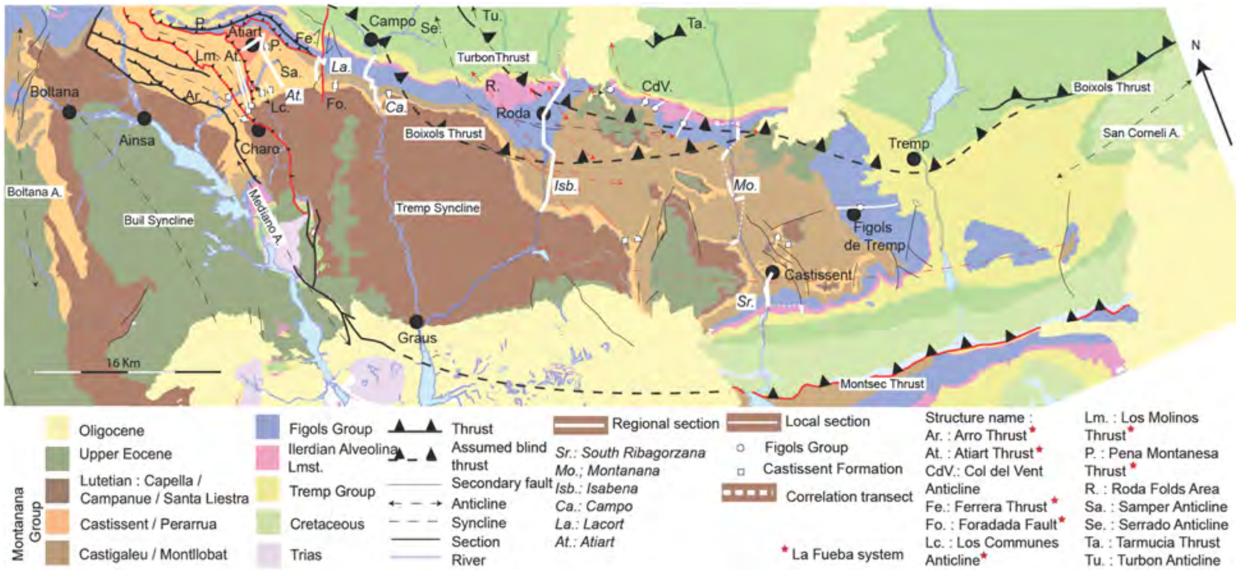

***Figure 1**: Geological map of the Graus-Tremp-Ainsa Basin. Cartography of Aragon area is from IGME maps. The Cataluna area is mapped from the geological map of Cataluna 1/250000. Structural features in the Roda de Isabena area and Boixols thrust are from Lopez-Blanco et al. (2003) and Ardèvol et al. (2000). Coll del Vent anticline location is from Vincent (2001). Red structures are considered as active during our studied interval (Ypresian). Location of measured sedimentological sections is specified.*

The result of our work is twofold. First we improve the understanding of the tectonic evolution of the Graus-Tremp-Ainsa basin. The main depositional sequences (TE1 to TE4; recognized first by Puigdefàbregas and Souquet, 1986), lasted approximately 1 to 3 Ma, and correspond to four main episodes of the basin evolution, characterized by four distinct depositional profiles. Especially, we identified 1) an underfilled stage with first a high flexural subsidence and a frontal anticline blind thrust tectonic control in a dominantly carbonate environment, followed by an increase of siliciclastic sediment supply (corresponding to the TE1/TE2), 2) an overfilled stage with an increase of the frontal thrust activity which evolves from an active emerged anticline blind thrust to a migrating thrust with lateral ramps which cause the decoupling of the Graus-Tremp uplifted wedge-top basin and the Ainsa subsiding foredeep domain (corresponding to the TE3/TE4).

Secondly, we propose a hierarchy of the controlling factors. At the larger studied resolution, the piggyback basin presents an underfilled and an overfilled stages driven by regional processes, i.e., flexural subsidence and orogeny uplift, which modulate sediment supply and accommodation. In this piggyback structural context, the thrust migration, which can decouple the overfilled basin from the underfilled one, induced the sediment supply increase by emergence of sedimentary thrust sheets. The eight Long Term Sequences constituting the TE depositional sequences, with an average duration of one million years, are mainly controlled by the alternation between intrabasinal quiescence periods and tectonics activity, resulting from the Montsec thrust migration. The southward migration of the thrust induced the development of lateral ramps that partitioned the basin, with local folding creating more subsiding depocenters. The Short Term Sequences, which show a period of about 400000 years, are mostly controlled by climate-eustatic variations, which are well-expressed during the early stage of piggy-back development, and during periods of relative tectonic quiescence of the underfilled basin stage. Hyperthermal climate events, such as PETM, ELMO (ETM2) and X-event (ETM3), are recognized in the stratigraphic record and might have enhanced on a short time period the sediment supply by increasing the precipitations and related erosion.

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Mineralogical distributions and their controlling factors in the Graus-Tremp-Ainsa Basin during Lower Eocene times

CHANVRY Emmanuelle[1], GARCIA Daniel[2], JOSEPH Philippe[3], DESCHAMPS Rémy[3] and TEINTURIER Stéphane[1]

[1] TOTAL, Pau, France
[2] ENSM, St Etienne, France
[3] IFP Energies nouvelles, Rueil-Malmaison, France

Lower Eocene sections from the Graus-Tremp-Ainsa Basin (Spain) show well exposed siliciclastic sequences encompassing continental to deep-sea accumulations in a foreland basin. The tectonic framework is dominated by the rise of the Pyrenean axial domain and the development of the Montsec frontal thrust which caused the transport of the Graus-Tremp-Ainsa piggyback basin. The climatic evolution from 56 to 48 My shows a general warming trend up to the Early Eocene Climatic Optimum (EECO) with short-term hyperthermal events (PETM, ELMO, X-EVENT).

The aim of this contribution is to constrain the controlling factors of the mineralogical distribution in the Graus-Tremp-Ainsa Basin, between the Aren Sandstone (Maastrichtian) and the Castissent Formation (Middle Cuisian). In order to unravel these controlling factors acting at different time and spatial scales and to get a basinscale view of mineral distribution, we develop a methodology to integrate a large number of consolidated samples, from various lithologies and grainsizes into a high resolution sequence stratigraphic framework. An automated mineralogy is derived from whole-rock geochemical data, and calibrated against direct mineral quantifications (petrography, DRX, Qemscan, microprobe).

Different parts of the basin show contrasting diagenetic overprints. The Graus-Tremp Basin presents an extensive kaolinisation of the uppermost units driven by meteoric fluid circulations and a preservation of the initial mineralogy in the lowermost units. The Ainsa Basin shows a severe albitisation of sandstones, coupled with the illitisation of smectites and the loss of the kaolinite in the lutites, in relation to burial. The primary mineral distributions are tentatively reconstructed and ascribed to different types of sediment sources. Tectonic forcing induces mineralogical variations in sandstones at the My timescale. These variations point to changes in sediment sources driven by the competing effects of intrabasinal tectonics (local thrust displacements) versus basinscale flexural subsidence linked to the orogen loading. The eustatic impact is expressed in short-term cycles (from 200 to 400 ky), and drives changes in hydrodynamic setting, grainsize and mineralogy. Climatic-driven changes are sensitive to higher frequency (100 ky) climatic events (PETM, ELMO, X-EVENT) leaving a mineralogical signal in clay fractions recorded along the Isabena Valley.

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Fluvial signatures in depositional system during Paleocene-Eocene Thermal Maximum (PETM) in Tremp formation, Spain

Chen Chen[1], Sébastien Castelltort[1], Laure Guerit[2], Brady Foreman[3], Chris Paloa[4]

[1]University of Geneva, Department of Earth Sciences, Geneva, Switzerland
[2]Geoscience Environment Toulouse, Paul Sabatier University, 14 Avenue Edouard Belin, Toulouse, France
[3]Department of Geology, Western Washington University, Bellingham, Washington 98225, USA,
[4]Department of Geology and Geophysics, and St. Anthony Falls Laboratory, University of Minnesota, Minnesota, USA

How does global warming change the frequency and intensity of extreme weather events? The response of the question is partly preserved in the sedimentary records across the PETM in the southern Spanish Pyrenees foreland basin. Based on outcrops and borehole information (Pujalte, Schmitz et al. 2014) from the Tremp-Graus Basin, it is shown that a sea-level fall of at least 20 m occurred less than 75 kyr prior to the PETM. In the central part of the Tremp-Graus basin, the Paleocene to early Eocene record can be documented at the Esplugafreda section. A paleo-incised valley carved into the fluvial deposition Esplugafreda fm. The incised valley is interpreted as a sequence boundary produced in response to the pre-PETM sea level fall. The valley was then filled by channel-like conglomeratic sandbodies at the bottom and finer reddish floodplain deposit in the rest of the section. The incised valley is capped by the Claret Conglomerate — an extensive sheet-like unit which ranges in thickness between 1m and 4m. The Claret Conglomerate is generally interpreted as the river response to a dramatic climate change at the PETM because of its occurrence at or close to the PETM signal recorded in the stable isotope composition of paleosoil nodules (Pujalte, Schmitz et al. 2014). The conglomerate unit ends abruptly and is overlaid by fine-grained yellowish soil which is mainly made up of silty mudstones with abundant small size carbonate nodules suggesting another shift in the hydrological cycle after the PETM. Sea level kept rising after the PETM and all of the section was inundated by the ocean leading eventually to deposition of Ilerdian marine limestone on the top of the section.

Several studies (Schmitz and Pujalte 2003, Schmitz and Pujalte 2007, Pujalte, Schmitz et al. 2014) suggested that grain size increased significantly across the PETM based essentially on the observation of the coarse-grained Claret Conglomerate. We tested this assumption by performing a series of systematic quantification and statistical analysis of grain size change and flow depth within conglomerates in the formations below and at the Claret conglomerate unit.

We find that the size of conglomerate in transport and flow depth remained similar to, or even smaller than, pre-PETM conditions. This suggests that, if more seasonal and extreme precipitation occurred, they are not necessarily borne out in the predicted deeper flow depths and coarser grain sizes, but rather trigger a shift to multiple active channels. However, an alternative or complementary explanation may rest in pollen data found in coeval marine records and which document a dramatic vegetation shift from permanent conifer forests prior to the crisis into periodic vegetation in brief periods of rain during the hyperthermal episode. Such change induced by long periods of intense droughts, could have enhanced erodibility of channel banks by decreasing root-controlled cohesion of fine-grained floodplains and interfluves, promoting their lateral mobility and the observed fluvial metamorphosis. Thus, although water is regarded as the main agent sculpting fluvial landscapes, the absence of it during extreme droughts rather than its presence during extreme precipitation events, may be a dominant control on fluvial metamorphosis and landscape evolution.

Heavy-mineral assemblages as a provenance indicator in the Jaca basin (Middle-Late Eocene, southern Pyrenees)

Xavier Coll[1], David Gómez-Gras[1], Marta Roigé[1] & Narcís Mestres[2]

[1]Departament de Geologia de la Universitat Autònoma de Barcelona, Bellaterra (Catalunya), Spain.
[2] Institut de Ciència de Materials de Barcelona, Consejo Superior de Investigaciones Científicas, Bellaterra (Catalunya), Spain.

Heavy-mineral analysis (HMA) is one of the most sensitive and widely-used techniques in the determination of sandstone provenance. Heavy minerals provide diagnostic information for provenance interpretation, as well as for tectonic setting, that cannot be achieved by other means. The Jaca sequence records a main paleogeographic change from the deep-marine sedimentation stage, recorded by the Upper Hecho Group turbidites (Upper Lutetian), to the generalization of terrestrial sedimentation in the Bartonian-Priabonian. Our study focuses on the the clastic systems of the northern Jaca basin (Middle-Late Eocene, South-Central Pyrenees), which encompasses the Banastón and Jaca turbidite systems, the Sabiñánigo and Atarés delta systems, the Santa Orosia alluvial system and the Canciás alluvial fan.

Although provenance constraints for these systems have been based on paleocurrents, basin architecture and sandstone petrography, their heavy-mineral content remains unknown. We explore the use of heavy-mineral assemblages as provenance indicators, by means of optical petrography and Raman spectroscopy, combined with available petrological data, aiming to constrain changes in the source area along the basin's evolution. All the clastic systems display impoverished heavy-mineral suites, mainly constituted by titanium oxides, apatite, zircon and tourmaline.

Heavy-mineral assemblages in sediments depend on weathering, transport, hydraulic processes, diagenesis and mainly burial depth. All these processes act on heavy mineral grains, from its source area to its sedimentation, burial and re-exhumation, and can lead to an impoverished heavy-mineral association, where only the most resistant minerals such as zircon, tourmaline, apatite, rutile and other titanium oxides will remain. Most of the heavy mineral content derived from an orogen is usually dissolved during diagenesis and therefore erased from the sediment record depending on the burial depth. The most likely reason for the observed impoverishment in the turbidite suites is the burial depth acquired by these sediments, which would lead to the dissolution of less stable heavy minerals. Impoverishment of the heavy mineral suites in the alluvial systems may be due to the fact that their major input is derived from the recycling of the turbidites. However, some of the surviving grains can be linked to specific source areas and are diagnostic provenance indicators.

Our results show a major heavy-mineral content shift along the transition from turbidites to shallow-water and continental deposits. The turbiditic systems display high content of apatite, whereas the alluvial systems are characterized by a heavy-mineral suite containing goethite and staurolite. Apatite is related to granitic rocks and points to a source area at the Axial Zone, in the eastern Pyrenees, where granites were exhumed. Staurolite is almost exclusively a product of medium-grade metamorphism and constitutes a diagnostic mineral of the amphibolite grade of metamorphism. Its presence only in north-sourced systems suggests this mineral as a northern provenance indicator. Goethite is the weathering product of pyrite and is here interpreted to be derived from pyrite grains and pyrite-bearing bioclasts recycled from the turbidite and deltaic deposits. Sediment recycling is a clear signal of a northern provenance.

An eastern provenance for the turbiditic systems of Banastón and Jaca is indicated by its apatite content, supplied from the Axial Zone in the eastern Pyrenees. The first occurrence of staurolite in the Rapitán complex, indicates a change in source area related to the emplacement of the Eaux-Chaudes/Lakora thrust that led to the uplift of new source areas to the north and minor exhumation of metamorphic-Paleozoic basement. The decrease in apatite content, the presence of staurolite and the high indexes of sediment recycling in the Santa Orosia and Canciás alluvial-fan systems, indicate a northern provenance mainly derived from the Hecho Group turbidites, with minor input from granitic rocks and metamorphic-Paleozoic basement. This compositional change is interpreted as related to the onset of the Gavarnie thrust. The uplift allowed the erosion of the turbidites producing a heavy-mineral suite rich in recycled pyrite (goethite). Moreover, Paleozoic basement was also exhumed in some areas and supplied staurolite grains to the foreland basin.

The building orogen exerted a major control on sediment supply to the South-Central Pyrenean foreland basin, where eastern and northern sources competed throughout its continentalization. Thus, the thrust activity of the Pyrenean prowedge highly controlled the infill of the Jaca basin. Heavy-mineral analysis combined with sandstone petrography allowed to constrain source area changes with major paleogeographic events along its evolution.

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The continental shelf: a conveyor and/or filter of sediment to deep water?

Grace Cosgrove[1], David Hodgson[1], William McCaffrey[1], Nigel Mountney[1]

[1] University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK

The continental shelf can act as both a conveyor and a filter of sediment during transfer of particulates from continents to the deep oceans. Quantification of coarse-grained sediment character can help to enhance sequence stratigraphic predictions of deep-water reservoir quality. Continental shelf processes are an important control on the character of sediment deposited in deep-water but remain poorly understood and quantified, in part due to the challenge of sampling coeval deposits along depositional profiles. The Miocene successions of offshore New Jersey provide an ideal setting to study the continental shelf and its function as a staging area for sediment delivery to the deep-sea. This is due to the preservation of complete clinothems, which are chronostratigraphically correlated, linked to reflection seismic data and can be tied to the eustatic sea-level curve.

Here, we present data collected from three cores (M27, M28 and M29) recovered during IODP Expedition 313, Offshore New Jersey, USA. The stratigraphic intervals targeted are quasi-coeval shallow- and deep-marine sandstones, spanning the Miocene seismic sequence boundaries m5.2-m5.7. A total of 560 m of core was sampled at c. 0.5 m intervals and quantitative grain size and shape analysis conducted on 967 sediment samples, using a CamsizerXT and associated software. Grain size and shape data have been collated according to the assigned shelf-edge process regime derived from core sedimentary facies; i.e. river- or wave- dominated process regimes. In order to investigate the control of sedimentary process, quantitative grain size and shape analysis was conducted on successive coeval topset, foreset and bottomset deposits. Multivariate statistical analysis tests the associations between variability in topset shelf-edge process regime and patterns of downdip sediment dispersal.

Statistical analysis of the two wave-dominated clinothems (Sequences m5.4 and m5.45) show the following statistically similar characteristics: (a) topset deposits contain ~25% mud by percentage volume, where the largest proportion of mud is at the base of upwardly coarsening packages; (b) foreset deposits contain ~20% mud by percentage volume, where the largest proportion of mud is at the top of upwardly fining packages; (c) significant downdip transport of sand-grade sediment into bottomset deposits, which contain only ~18% mud by percentage volume; and (d) an increase in sorting, sphericity and roundness along the longitudinal depositional profile, including transport of the most spherical, rounded and well-sorted sediments into the bottomset deposits.

Statistical analysis of the two river-dominated clinothems (Sequences m5.3 and m5.7) show the following characteristics: (a) topset deposits are highly heterogeneous - Sequence m5.3 contains 65% mud by percentage volume and has a mean grain size 0.038mm (coarse silt) and Sequence m5.7 contains 22% mud by percentage volume and has a mean grain size of 0.22mm (fine sand); (b) heterogeneity within topset deposits is supported by grain characteristic data, which shows that Sequence m5.3 is better sorted, with a more spherical and more rounded average grain character composition; (c) foreset deposits show statistically similar grain size distributions and grain character data, where foresets contain ~85% sand by percentage volume and have localised gravel-rich horizons; (d) both foreset deposits are very poorly sorted, highly spherical and rounded; and (e) bottomset deposits are highly heterogeneous, where mud content is ~18% and ~35% for Sequences m5.3 and m5.7 respectively, and the coarse sand content is ~ 45% and ~25% for Sequences m5.3 and m5.7 respectively .

Statistical analysis of this novel high-resolution grain character dataset indicates significant differences between wave- and river-dominated depositional sequences. The results support grain character partitioning that is dependant on topset process regime. Within wave-dominated clinothem sequences there is persistent sediment bypass of grain sizes coarser than 0.5mm (coarse sand) to foresets and a longitudinal sorting and grain character profile that becomes more well sorted, more spherical and more rounded basinward. Within river-dominated sequences there is more variability between topset deposits, and consistent foreset sedimentary characteristics and grain size profiles. This suggests that foreset deposits within river-dominated clinothems are actively filtering sediment during basinward transport. The results indicate that shelf-edge process regime has a quantifiable effect upon sediment bypass and grain-character partitioning. The methodology established here can be employed to re-evaluate the extent to which the shelf-edge process regime impacts upon sedimentary character downdip and contribute to a generic model for such variations on basin margins.

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Sediment Dispersal and Provenance Signal Variations in Small, Tectonically Active Sediment-Routing Systems, Southern California

Jacob A. Covault[1], Glenn R. Sharman[1], Zachary T. Sickmann[2], Matthew A. Malkowski[2], Daniel F. Stockli[3]

[1] Bureau of Economic Geology, University of Texas at Austin, Austin, Texas 78758, USA
[2]Department of Geological Sciences, Stanford University, Stanford, California 94305, USA
[3]Jackson School of Geosciences, University of Texas at Austin, Austin, Texas 78712, USA

Small, tectonically active sediment-routing systems are thought to promote the rapid, source-to-sink delivery of sediment and environmental signals, which can be variably partitioned over length and time scales. In these 'reactive' systems, changes in the rates and character of deposition might reflect external forcings operating in the terrestrial sediment source area, as well as changes in sediment dispersal pathways. To understand the source-to-sink variation in sediment dispersal and provenance signals during sea-level change in 'reactive' sediment-routing systems, we sampled modern rivers draining the northern Peninsular Ranges and the offshore latest Pleistocene-Holocene submarine fans in southern California for detrital-zircon U-Pb provenance analysis (1051 grains from eight samples). During the last glacial maximum interval of low sea level (~20 ka), the Oceanside and Carlsbad submarine canyon-fan systems received sediment from rivers that extended across the subaerially exposed continental shelf. Since the last glacial maximum, rising sea level deprived the Oceanside submarine canyon-fan system of sediment from the Santa Margarita and San Luis Rey rivers draining the largest basins in the Peninsular Ranges; longshore currents delivered sediment first to the Carlsbad submarine canyon, and ultimately, with continued sea-level rise, to the La Jolla submarine canyon-fan system.

The modern Peninsular Ranges river samples show a systematic north-south change in grain age populations broadly distributed across Cretaceous time (~135-70 Ma) to predominantly middle Cretaceous (~115-95 Ma). This change reflects variations in drainage-basin lithology and age of geologic units. The Oceanside submarine fan sample shows a broader distribution of ages than the upstream Santa Margarita and San Luis Rey rivers, and it is enriched in latest Cretaceous (85-75 Ma), late Jurassic (155-145 Ma), and Proterozoic (1.8-1.6 Ga) zircon ages. These same age populations lack a local bedrock source in the northern Peninsular Ranges but could have been recycled from Upper Cretaceous-Paleogene forearc strata of the coastal plains of the Santa Margarita and San Luis Rey drainage basins. We interpret that the Oceanside submarine canyon-fan system received a relatively large proportion of sediment from the coastal plains as a result of lower base level and requisite fluvial incision during the last glacial maximum. In contrast, the Carlsbad and La Jolla submarine canyon-fan systems exhibit a mixed distribution of ages reflecting input from all of the modern rivers. We interpret that longshore currents mixed river-derived sediment and delivered it to the Carlsbad and La Jolla canyon heads. Therefore, provenance signals in submarine fans can vary depending on the autogenic dynamics of sediment transport, reworking, and mixing. Fluvial incision in response to climate change can result in provenance reflecting local excavation of the coastal plain, and longshore drift can mix sediment to reflect the integrated sediment load contributing to a littoral cell. Even in ‘reactive’ sediment-routing systems, detrital records of sediment dispersal and provenance should be interpreted within a framework that acknowledges the influence of evolving sediment delivery processes.

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Thermochronological signal from the Western Axial Zone to the Aquitaine basin: unravelling a late Miocene exhumation

Charlotte Fillon[1], Frédéric Mouthereau[1], Sylvain Calassou[2], Raphael Pik[3], Nicolas Bellahsen[4], C. Gautheron[5], Orogen team project

[1] GET, Université Paul Sabatier, Toulouse, France
[2] Total, Pau, France
[3] CRPG, Université de Lorraine, Nancy, France
[4] ISTEP, Université Pierre et Marie Curie, Paris, France
[5] GEOPS, Université Paris Sud, Orsay, France

During the last decade, the Pyrenees have been extensively studied for understanding various geodynamic processes, from hyper-extension to post-orogenic evolution of foreland basins. In this framework, numerous low-T thermochronological studies (~300 ages across the range) have been published, documenting the different phases of pre-, syn- , and post-orogenic exhumation. The orogen climax is dated to late Eocene and the latest compressional features in the southern Pyrenean foreland are dated of late Oligocene; the orogen is supposed to be mainly inactive since then.

Nevertheless, there is growing evidence from independent methods that a late Miocene (around 10 Ma) uplift occurred in the western Pyrenees, which generalizes the post-orogenic signal already known in the south central area. This might lead us to re-think the causes for such an exhumation signal during "post-orogenic" times. In previous studies, the post-orogenic exhumation of the South-central Pyrenees was linked to the excavation of valleys caused by the opening of the endorheic Ebro basin. To the West, the tectonic out-of sequence reactivation of the Gavarnie thrust has been invoked to explain the late Miocene AHe ages in the Bielsa massif.

In this study we develop a source-to-sink approach by tracking the thermochronological signal of exhumation from the western Axial Zone to the Aquitaine basin. Firstly, we investigate the pattern and extent of late Miocene exhumation in the western Axial Zone, and secondly we link the exhumation history to the vertical movements registered in the Aquitaine basin.

We thus present time-Temperature paths from a new dataset of AHe, AFT and ZHe ages from three different massifs in the Axial Zone, as well as a new dataset of ZHe and AFT data from borehole samples in the Aquitaine basin. In the light of these new data, we summarize all evidences for the post-orogenic phase and attempt to provide explanation for it: is exhumation driven by Aquitaine foreland basin evolution? Does it reflect a tectonic reactivation of the Pyrenees? or is the signature of a regional/global climate change conditions ?

This study is part of the Orogen projet, an academic-industrial collaboration (CNRS-Total-BRGM).

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Isolating a climatic signature on alluvial deposition during the Paleocene-Eocene Thermal Maximum: Piceance Creek Basin, Colorado, USA

Brady Z. Foreman[1], Anna Lesko[1], Dirk M. Rasmussen[2], Daniel Maxbauer[3], Elizabeth H. Denis[4]

[1]Western Washington University, Bellingham, Washington, USA
[2]Colorado Mountain College, Leadville, Colorado, USA
[3]University of Minnesota, Minneapolis, Minnesota, USA
[3]Pennsylvania State University, University Park, Pennsylvania, USA

The Paleocene-Eocene boundary is marked by an abrupt, negative carbon isotope excursion found in organic and inorganic proxy records. This negative isotope excursion, known as the Paleocene-Eocene Thermal Maximum (PETM), signifies the rapid release of isotopically-light exogenic carbon into Earth's atmosphere and oceans over the course of less than 10,000 years (McInerney & Wing. 2011). Estimates for the amount of carbon released range, but it was likely in excess of several gigatons (McInerney & Wing, 2011). Associated with the elevated atmospheric carbon dioxide levels were increases in global temperatures of 5-8°C and massive changes in both marine and terrestrial ecosystems (McInerney & Wing, 2011). The hydrologic cycle was also altered, with substantial evidence for increased runoff into coastal marine systems (e.g., Robert and Kennett, 1994; Crouch et al., 2003; Pagani et al., 2006;). In comparison the magnitude and direction of changes in the terrestrial hydroclimate within continental interiors is poorly understood. The magnitude of climate perturbation and the ability to constrain the duration of the event independent of lithostratigraphy make it an ideal field test of source-to-sink geomorphic response to climate change. However, recovering a uniquely climatic signature on stratigraphy also requires identifying the variations in other boundary condition parameters.

This study integrates several proxy records with detailed lithologic descriptions of the early Paleogene Wasatch Formation in the Piceance Creek Basin of northwest Colorado, USA to isolate a climatic signature of the PETM on alluvial strata. We provide new carbon isotope records in the context of extensive descriptions of fluvial sandbody geometries, flow depths, and lithofacies analyses. We employ traditional sandstone petrographic and U-Pb detrital zircon geochronologic methods to identify provenance shifts within the basin, along with paleocurrent measurements to reconstruct paleodrainage spanning the PETM. We use a new age model for the early Paleogene to recreate a decompacted sedimentation history in the basin and associated tectonic subsidence history. We targeted a long, near continuous section of overbank lithofacies to apply recent paleosol morphologic and geochemical methods (Nordt & Driese, 2010; Adams et al., 2011) in order to recover floodplain drainage and mean annual rainfall estimates. We also assess changes in fire frequency spanning the PETM using polycyclic aromatic hydrocarbons (PAHs) to evaluate the causes behind the inferred geomorphic responses.

Our results document: 1) a more robust chemostratigraphic record of the PETM in the basin, 2) substantial increases in sandbody width, thickness and fluvial channel width and depth coeval with the onset of the PETM, 3) a shift from lower flow regime sedimentary structures to upper flow regime sedimentary structures at the onset of the PETM, 4) no changes in sandstone composition, U-Pb detrital zircon age spectra, nor paleocurrents spanning the PETM, 5) no major changes in long-term basin sedimentation rates or tectonic subsidence associated with the PETM, 6) tentative interpretations of greater variation in floodplain drainage associated with the PETM, but a similar mean precipitation, and 7) no evidence for increased fire frequency during the PETM.

These results allow us to confidently ascribe major changes in grain size, channel-stacking, channel dimensions, and sedimentary structures within the Piceance Creek Basin to hydrologic changes associated with the PETM. The basin is several thousand kilometers from the paleoshoreline eliminating the concern for eustatic controls, and the lithologic, paleocurrent, and subsidence analyses argue against major tectonic controls on stratigraphic variation. Overall, we argue river systems experienced greater variation in channel-forming discharges during the PETM most likely related to fluctuations in rainfall patterns recorded in floodplain drainage. We are unable to resolve if these are seasonal variations or variations that occurred on another, longer timescale. The net result was greater channel mobility, through a combination lateral migration and avulsion, that generated larger fluvial sandbodies. In the absence of paleofloral records during the PETM we are unable to comment on potential vegetation controls on channel behavior. However, our PAH record suggests fire frequency was unlikely an influence on channel behavior. Thus, we conclude the major geomorphic responses recorded in the stratigraphy were driven predominantly by hydrologic changes during the PETM.

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Propagation of Environmental Signals within Source-to-Sink Stratigraphy
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Sediment distribution in the South-Pyrenean Foreland System through time.

Miguel Garcés[1], Miguel López-Blanco[1], Luis Valero[2,3], Elisabet Beamud[2,4], Elisenda Costa[2], Belén Oliva[5], Andreu Vinyoles[1], Pau Arbués[1], Patricia Cabello[1], Lluís Cabrera[1].

[1]Department of Earth and Ocean Dynamics, Universitat de Barcelona, Spain
[2]Institute of Earth Sciences Jaume Almera, CSIC, Barcelona, Spain
[3]Universitat Autònoma de Barcelona, Spain
[4]Paleomagnetic Laboratory CCiTUB-ICTJA CSIC, Barcelona, Spain
[5] Universidad Autónoma de Madrid

Foreland systems are among the regions on Earth where the interplay between deep and surface processes is best exemplified. Mountain building, erosion and sediment transfer are intimately coupled to keep the mass balance during the growth of the orogenic wedge. The stratigraphic record of foreland basins thus results from a complex evolution where triggers and feedbacks are not easily discriminated. Understanding the causal relationships which operate in foreland systems requires that the sedimentary record is placed in a precise chronostratigraphic frame.

Significant advances basin-scale correlations in the South-Pyrenean Foreland Basin are achieved thanks to the many magnetostratigraphic studies carried out in the past decades. This has allowed the construction of a reliable picture of the evolving sedimentary environments and routing systems through time.

During the Paleogene and Neogene the NE Iberian plate underwent significant paleogeographic changes which include several basin-scale transitions between open to closed drainage and, at smaller scale, the basin partitioning associated to the emplacement of the South-Pyrenean thrust units. These changes had a strong impact on basin filling, overfilling and later erosion, evolution which was ultimately marked by the variable role of tectonics, climate and eustatism. In this work we place the stratigraphic records in an integrated chronostratigraphic frame and review the evolution of the South-Pyrenean sediment transfer systems and sinks, from the middle Eocene chain-parallel turbiditic troughs to the late Eocene to Miocene internally drained Ebro basin, and the final fluvial incision and drainage towards de western Mediterranean. The role of tectonics and climate in the basin fill architecture are analyzed.

Source-to-sink relations along the transform margin of central California and the role of tectonic inheritance

Stephan A. Graham[1], Matthew A. Malkowski[2], Zachary T. Sickmann[3]

[1]Department of Geological Sciences, Stanford University, Stanford, CA, USA 94305
[2] U.S. Geological Survey, 2885 Mission Street, Santa Cruz, CA 95060
[3] Department of Geological Sciences, Stanford University, Stanford, CA, USA 94305

The San Andreas transform fault system has imposed controls on the topography and bathymetry of the central California margin since its inception in the mid-Cenozoic, yet sediment source-to-sink relations in the region remain profoundly influenced by the predecessor Cretaceous-Paleogene convergent margin morpho-tectonic regime. Two major fluvial regimes characterize the region: (1) the Sacramento and San Joaquin river systems (SSJR), which feed a major bayhead delta complex in eastern San Francisco Bay, and (2) a suite of three comparatively smaller rivers (MBR) that empty into Monterey Bay. The SSJR basin, ca 153,000 km^3, drains the Sierra Nevada, Klamath Mountains and eastern Coast Ranges and consists of numerous small to moderately large rivers and creeks. At current sea level, SSJR sediment is largely sequestered in the Sacramento-San Joaquin Delta and San Francisco Bay, a structural basin within the San Andreas orogen. The continental slope beyond the Golden Gate hosts numerous gullies and only small submarine canyons. In contrast, the Monterey Bay region features three small rivers with total drainage of 14,000 km^3 that head in the California Coast Ranges within the San Andreas orogen. These rivers lack deltas at their termini and instead supply longshore drift cells, which in turn feed a major submarine canyon (Monterey Canyon) that dominates the slope of outer Monterey Bay and a large submarine fan on the abyssal plain beyond. The SSJR system gathers *external* to the San Andreas transform system in topography that is relict from the convergent phase of margin evolution, whereas the MBR system reflects topography formed *internal* to region of San Andreas deformation, which nevertheless consists of dismembered petrotectonic elements of the older convergent margin system.

The composition of sediment routed through the source-to-sink systems of central California bear the relict signature of the older convergent margin system due to the relatively amagmatic nature of the younger transform system at this latitude. In detail, however, detrital zircon (DZ) and elemental analyses reflect the topographic and geologic differences between the external vs internal nature of the SSJR and MBR systems. In the case of the SSJR system, which drains the San Andreas hinterland, detrital zircon U-Pb ages show pronounced down-system variations that progressively become homogenized within the S-SJ Delta. La/Yb ratios increase along the SSJR system, reflecting the change from more primitive arc and ophiolitic rocks of the Klamath Mountains and northern Sierra to more fractionated arc rocks of the central and southern Sierra Nevada batholith. In the case of the Monterey Bay sediment dispersal system, developed entirely within the San Andreas orogen, shorter fluvial drainages retain their individual distinctive DZ provenance signatures all the way to the ocean. Despite partially mixing in the littoral and upper submarine canyon environments, DZ provenance signatures are not thoroughly mixed until the lower reaches of submarine canyons. Thus, while sediment provenance of both source-to-sink systems reflects Mesozoic convergent margin petrotectonic elements, the spatial distribution of source heterogeneity with respect to drainage patterns is a function of ancient vs. current tectonic regime and the scale of that influence.

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Source to sink study at continent-scale (Africa): mantle dynamics controls and implications for the sediment routing system

François Guillocheau[1], Cécile Robin[1], Guillaume Baby[1], Brendan Simon[1], Delphine Rouby[2], Artiom Loparev[2]

[1] Géosciences Rennes, UMR 6118, Université de Rennes 1- CNRS, OSUR, 35042 Rennes Cedex, France
[2] GET, UMR 5563 CNRS-IRD-UPS, Observatoire Midi Pyrénées, 31400 Toulouse, France

A source to sink approach was performed at the scale of a continent – Africa - in the frame of the TopoAfrica project, with three main objectives (1) the characterization of the relative importance of deformation (uplift) and climate (precipitation) (2) the quantification of the deformation, its nature and causes, (3) the effect of those deformations on the past African topography and on the sediment routing system. We mainly focused on Western, Central and Austral Africa, characterized by anorogenic relief (plains and plateaus) record of long (several 100 km) to very long (several 1000 km) wavelength deformations, respectively of lithospheric and mantle origin.

The **sink** measurement was based on the seismic stratigraphic analysis of numerous regional seismic lines (from the upstream part of the margin to the abyssal plain) merge of industrial and academic data, calibrated in ages and lithologies on reevaluated wells to get the best possible ages. Volumes measured between successive time-lines, were compacted for a comparison with solid eroded volumes. Uncertainties were calculated (including ages, time-depth conversion law, porosities…) using the VolumeEstimator software (Guillocheau et al., 2013, *Basin Research*).

The **source** study was performed using dated stepped planation surfaces (etchplains and pediplains) - key morphological features of Africa - mappable at catchments-scale (Guillocheau et al., in press, *Gondwana Research*). During Late Paleocene to Middle Eocene times, Africa experienced a very hot and very humid climate leading to the formation of an African-scale weathering surface (etchplain) known as the African Surface. This surface today deformed and preserved as large plains, domes or plateaus, can be used as (1) a marker of the very long wavelength deformations and (2) a reference level to measure eroded volumes since 40 Ma. Some other younger planation surfaces were also mapped of (1) Early Oligocene and (2) Late Miocene ages.

(1) Deformation (uplift) is the dominant control of the sediment budget. Climate (precipitation) changes only enhance or inhibit a deformation-controlled flux.

(2) The sources of clastic sediments are or closed marginal bulges or far field domes due to mantle dynamics with by-pass (transfer zones) along long-lasting polygenic surfaces located in between.

(3) Africa-scale deformations occurred during Late Cretaceous (Turonian-Coniacian) and around the Eocene-Oligocene boundary with a break contemporaneous of intense chemical erosion from 75 Ma and mainly from 65 to 40 Ma. Most of the African relief and topography are younger than 40 Ma. Late Cretaceous relief are only preserved in the Guinea Rise and the Southern African Plateau.

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Where is my sink? Reconstruction of landscape development in southwestern Africa since the Late Jurassic

Hodgson, D.M.[1], Richardson, J.C.[1] & Paton, D.[1]

[1] School of Earth and Environment, University of Leeds, UK

Quantifying the rates and timing of landscape denudation provides a means to constrain sediment flux through time to offshore sedimentary basins. However, constraining the flux of sediment between the drainage basin and the sedimentary basin is challenging when assessing configurations in deep-time (i.e., Cretaceous and older) and close to active plate boundaries. Modern dating techniques provide a means to understand onshore drainage basin configurations through time more accurately and when combined with remote sensing techniques, can aid offshore analysis by linking catchments areas to drainage evolution. The Late Mesozoic evolution of drainage basins in southern Africa is poorly constrained despite the presence of several onshore and offshore sedimentary basins. A novel approach has been developed to calculate the volume of material eroded since the Late Jurassic at different time steps by constructing structural cross-sections and extrapolating thicknesses of eroded material. Using different assumptions, the calculated volumes of material eroded from southwestern Africa range from 2.52 x10^6 km^3 (11.3 km of vertical thickness removed) to 8.87 x10^5 km^3 (4.0 km of vertical thickness removed). A significant mismatch in the volumes of material eroded onshore and the volume of sediment deposited in offshore basins in the Mesozoic has been identified. For the southward draining systems alone, the calculated removal of 7.81 x10^5 – 2.60 x10^5 km^3 of material is far greater than the volumes of sediment recorded in offshore sedimentary basins (268 500 km^3). The large-scale exhumation (up to 11 km, since the Late Jurassic), initiated by rifting, resulted in the deposition of the Uitenhage Group in extensional basins, the only onshore representation of major landscape denudation. Reconstruction of the drainage systems using geomorphic indicators and clast provenance of the Uitenhage Group, as well as extrapolated surface exposure ages, indicate the southern draining systems were active from the Late Jurassic with coeval activity in axial and transverse drainage systems. The calculated volumes are tied to published apatite fission track (AFT) dates to constrain the changes in exhumation rate through time (using multiple scenarios), which indicate a significant amount of Early Cretaceous exhumation (up to 1.26 x10^6 km^3, equivalent to 5.70km of vertical thickness). For the first time, this has permitted long-term landscape evolution to be used to support the interpretation that some of the ‘missing’ sediment was deposited in sedimentary basins on the Falkland Plateau as it moved past southern Africa during the Early Cretaceous (Fig. 1). This implies that in this instance, the sinks are separated from their source areas by ~6000 km.

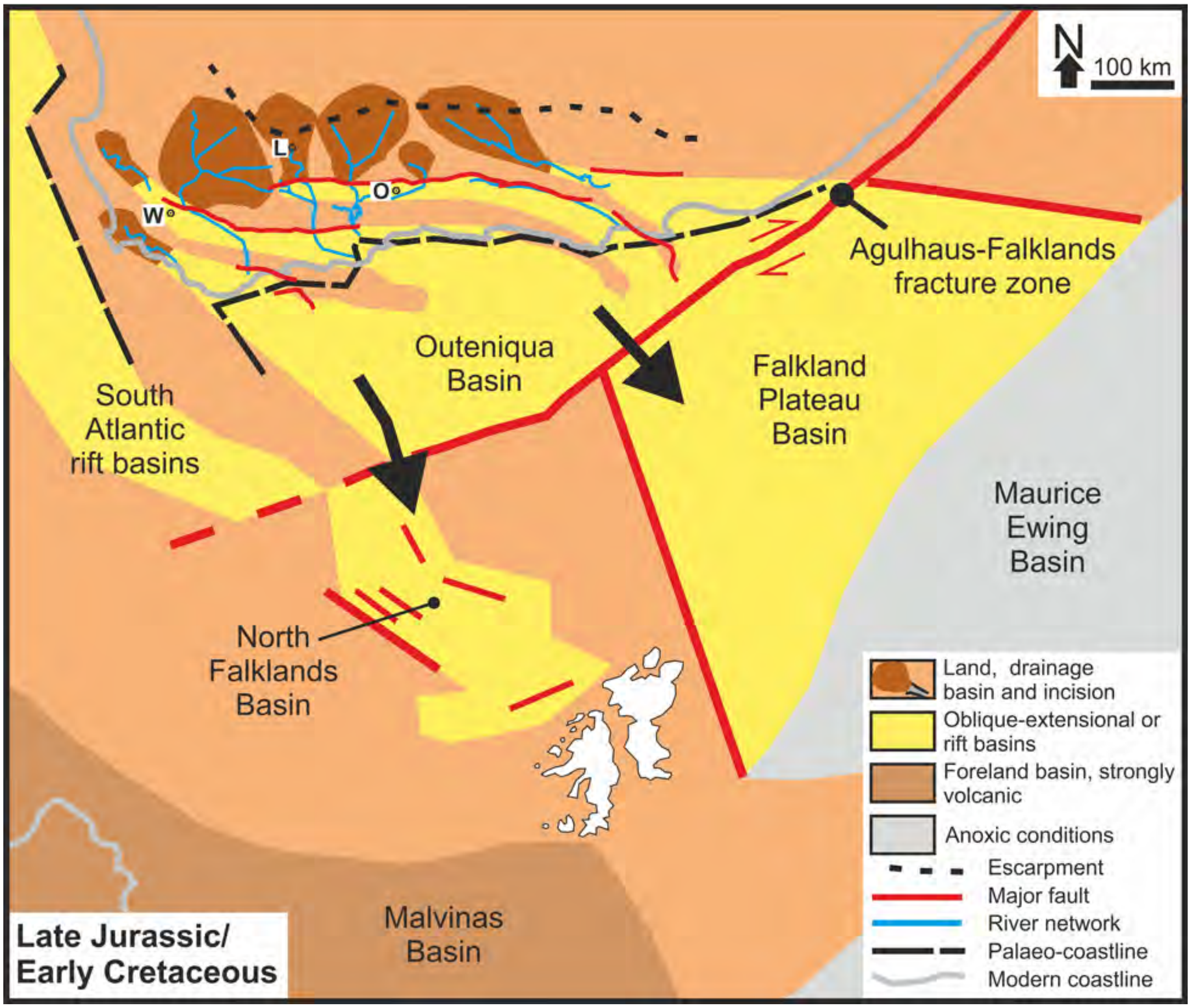

Figure 1: Paleogeographic reconstruction of the Late Jurassic to Early Cretaceous of the southern South Atlantic region. Note that the Falkland Plateau Basin and the North Falkland Basin could both have formed downstream depocentres of the Outeniqua Basin. From Richardson et al. (2017)

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Climatic and tectonic record of the early Eocene Pyrenean foreland basin, a continental-marine correlation model based on a multi-proxy approach

Louis Honegger[1], Sébastien Castelltort[1], Julian Clark[2], Thierry Adatte[3], Cai Puigdefabregas[4], Mason Dykstra[2], Andrea Fildani[2], Jorge Spangenberg[5]

1: Département des Sciences de la Terre, Université de Genève, Rue des Maraichers 13, 1205 Genève, Suisse
2: Statoil Research Center, 6300 Bridge Point Parkway, Building 2, Suite 500, Austin, Texas, 78730 USA
3: Institut des Sciences de la Terre, Géopolis, Université de Lausanne, 1015 Lausanne, Suisse
4: Universitat de Barcelona, Departament de Geodinàmica i Geofísica, C/ Martí i Franquès, s/n, 08028 Barcelona, Spain
5: IDYST, Géopolis, Université de Lausanne, 1015 Lausanne, Suisse

Geochemical signal in the sedimentary record has proven to be, amongst other markers, a cornerstone in the perspective of unravelling Earth's past climatic history.

In order to better apprehend the evolution and partitioning of ancient deposits, we measure a climatic signal in a slope deposits section of the early Eocene Pyrenean Ainsa basin and correlate it with its continental time-equivalent in the Tremp-Graus basin.
Assumptions about the mechanisms driving the deposition in the two environments are put forward and allow us to draw a high resolution correlation and timing model between two sections: the Isábena section encompassing a major fluvial excursion, the Castissent formation, and the Pueyo section including the turbiditic systems of Fosado, Arro and Gerbe

We identify the controlling factors of the marine as well as in the continental depositional system and attempt to untangle climatic, eustatic and tectonic drivers from each other with the aim of reconstructing a source-to-sink history of the basins.

To address this problem, we use stable isotopes on bulk rock carbonates to trace sea level variations and combine this method with elemental analysis, which allows us to corroborate and interpret independently the data set.

This correlation model based on fieldwork and previous mapping, permit us to test some fundamental sequence stratigraphy models and debate about the factors controlling stratigraphic patterns in the fluvial successions that are still debated today (Sømme, 2009)

Tracking large river systems during growth of the northern Andes

Brian K. Horton

Institute for Geophysics and Department of Geological Sciences
Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA

In retroarc regions of ocean-continent (Andean-type) convergent plate boundaries, detrital zircon U-Pb geochronology can constrain the paleodrainage history of large rivers and the relative topographic evolution of magmatic arc, fold-thrust belt, and cratonic source regions. Northern South America contains major continental-scale fluvial systems, including the Amazon, Orinoco, and Magdalena rivers (Fig. 1). The geological precursors of these rivers, although rarely identified, are preserved in the stratigraphic records of hinterland, wedge-top (piggyback), and foreland basins. Provenance studies combined with deposystem analyses provide the most direct means of identifying such proto-rivers. The lack of large-scale regional exhumation in most Andean-type systems renders detrital thermochronological approaches less effective.

Accurately reconstructing Cenozoic paleodrainage is essential for understanding construction of the northern Andes, evolution of major deltas and submarine fans (potential hydrocarbon targets), timing and pathways of the American biotic interchange, and biodiversification in the Amazon/Andean rainforest. This presentation synthesizes geologic records for two regions that address how the north-flowing Magdalena river evolved into its present form, and how the shared Magdalena-Orinoco-Amazon drainage divide was established. Crucial to this effort is the existence of diagnostic sources represented in magmatic arc, fold-thrust belt, and cratonic source regions. U-Pb age distributions from modern river sands of 7 representative drainage networks in Colombia highlight the distinctive signatures of competing sources, including the Guyana shield, Eastern Cordillera, Central Cordillera, and several block uplifts (San Lucas block, Santander massif, and Garzón massif). U-Pb results from Jurassic through Neogene stratigraphic units, including several type sections, enable comparisons of provenance shifts within key stratigraphic intervals across multiple sites within the north-trending Magdalena Valley hinterland basin.

In the Middle Magdalena Valley, U-Pb ages from 3 wells and 6 exposed successions (111 samples) along the narrow intermontane basin show upsection changes in age spectra consistent with (a) Jurassic growth of extensional subbasins fed by local igneous sources, (b) Cretaceous deposition in an extensive postrift setting, and (c) protracted Cenozoic growth of basin-bounding ranges during Andean shortening. Provenance shifts of mid-Paleocene and latest Eocene–earliest Oligocene age are consistent with incipient uplift of the flanking Central Cordillera and Eastern Cordillera, respectively. U-Pb age spectra for Oligocene through Pliocene basin fill reveal complex along-strike (N-S) and cross-strike (E-W) variations reflective of compartmentalized transverse rivers demarcated by point-source contributions from the Central and Eastern Cordilleras. The late Miocene appearance of <100 Ma grains and a regional switch to broad, multimodal age distributions suggest the initial integration of the longitudinal proto-Magdalena River, linking the

Middle and Upper Magdalena Valleys, and driving increased sedimentation rates farther north in the offshore Magdalena submarine fan of the southern Caribbean margin.

In the Upper Magdalena Valley, detrital zircon U-Pb ages combined with sandstone petrographic, stable isotopic, and bedrock apatite fission track data define the Neogene exhumation history of the Garzón basement massif, which forms the Magdalena-Orinoco-Amazon drainage divide. The results indicate basement exhumation by ~12.5 Ma, with full establishment of a substantial orographic barrier by 6–3 Ma, when >1 km/Myr of material was exhumed. This drainage history is consistent with paleontological data suggesting late Miocene divergence of the three major river systems, with associated transcontinental drainage of the Amazon River.

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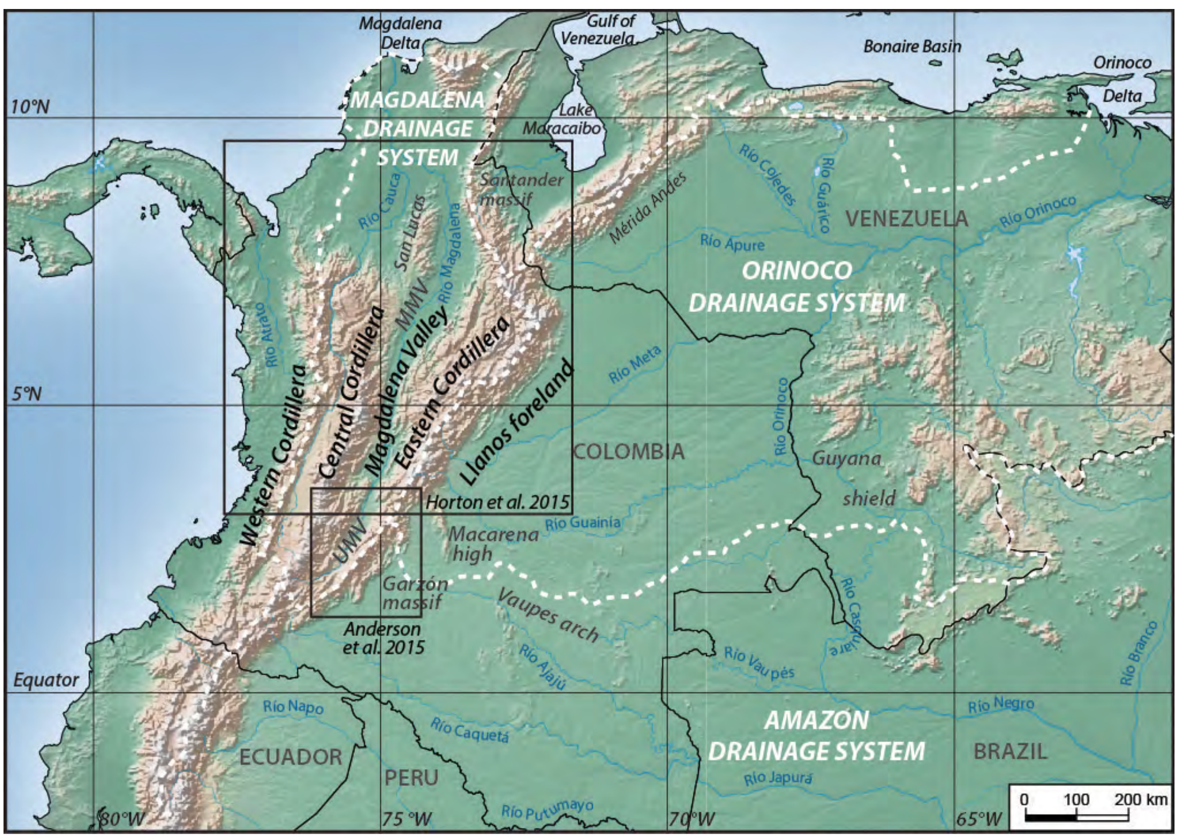

Figure 1. Map of northwestern South America showing major river systems (Amazon, Orinoco, Magdalena), tectonic elements of the northern Andes, and study regions in the Middle Magdalena Valley (MMV) and Upper Magdalena Valley (UMV) *(after Anderson et al., 2016).*

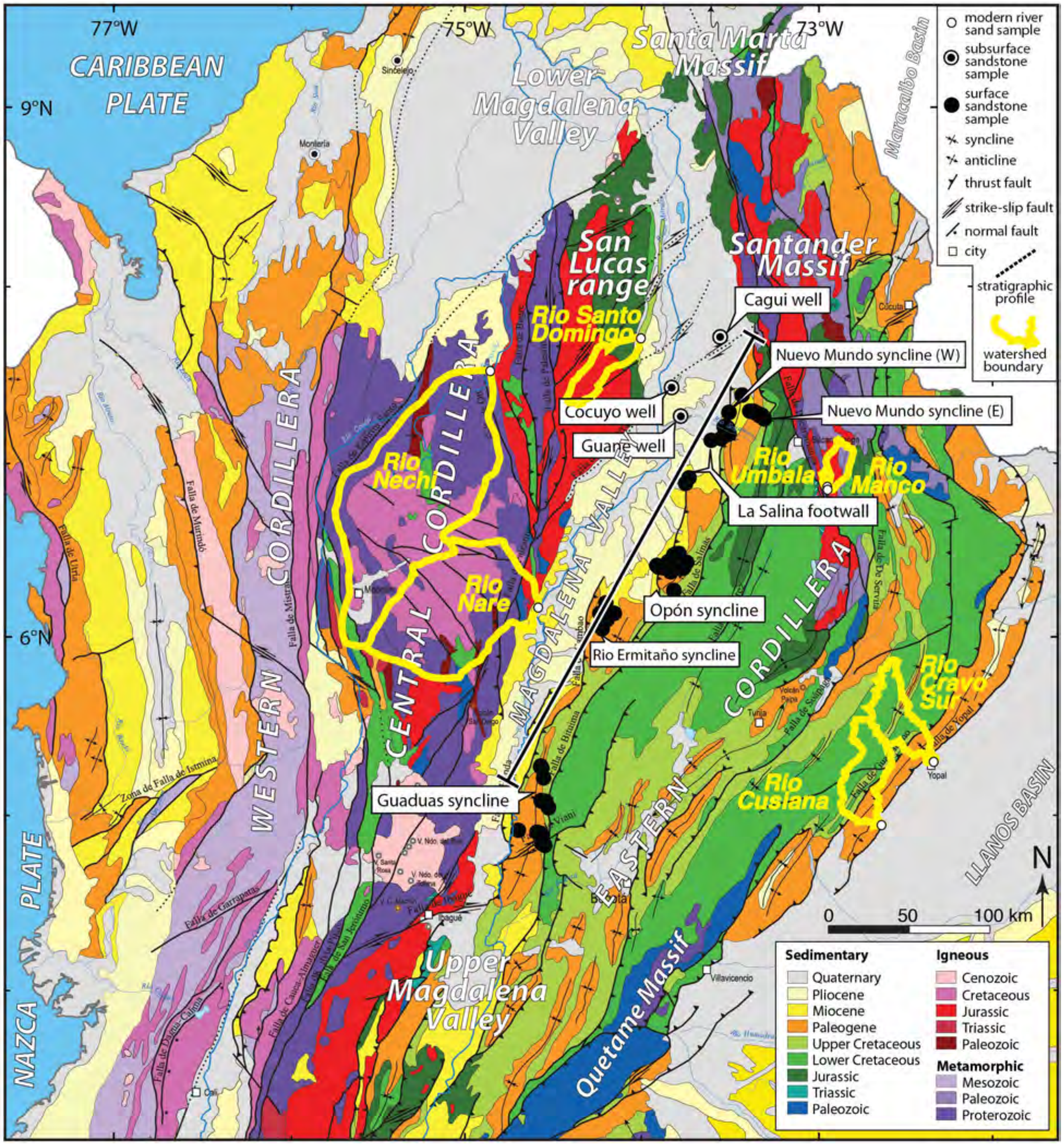

Figure 2. Map of the northern Andes of Colombia showing geologic units, tectonic provinces, selected drainage networks (7 modern river sand samples), and study localities within the Middle Magdalena Valley (111 sandstone samples from 6 surface and 3 subsurface localities) *(after Horton et al., 2015).*

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Channel-forming discharge in source-to-sink analysis

Evan R. Jones[1], Piret Plink-Björklund[1]

[1]Colorado School of Mines, Golden, CO, USA

Source-to-sink analysis (S2S) is a powerful tool for making quantitative predictions about the scale of various linked components of sedimentary systems. Improving the predictive accuracy in the quantification of size and hydrology of the drainage basins that supply water and sediment to river systems is a critical step in constraining the up-dip portions of a sediment routing system, and therefore has important impacts on our ability to predict the size and type of other connected sediment dispersal systems and terminal sediment sinks. There is very little preservation potential for catchment areas in the sedimentary record because of their upland position in a sedimentary system. Efforts to maximize the quality and amount of information we can extract about a catchment area from the connected alluvial, shallow marine, and deep marine deposits are critical for a wide variety of applications ranging from paleogeographic and paleoclimatic reconstructions to exploration and management of petroleum, mineral, and water resources.

The discharge event that is in geomorphic equilibrium with a river channel, the channel-forming discharge, is typically considered to be the bankfull flow state in studies of ancient rivers (e.g. Hajek and Heller, 2012; Holbrook and Wanas, 2014; Bhattacharya et al., 2016). The recurrence interval of the geomorphically formative discharge in modern rivers is typically estimated 1-2 years (e.g. Bray, 1975). This 1-2 year recurrence interval is a good benchmark for rivers with perennial and persistent flow, but in rivers with increasing discharge variability the recurrence interval of bankfull discharge (e.g. Pickup and Warner, 1976; Doyle et al., 2007) or the geomporphically efficient discharge (e.g. Basso et al., 2015) also increases. Recurrence intervals of channel-forming discharge of 3-6 years are documented for dryland rivers in the Australian Outback (Pickup and Warner, 1976), and in the Burdekin River, AU km-scale bedforms are documented to be in equilibrium with decadal-scale flood events (Alexander and Fielding, 1997; Amos et al., 2004).

An analysis of daily gauging data in 415 rivers worldwide (Jones et al., submitted) shows that across all rivers discharge of a specific magnitude has a statistically indistinguishable recurrence interval, and a somewhat characteristic median recurrence interval (Fig. 1). If rivers with increasingly variable hydrology have a channel-forming discharge with increasingly longer recurrence interval, it then follows that these channel-forming discharge events will also increase in discharge magnitude. This has important implications for source-to-sink studies, as this finding predicts that for a constant catchment area the cross-sectional area of the connected trunk-channel will increase with increasing discharge variability (Fig. 2)

The propagation of the signal of erratic vs. persistent discharge in a catchment area is manifested at a number of scales in fluvial stratigraphy ranging from the suite of sedimentary structures preserved in channel-fills, the organization of macroforms (bar-forms in channels), and the equilibrium channel geometry. Rivers with persistent hydrology have shorter recurrence intervals of channel-forming discharge and channel forming discharge events are lower magnitude discharge events. Suites of sedimentary structures in channel-fills reflect systematic bedload transport of sediment (e.g. dune and ripple cross-stratification), macroforms reflect systematic bar migration (e.g. laterally accreting point bars), and channel aspect ratios are low as in meandering single-thread rivers (e.g. Gibling, 2006). Rivers with more variable hydrology have increasingly longer recurrence intervals of channel-forming discharge and channel-forming discharge events are of increasingly high magnitude (i.e. flood) discharge events. Suites of sedimentary structures in such channel-fills reflect high-velocity suspension transport and rapid deposition in the waning stage of flood events (e.g. UFR plane beds, scour-and-fills, convex-up bedforms; Fielding, 2006; Plink-Björklund, 2015), macroforms are organized into low-angle sigmoidal downstream-accreting barforms (Plink-Björklund, 2015), and channel aspect ratios are large as the entire channel belt is active during floods. The predicted equilibrium cross sectional area of a channel will also be higher in high discharge variability systems compared to persistent systems as they are in equilibrium with a higher magnitude discharge state.

We analyse six well studied ancient examples (Ferron Sandstone, Dunvegan Fm., Baharia Fm., Kayenta Fm., Colton-Wasatch Fms., and MacMurray Fm.), and apply scaling relationships between discharge of variable recurrence interval and catchment area (Jones and Plink-Björklund, submitted). We discuss criteria for applying these scaling relationships based on our interpretation of the hydrologic signal (variable vs persistent) interpreted from channel fills, fluvial architecture, and environmental indicators. Improved interpretation of the magnitude and recurrence interval of the geomorphically efficient flow (the channel forming discharge) leads to improved source-to-sink predictions of catchment area in these ancient systems.

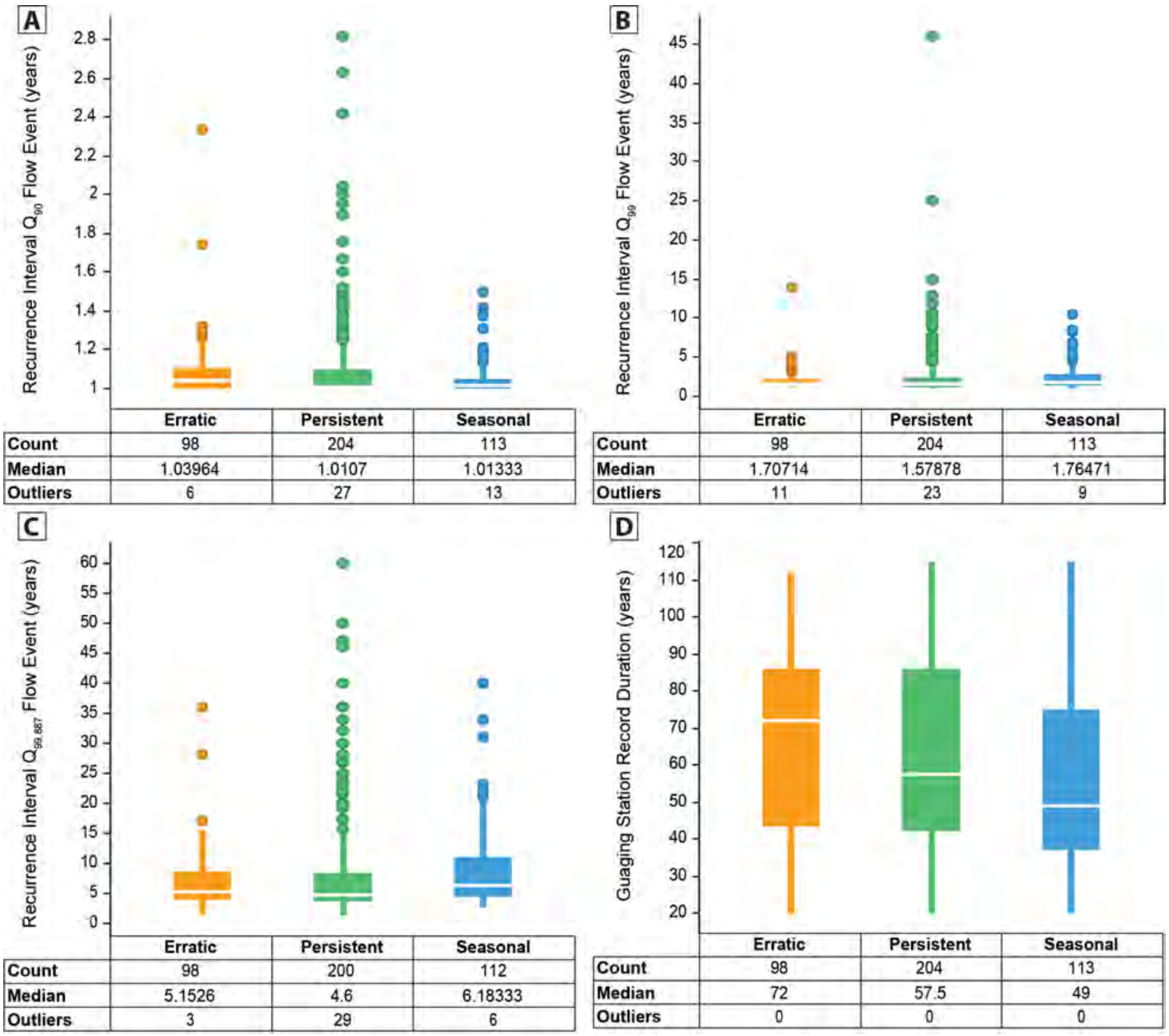
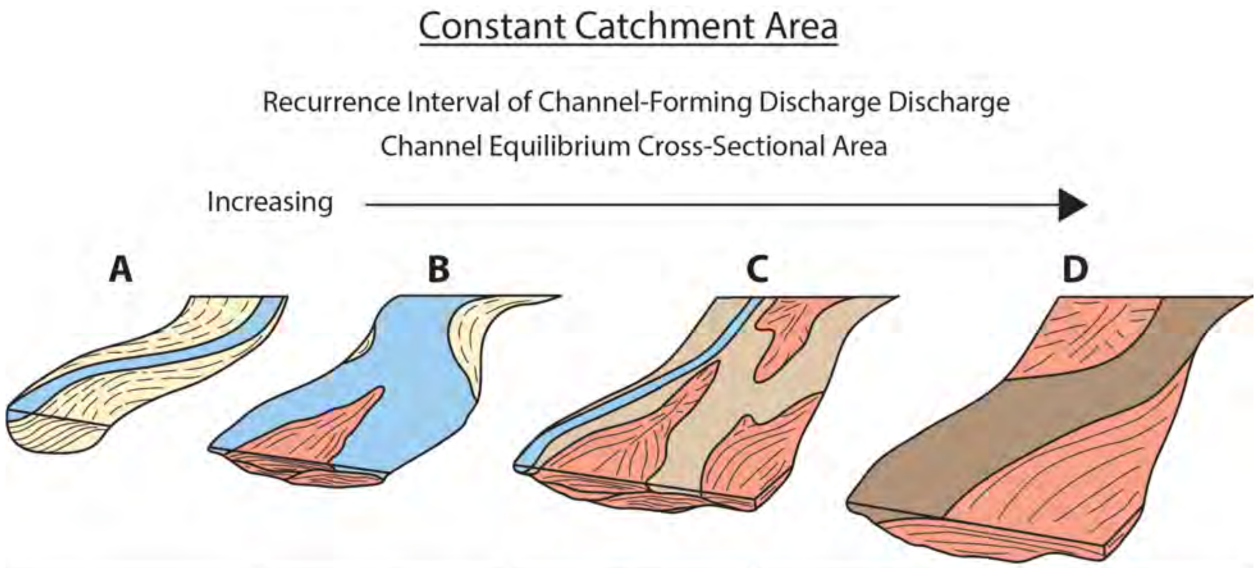


Figure 1: Measured recurrence intervals for A) 90th, B) 99th, and C) 99.87th percentile discharge and D) the duration of the gauging record for all 415 rivers with gauging data in this study. Median recurrence intervals for a 90th, 99th, and 99.87th percentile flow statistically indistinguishable across hydraulic regimes. Outlier recurrence interval systems typically only have one year on record where a single flood event represented all days above the given flow threshold. The Qmax discharge will represent one day over the gauging record, so the recurrence interval of Qmax is the duration of the gauging record. The median gauging record duration for the dataset is 66.7 years.



	A	B	C	D
Recurrence Interval Channel Forming Discharge	~1.5 yrs	~3-5yrs	~5-10 yrs	~50-100 yrs
Percentile Discharge of Channel-Forming Discharge (415 rivers; Jones et al., submitted)	Q99	Q99.87	Q99.91	Qmax
Channel Aspect Ratio	~10:1	~25:1	~35:1	~50:1
Sediment Transport	bedload	mixed	suspension	suspension
Bar Accretion	lateral	mixed	downstream	downstream
Sedimentary Structures	Froude-subcritical	mixed	Froude-supercritical	Froude-supercritical
Base-Flow	persistent - high	persistent - moderate	ephemeral - low	groundwater flow
In-Channel Fines	Top of Fining-Up Sequences	Lenses; mostly bar-tops	draping barforms	draping barforms; pedogenically modified
In-Channel Bioturbation	Bar-Tops	Bar-Tops	common	common; penetrative

Figure 2: Effects of increased recurrence interval of channel-forming discharge on the geometry, architecture, and channel-fill styles of trunk channels connected to a catchment area of the same size.

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June 5-9th, 2017 — Tremp & Ainsa, Spanish Pyrenees

Multiproxy approach to climate signals in the middle-upper Eocene deep water deposits of the Ainsa Basin, Spain

Charlotte Läuchli[1], Miguel Garcès[2], Elisabet Beamud[2], Luis Valero[2], Thierry Adatte[3], Jorge Spangenberg[3], Julian Clark[4], Cai Puigdefabregas[5], Sébastien Castelltort[1]

[1]University of Geneva, Genève, Genève, Switzerland
[2]UB-CSIC, Barcelona, Spain
[3]University of Lausanne, Vaud, Switzerland
[4]Statoil, Austin, TX, USA
[5]University of Barcelona, Barcelona, Spain

Excellent exposure and preservation of entire source-to-sink systems make the south Pyrenean foreland basin an ideal research site to study sequence stratigraphy, climatic-cyclicity over mutlimillenial times scales and correlation between continental and deep basin deposits. The Ainsa basin, situated between the Tremp-Graus (fluvio-deltaic sediments) and the Jaca (distal deep marine sediments) basins, is composed of very well preserved syn-tectonic sediments typical of a proximal deep basin with submarine fans and hemipelagic deposits of the slope, base of slope and basin floor environments. The Ainsa succession is made of eight Sediment Gravity Flow systems (SGFs: Fosado, Los Molinos, Arro, Gerbe, Banaston, Ainsa, Morillo and Guaso), which were deposited during the Ypresian and the Lutetian (Lower to Middle Eocene) epochs. The total stratigraphic thickness reaches approximately 4 km. Each individual system is composed of a dominantly sandy interval of channelised sandbodies of submarine canyon fill, mass transport deposits and fan, and of a dominantly marly interval of hemipelagic slope wedge and interfan marlstones. The source of the sediment in the Ainsa basin can thus be both intrabasinal or extrabasinal. The Ainsa basin sediments thus preserve information both about environmental variables external to the basin, such as climate and regional tectonics, as well as intrabasin environmental variations such as burial history and diagenetic evolution.

The classical interpretation of the systematic alternance between periods with more important supply of coarse sediments (channelised sandbodies, mass transport deposits) and periods with hemipelagic deposits consists in invoking eustasy, pulsed tectonics, or a combination of both (Cantalejo and Pickering 2014). However, it remains difficult to isolate a purely eustatic signal in deep marine sediments where quantifying paleo-waterdepth is challenging.

In the frame of a broader project aimed at deconvolving climate signals in the Ainsa submarine stratigraphic record, we sampled and logged in July 2016 a continuous section spanning the Gerbe , Banaston and Ainsa SGF deposits with a thickness of ca 1.4 km and an average resolution of 10 m between each sample. A multiproxies approach is performed based on stable isotope analysis, whole rock geochemistry and clay mineralogy. In addition, at each location, we also sampled for magnetostratigraphy in order to bring new constraints on the chronostratigraphic framework of these successions. Preliminary results on stable isotope indicate correlation of the δC13 signal with the one documented eastwards in coeval slope deposits of the Fuendecampo area (Honegger, 2015). A normal to revere polarity inversion is documented at the level of Banaston, confirming earlier magnetostratigraphic assignments by Bentham (1996).

Results will help tying stratigraphic patterns and proxy signals to independently established climate records such as eustatic charts (e.g. Kominz et al., 2008) and global climate curves (Zachos et al., 2001).

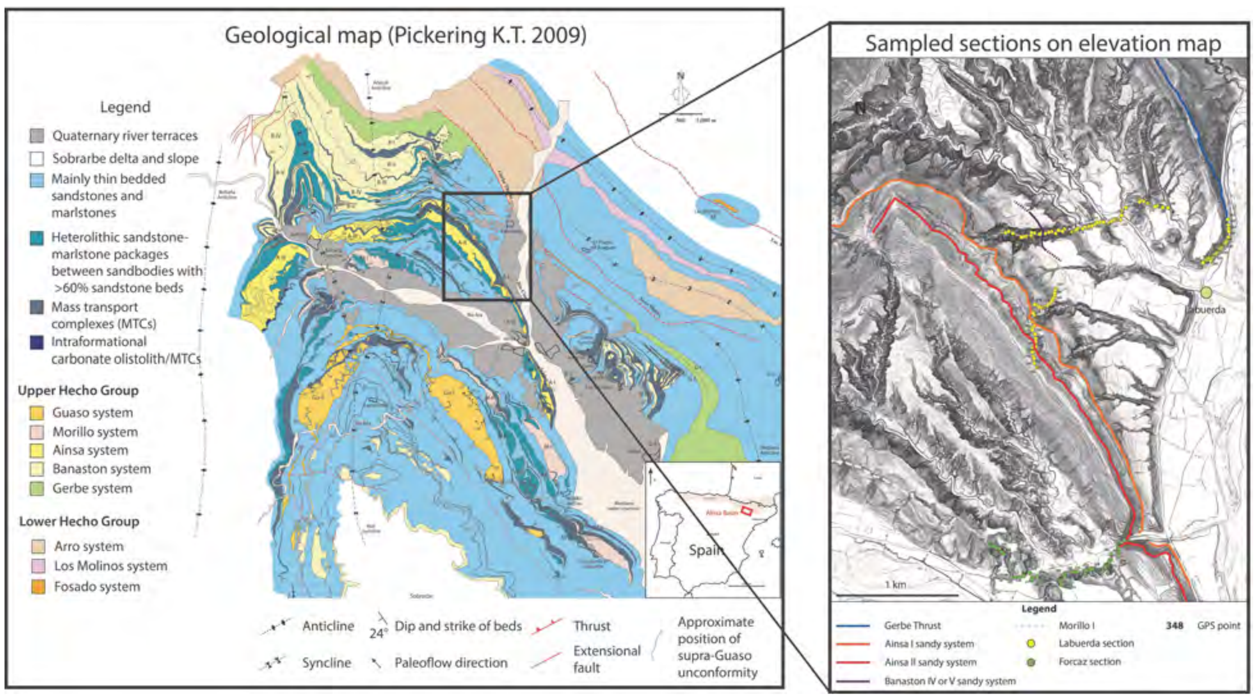

Figure 1: Geological map of the Ainsa Basin and sampled section on elevation map

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Unmixing mixed arc provenance signals caused by recycling of zircon from foreland tuffs: a case study from the Paleogene of NE Mexico

Lawton, Timothy F.[1], Stockli, Daniel F.[2], Kortnya, Cullen D.[2], Juárez-Arriaga, Edgar[1]

[1] Centro de Geociencias, Universidad Nacional Autónoma de México, Querétaro, 76230, México
[2] Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78712, USA

Well-defined age peaks in detrital-zircon U-Pb age distributions with inferred magmatic arc provenance are commonly interpreted as the result of deposition of first-cycle zircon derived directly from arc carapace or ash clouds transported over the sedimentary basin. These first-cycle grains are generally excellent indicators of maximum depositional age of units in the basin. Nevertheless, recycling of tuff-rich units uplifted by inversion of sedimentary basins can provide well-defined age groups within a U-Pb age distribution, particularly if the strata hosting the tuffs are too fine-grained to produce older detrital zircon grains sufficiently coarse to be analyzed. We describe a case study in which recycled zircons from foreland ash beds in northeastern Mexico generated important Cretaceous age peaks that could be interpreted as having a source in the Cordilleran magmatic arc on the western edge of the continent.

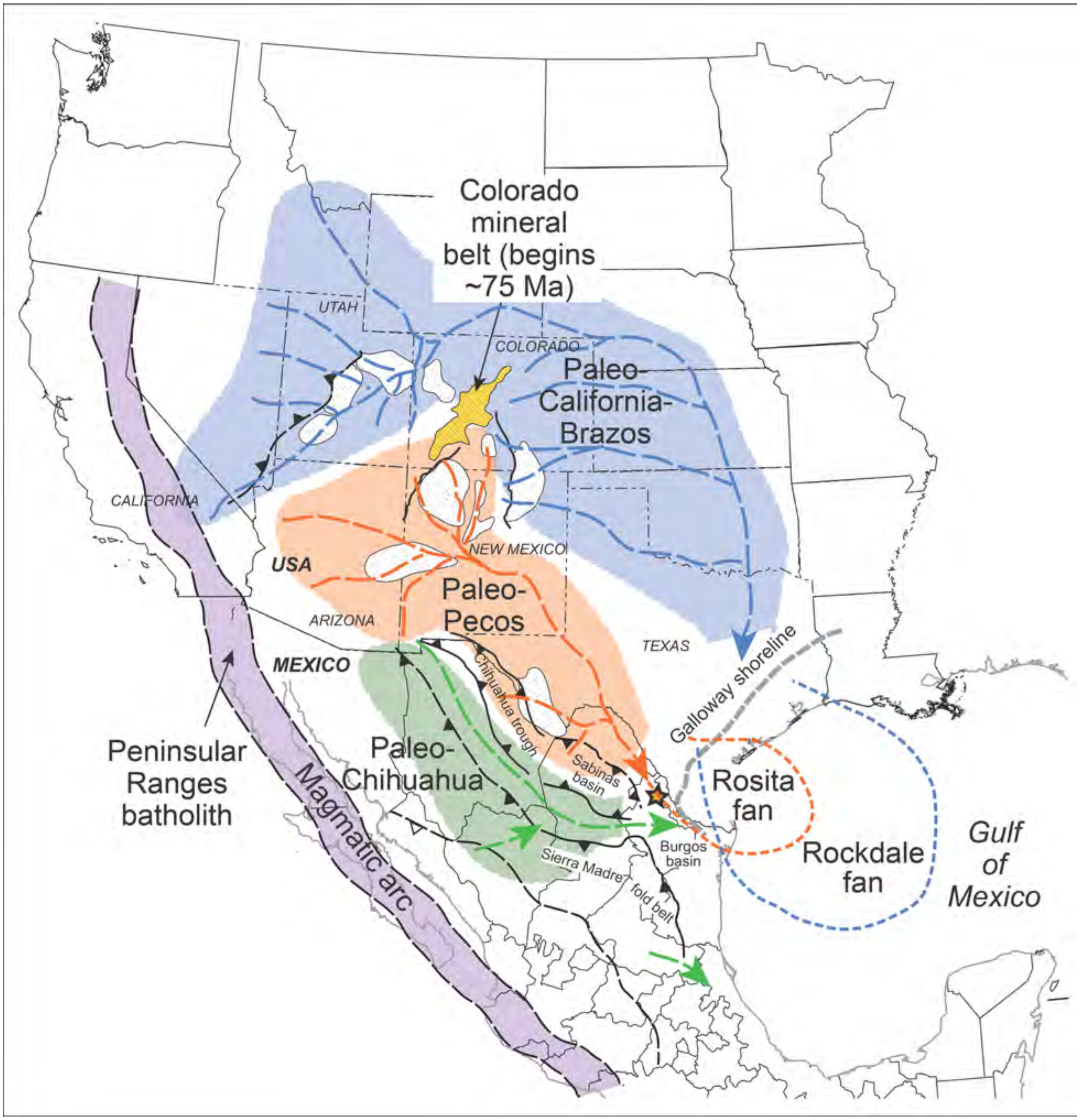
The Upper Cretaceous foreland basin succession of northern Mexico consists of Cenomanian-Santonian turbidites that grade eastward to siliciclastic shales and carbonate pelagites deposited in forebulge and back-bulge settings, and grade with time to prodelta, delta-front, and delta-plain deposits. Two important tuff-rich stratigraphic intervals are present in the distal deposits of the foreland basin: (1) the Buda-Boquillas-Eagle Ford interval contains abundant ash beds in the age range ca. 98-92 Ma, erupted from magma chambers recorded by the Peninsular Ranges batholith and equivalents of southwestern California and the Baja Peninsula of northwestern Mexico; (2) a succession of carbonate pelagites known as the San Felipe Formation and equivalent shale termed the Caracol Formation contains reworked ash-fall tuffs in the 84-75 Ma age range, probably derived from magma chambers of the Sinaloa batholith to the west.

Preliminary U-Pb detrital-zircon data from Wilcox Group strata exposed along the western flanks of the Burgos basin in northeastern Mexico indicate an age distribution dominated by Paleoproterozoic-Mesoproterozoic and Mesozoic zircon ages. Proterozoic grains define peaks at ~1.7 Ga, ~1.4 Ga, and ~1.1 Ga, and Mesozoic grains display well defined peaks at ~94 Ma, ~72 Ma, and ~58 Ma, and subordinate Early-Middle Jurassic peaks. The depositional age range of the samples is approximately 60-51 Ma, but the zircon age distribution contrasts with correlative strata in the proximal Sierra Madre foreland of northeastern Mexico, 150 km to the southwest. Previous analysis of geochronology-based Paleogene sediment routing systems in the Laramide province of the western U.S. has suggested that the Cretaceous grains were transported via the California River system of Paleocene-Eocene age from the continental-margin arc of southern

California, northeast through Utah and Colorado and thence south to southwest Texas. In contrast, depth profiling of detrital zircon indicates that some analyzed zircon grains consist of ~1.7 Ga cores and ~1.4 Ga rims, consistent with inheritance of zircon formed in Laurentian basement rather than accreted basement characteristic of the continental-margin arc. The associated Late Cretaceous grains were likely derived from the Colorado Mineral Belt of western Colorado and mixed with basement grains derived from uplifts in southern Colorado and northern New Mexico. Rather than experiencing transport from the continental arc of southern California and northeastern Mexico, the grains with ages ~94 Ma were likely derived from detachment folds that exposed the Eagle Ford Formation—and its abundant tuffs—in the distal foreland of the Sabinas basin. We thus infer the presence of a paleo-Pecos River drainage with headwaters in northern New Mexico and southern Colorado, with local tributaries yielding zircon stripped from structures of the inverted foreland in northern Mexico (Figure 1). Jurassic grains were likely derived from the inverted Chihuahua trough, a Jurassic-Early Cretaceous extensional basin, but sediment derived from the Sierra Madre fold belt was routed into an orogen-parallel axial system that may have connected with the paleo-Pecos drainage downstream of our sample site.

Our case study demonstrates the value of an integrated provenance modeling assessment of U-Pb zircon data in analysis of continental sediment-routing systems. In this case, assessment consists of: (1) determining predicted zircon age-group cohorts from the southern Rocky Mountain Laramide province consistent with analyzed age distributions; (2) depth profiling of grains to evaluate hypotheses of crustal inheritance; and (3) evaluating the possibility of foreland zircon recycling through geochronologic analysis of foreland stratigraphic settings. The paleo-Pecos drainage basin of Figure 1 predicts substantially different sandstone composition and potential reservoir downstream reservoir quality than the previously-posited California paleoriver system.

Figure 1 (next page). Inferred Paleogene drainage basins (solid colors) with names of paleo-river systems and specific sediment-routing networks (dashed lines) of the Southern Rocky Mountain Laramide province and Mexican (Huastecan) orogen in northern Mexico, adapted from Blum et al. (in press, Geosphere). Approximate location of active magmatic arc on western margin of North America is indicated; the Peninsular Ranges batholith occupies southern California and the northern half of the Baja Peninsula, which is restored to precede opening of the Gulf of California. Chihuahua trough and Sabinas basin are inverted Jurassic-Early Cretaceous basins. Stippled polygons in United States are Laramide intermontane basins; basins of southern New Mexico and Arizona not depicted. Dashed polygons in Gulf of Mexico are deep-water Wilcox Group fans.



Colorado mineral belt (begins ~75 Ma)
UTAH
COLORADO
Paleo-California-Brazos
CALIFORNIA
NEW MEXICO
USA
Paleo-Pecos
ARIZONA
TEXAS
MEXICO
Galloway shoreline
Chihuahua trough
Peninsular Ranges batholith
Paleo-Chihuahua
Sabinas basin
Rosita fan
Magmatic arc
Burgos basin
Rockdale fan
Gulf of Mexico
Sierra Madre fold belt

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The application of open system theory to sedimentary systems: the concept of environmental signal and noise revisited

Haipeng Li and Piret Plink- Björklund

Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, USA

An open system is one that exchanges both energy and materials with its environments. The open system theory was first successfully applied to biology, and later proved to be a powerful tool in other fields as well[1,2]. Sedimentary systems are subject to both energy and materials exchange with their surroundings, hence they should be treated as open systems. Most, if not all, studies in sedimentology focus only on a certain part of the whole source to sink system, and try to infer the evolution history using preserved sedimentary record. Based on theoretical analysis and outcrop data, this paper refines the definition of signal and noise and summarizes characteristics and first-order principles of environmental signal propagation. Some of these principles are defined for the first time in this paper. Potential challenges and research opportunities are also highlighted.

Redefining the signal and noise

The concept of signal and noise, initially defined in electrical engineering[3], has been adopted in sedimentology in the last decade[4,5], but in most cases lacks a clear definition, which hampers communication among researches. A signal in the engineering field is typically defined as a function that conveys information about the behavior or attributes of some phenomenon[6], and its Latin root word *"signum"* means to distinguish[7]. The definition of a signal needs to satisfy the above properties: 1) describe the behavior or attributes of some phenomenon; and 2) can be distinguished. It is the *changes* in environments that sedimentologists are most interested in. Therefore, an environmental signal can be defined as a change in an environmental variable that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.

Environmental signal can be classified based on its origin, spatial and temporal properties. Different from the traditional notion, we argue that an environmental signal could be generated both within and outside the system of interest; the only difference lies in that a signal outside the system must generate measurable changes in system inputs in order to be detected, including the arrival patterns, composition, and energy.

Similarly, a noise is here defined as the product of autogenic processes under constant allogenic forcings. Recent modeling work[8] and experiments[9,10] have shown that autogenic deposits can respond to changes in allogenic forcings, i.e. environmental signals; therefore, some of the autogenic deposits record environmental signals and can be used to interpret environmental changes.

Properties of signal propagation and preservation

Based on theoretic analysis and outcrop data, the following properties of signal propagation and preservation can be deduced:

1) A natural system tends to reach maximum entropy, and this tendency drives autogenic processes and produces noises. This is the very fundamental principle that applies to all natural systems[11]. Though all open systems evolve towards the direction of maximum entropy, few, if any can reach that state due to material and energy exchange. This property leads to the heterogeneity of signal preservation.

2) A sedimentary system that cannot reach its maximum entropy will inevitably result in heterogeneity in its deposits, and thus heterogeneity in signal preservation, i.e., not all parts of the system contain the same signal. A recent study[12] has shown how one- and two-dimensional studies could lead to erroneous interpretations of environmental signals. Based on this property, we argue that it is the likelihood (a function of accommodation, hydrological regime, sediment concentration and some other parameters) of deposition immediately next to signal inputs that matters, instead of the whole volume capacity of the sink[5].

3) A signal outside the system of interest will nearly always be modified (attenuated or amplified) during propagation, and under rare circumstances (e.g., a signal very close to system) it may be preserved unchanged.

4) Noises can shred or mask signals. Noises can also propagate in a similar way a signal does, but they are limited both in time and extent. Combined with heterogeneity in signal preservation, interpreting signals using relatively limited data is risky.

5) As stated in the definition of signal, an environmental variable, such as precipitation, has its own statistical properties. These properties are defined as background information. The probability of a signal propagating and being preserved depends not only on its magnitude and frequency[4,5], but also upon the ratio between the signal and background information (Equation 1):

$$\gamma = \frac{S}{B} \qquad (1)$$

in which S is the magnitude of signal, while B stands for background information. This property is based on the premise that the zone between the signal and the system is in equilibrium. In this case, the relative changes might be more important than absolute magnitude. This is demonstrated by hydrological regime changes in paleo-rivers that responded to initial warming in Paleocene by shifting their hydrological regime from persistent to highly variable, but preserved their hydrological regime at the Paleocene-Eocene transition, when the magnitude of temperature change was larger, due to a higher γ value during the initial Paleocene climate change. The parameter γ may also work well in other systems of interest if the transfer zone was in or close to equilibrium before the signal propagation.

Challenges and research opportunities

Though much progress has been made lately, the following key challenges and research opportunities are identified:

1) It has long been recognized that responses of sediment supply to external forcing are complex (non-linear)[5,13,14], and that there is usually a time lag between environmental signal and its resultant sediment supply change. Thus, matching signal with contemporary strata without evaluating possible time lag is a source of error. Therefore, effectively evaluating the possible time lag between a signal and its resultant inputs requires more community efforts.

2) It is common practice in sequence stratigraphy to attribute a certain sequence boundary to a specific control, such as eustatic sea level without any quantitative evidence. Yet, any stratigraphic change is more likely to contain contributions from multiple contemporary signals, but it is hard, or even impossible to reconstruct the proportional contributions of different contemporary signals, especially when considering the time lag effects. Perhaps the hope to solve this problem lies in statistical probability analysis, and progress in quantifying the effects of eustatic controls has been made recently[15]. Another hard, yet possible way, is to find unequivocal parameters for different signals.

3) In addition to proportional contributions, there are possible counteracting effects of different contemporary signals. Some studies[16,17] show that different environmental signals might cancel out each other's effects, but we currently largely lack understanding of the interaction between different signals. Thus, some signals that are not preserved might still have existed. Therefore, a better understanding of the feedbacks between different signals is necessary for interpreting signals from sedimentary records.

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Depositional environments and sediment partitioning during early stage foreland basin thrusting: The Late Ilerdian-Early Cuisian Roda Sequence, South Pyrenean Foreland Basin (Spain)

Allard W. Martinius[1,2] and Cai Puigdefábregas[3]

[1] Statoil ASA, Trondheim, Norway
[2] Technical University of Delft, The Netherlands
[3] University of Barcelona, Spain

The Late Ilerdian-Early Cuisian Roda Sequence spans approximately 3 Ma and formed in the South Pyrenean Foreland Basin (Spain). It is mapped in detail across the present-day Tremp-Graus, Ager and Ainsa sub-basins, and across the Boltaña Anticline into the Jaca sub-basin. The South Pyrenean Foreland Basin basin formed during the early stage of oblique collision of the Iberian Plate with the Eurasian Plate, and was bounded to the north by the Pyrenean chain and to the south by the Sierras Marginales. Within the basin, a time-sequenced series of curved thrusts developed (controlled by the location of inverted Mesozoic extensional faults) of which the Montsec thrust was decisive for the development of the Roda Sequence. This thrust sheet was displaced in a mostly southward direction and has an E-W orientation; it carried the Ilerdian-Cuisian sediments of the present-day Tremp-Graus and Ainsa sub-basins. It is well-expressed at the surface as well as partly buried by younger sediments. The Montsec thrust sheet is bounded east and west by the corresponding lateral ramps oriented SW-NW (Segre line), and SE-NW (La Fueba thrust system). Beyond the SE-NW oriented lateral ramp, the present-day Ainsa and Jaca sub-basins are located. The thrust had a significant influence on sediment dispersal patterns and the nature and location of depositional environments during the development of the Roda Sequence.

During the Late Ilerdian-Early Cuisian Roda Sequence, the South Pyrenean Foreland Basin was an approximately 50 km wide. The basin formed part of the paleo-Gulf of Biscay that extended significantly further eastward along the southern margin of the growing Pyrenees until the Catalan coastal ranges. In its eastern part, the basin was closed north of the Montsec Thrust but south of it, the basin continued eastward, and the Late Ilerdian-Early Cuisian Roda Sequence corresponds to the Ilerdian Sagnari-Corones delta sequence in the present-day Ripoll Basin (shallow carbonates and sandstones, and deeper marine marls) of the 'Lower Pedraforca Unit'.

Intermittent compressional movements and thrust development at variable magnitudes in time and space imposed allogenic control during the development of the Roda Sequence. This resulted in 1) pluriform depth profiles in various directions across the foreland basin, and 2) a complex process-response of depositional facies in various parts of the basin. Along the northern margin, close to the Pyrenean chain, and in particular in the eastern section, a 'foredeep' developed with larger water depths than further south where the basin shallowed onto the actively moving

Montsec Thrust. The Montsec Thrust became emerged during the Late Ilerdian-Early Cuisian and formed a topographic high, and a similar N-S water depth profile developed in the Ager sub-basin from the Montsec Thrust out to the Sierras Marginales. In the western section of the basin (the Jaca sub-basin), a more uniform foreland basin development is recognized. Therefore, progradational, retrogradational and aggradational patterns in the various time-equivalent depositional systems developed in response to the local A/S trend.

To describe the distribution of, and transitions between depositional environments as well as sediment dispersal patterns, four main depositional zones are defined: the Tremp-Graus sub-basin, the combined Ainsa and eastern part of the Jaca sub-basins, and the Ager sub-basin. These are discussed for two Roda Sequence time slices: the Late Ilerdian (53.5 Ma) and the Early Cuisian (52 Ma).

Roda Sequence time slice 1 – Late Ilerdian (53.5 Ma)

Tremp-Graus sub-basin

In the innermost eastern part of the Tremp-Graus sub-basin, small, shallow-water deltas prograded towards the SW to NW fed by minor rivers with a small catchment area. Extensive tidal flats and mixed siliciclastic-carbonate shallow-water environments were present along this eastern basin margin. Contemporaneously, further west, two main, several km wide and long, elongate and basin-margin hugging Gilbert-type deltas formed in deeper water. Granite derived siliciclastic sand, including carbonate and feldspars, was derived from the Pyrenean chain through braided fluvial systems flowing southwestward and located in the proto-Gurb and proto-Sis palaeovalleys respectively. Along the southern basin margin, carbonate platform deposits formed (Montrebei section).

The Roda Gilbert-type delta (fed through the proto-Sis palaeovalley) built out on an inner carbonate platform shelf with abundant life. At initiation of delta progradation, water depths several km's away from the basin margin are estimated to have been at around 40 to 60 meters and within the photic zone. Over time, increased southward directed sediment supply controlled rapid delta progradation (the Roda Sst Mbr). Main delta lobe progradation, compensational stacking and abandonment was controlled by allogenic processes at 4^{th} order. During abandonment of the main delta lobes, rich, wave-resistant bivalve- and coral-dominated hardground fauna's developed suggesting water depths of around 5 to 10 meter. Autogenic processes and compensational stacking controlled the development of multiple sub-lobes constructing each main lobe. Sub-lobes responded quickly to fluctuating sediment input (magnitude and direction) and efficiently recorded high-frequency variations in the interplay of fluvial discharge variations, sedimentation rate and the creation of accommodation space. Strong longshore currents caused the deflection of delta lobes in a SE and SW direction due to complex tidal current rotational patterns, and lobe deposits interfingered basinward with distal delta front and prodelta to offshore siltstone deposition.

Elongate, laterally migrating lower delta-front attached tidal bars developed in the most distal parts of the Roda Gilbert-type delta lobes. These bars formed by dunes showing abundant and well-developed tidal bundles formed by strong regional W–NW directed ebb-dominant tidal currents and formed during high-frequency relative base level falls.

Beyond the Gilbert-type deltas fed by the proto-Sis and Gurp palaeovalleys, southward and farther west into the basin, mud-prone offshore shelf sediments accumulated, developing a thick (up to 350 m thick) succession. Southward, carbonate deposition dominated and water depths shallowed onto the emergent Montsec Thrust. Westward, water depths gradually increased up to depths of approximately 80 m (the sub-photic zone; Yeba Marls in the Ainsa sub-basin). The transition from this shelf zone into deeper water environments was very gradual and smooth and located at the position where later in time the SE-NW orientation lateral ramp of the Montsec Thrust (and associated minor thrusts) would develop. The transition zone was determined by the initial formation of the lateral ramp.

Ainsa and Jaca sub-basins
Above and west of the oblique Montsec lateral ramp, water depths increase further and slumps and thin turbidities developed (represented by the Yeba marls in the present-day Ainsa sub-basin) shedding sediment into the relative deepest and largest part of the foreland basin (the present-day Jaca sub-basin) where only marl deposition occurred.

Ager sub-basin
South of the Montsec Thrust, a thick succession of shallow-water tidal compound dunes (up to 6 m thick) was deposited suggesting a relatively high rate of accommodation space generation and a sedimentation rate that kept pace (the Baronia Fm). Compound dunes are formed by a highly bioturbated, muddy, fine grained sandstone with an open-marine *Cruziana* ichnofacies at the base, overlain by ripple-laminated sandstone that contains mud drapes, and capped by fine- to coarse-grained sandstones that contain both planar and trough cross-strata with unidirectional or bi-directional paleocurrent directions and occasional thin mud drapes on the foresets. Cross strata that formed by simple superimposed dunes dip in the same direction as the inclined master bedding planes within the compound dune, forming a forward-accretion architecture. The compound dunes alternate vertically with highly bioturbated muddy sandstones (up to 10 m thick) that represent the low-energy fringes of the dune fields or periods of high sea level when current speeds decreased. Compound dunes are 500–1000 m long in the direction of the current, and at least 350–600 m wide in a flow-transverse direction. The characteristics of this compound dune field and its strong tidal control are typical for a tidal strait depositional environment. Towards the west, the compound tidal dune field transitioned into a depositional environment dominated by carbonaceous silt and fine-grained sand with bedforms decreasing towards ripple fields. Towards the east, an opening towards the semi-enclosed but large present-day Ripoll Basin existed which was dominated by carbonate platforms during the Late Ilerdian (Cadí Fm) and deltaic and fluvial clastics (Corones Fm). This basin was large enough to develop rotational tidal currents that had to pass in and out through the Ager Strait.

Roda Sequence time slice 2 – Early Cuisian (52 Ma)
During the Early Cuisian, the paleobathymetry and paleomorphology of the South Pyrenean Foreland Basin changed mainly because of the ongoing collision and further development (southward movement) of the Montsec Thrust creating incipient relief. The asymmetric depth profiles in the area of the present-day Tremp-Graus sub-basin as well as the Ager sub-basin became less pronounced (overall shallowing) and less asymmetric.

Tremp-Graus sub-basin

In the eastern-most part of the Tremp-Graus sub-basin, tidal flats and low-gradient and shallow-water deltaic environments expanded westward. In the Isábena valley, a vertically stacked series of coarse-grained, thin but relatively small retrogradational fan-delta lobes developed in shallow water and hugging the paleocoastline (the Esdolomada Mbr). The fan-delta continued to be fed by rivers flowing through the proto-Sis paleovalley deriving sediment from a large catchment area. In a direction perpendicular to the coastline, they were approximately 2 km wide and transitioned into sandy marl deposits. These were deposited contemporaneous with a series of thin (up to 6 m thick) elongated tidal sandstone bodies interpreted as detached tidal bars and up to 5 km long and 2 km wide. Bar crests were generally oriented northwest to southeast, parallel to the tidal palaeocurrents and to the nearby palaeoshoreline. Subaqueous tidal flat and shallow muddy shelf environments in between delta lobes and tidal bars, dominated by inter- to subtidal gastropod communities, were common.

Adjacent to this retrogradational fan delta and tidal bar system, relatively small, mixed siliciclastic-carbonate coarse-grained basin margin fringing river-dominated deltas existed (for example, in the Merli area). These had small catchment areas and well-developed shorefaces.

Ager sub-basin

South of the emergent Montsec Thrust, in the Ager sub-basin, the Baronia compound tidal dune field became moribund and the basin initially deepened. A sediment-starved marine shelf environment formed in which silty mudstone (the Passarella Fm) was deposited. Subsequently, the connection to the Catalan Basin closed and a series of relatively small basin margin-fringing deltas with mouth bars developed in the Ager Bight that prograded onto a silt- and mud-dominated shelf (the Ametlla Fm). Towards the west, these environments transitioned into a silty and bioclastic shelf.

A decrease in accommodation space, probably related to a phase of rapid thrust sheet displacement and uplift, caused a base level fall and created series of up to 35 m deep incised valleys. Continued subsidence related to thrusting initiated renewed flooding of the Ager sub-basin, landward stepping of the shelfal depositional system, and infilling of the incised valley; tidal bars were common. Coastal plain brackish-water environments subject to minor marine incursions developed towards the top of the Roda Sequence in the present-day Ager sub-basin. Macrofauna assemblages and inferred paleoenvironments are almost identical to those in the Tremp-Graus sub-basin.

Ainsa and Jaca sub-basins

In the area of the present-day Ainsa and eastern-part of the Jaca sub-basins thin and fine-grained turbidite layers, observed within the Yeba marls section, indicate a gradual deepening towards the west.

Source-to-Sink (S2S) analysis and applicability to Earth studies

Ole J. Martinsen

Statoil Exploration, Bergen, Norway

Source-to-sink analysis involves a complete, Earth systems model approach to analyzing basins and basin margins from the ultimate onshore drainage point to the toe of related active shallow as well as deep-water sedimentary systems. Several methods and techniques have evolved in recent years, from experimental and numerical modeling through analysis of modern and recent systems, to analysis of ancient systems. Our morphometric model bridges between the previous approaches and dividing and analyzing source-to-sink systems based on linked geomorphic segments along the complete source-to-sink profile. This approach builds on uniformitarian principles, but allows for variability related to various climatic periods in Earth history. The prevailing method is driven by the need to understand ancient, prospective subsurface systems and is an original, first-order approach to source-to-sink system analysis. It is built around using conventional exploration data and methods and complements sequence stratigraphic analysis. The method has been applied with success in internal exploration projects and has helped steer exploration efforts and increased technical confidence in exploration decisions.

Outstanding challenges in source-to-sink analysis include understanding S2S systems variability along strike, relation to major tectonic controls and climatic variability. Variability between icehouse and greenhouse conditions is still unconstrained as well latitudinal variability within either one of these main climatic settings. In studies carried out in extreme, non-glacial climatic settings, for example, it is shown that these systems often are in morphometric disequilibrium, meaning there is no predictive relationship between for example the size of the catchment and the sink. In various tectonic settings, such as thrust belt and foreland basins, semi-quantitative relationships between morphometric parameters characterizing the source to sink systems still have to be established. And last but not least, strike variability in all tectonic settings needs better understanding.

Signal propagation in a natural catchment-fan system: Pleistocene paleo-erosion rates in the Great Basin, U.S.A.

Cody C. Mason[1], and Brian W. Romans[1]

[1]Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

Relationships between changing boundary conditions in catchments, e.g., climate and tectonics, and changes in linked erosion-deposition dynamics and sediment flux to basins through time are not well constrained by existing empirical data. While changes in catchment boundary conditions, specifically related to climate, are known to modulate sediment production and source-to-sink transfer, successful recovery of such signals from stratigraphy remains elusive. Here we use the linked catchment-fan system of the Pleasant Canyon Complex (PCC) in Panamint Valley, California, as a natural laboratory to quantify changes in paleo-erosion rates from stratigraphy over 10^6 yr timescales. We measured cosmogenic radionuclides (CRNs; ^{26}Al and ^{10}Be) in 13 samples from an exhumed alluvial-lacustrine succession, and 2 from modern sediment at feeder catchment outlets to quantify catchment-averaged paleo (and modern) erosion rates through time. In this framework, we assume variation in catchment-wide paleo-erosion rate is the signal of changing boundary conditions, as stored in the depositional segment of the system.

Catchment-fan systems are particularly well suited for studies of erosion-deposition linkages due to short reaction timescales to external forcing in catchments, and little en route sediment storage and remobilization over timescales > ~$10^{3\text{-}4}$ yrs (Allen and Densmore, 2000; Densmore et al., 2007; Armitage et al., 2011). While large fluvial systems may buffer signals of changing boundary conditions, small systems are thought to be more reactive to perturbations, and to rapidly transmit signals as changes in sediment loads (Allen, 2008). The PCC source-to-sink system is relatively small: catchment length of ~16 km, catchment area of ~30 km^2, and a maximum relief of 2.34 km. The depositional segment includes measured stratigraphic thickness of ~165 m exposed over an area of ~3 km^2.

Panamint Valley is a late Cenozoic oblique rift basin situated between the Sierra Nevada Range to the west, and Death Valley National Park in the east. Early Panamint sedimentary basin geometry and evolution was controlled by Miocene through Pleistocene low-angle detachment faulting (still active?), while late Pleistocene deformation was controlled by oblique dextral transtension associated with the eastern California shear zone (Smith, 1979; Burchfiel et a., 1987; Cichanski, 2000). Low-temperature thermochronology (apatite U-Th/He) from the Panamint Mountains indicates that rapid cooling and tectonic exhumation initiated close to 4 Ma and has remained relatively constant since (Bidgoli et al., 2015).

Mid- to late-Pleistocene paleoclimate in Panamint Valley is interpreted to be similar to that of the broader Great Basin—relatively hot and arid interglacials contrasted with relatively cool and wet glacial periods. Late Pleistocene glacial times favored evaporation-precipitation ratios that promoted deep lake formation in Panamint Valley. Relict marine isotope stage 6–2 (MIS 6–2) lacustrine landforms attest to the dramatic change in climate and hydrology in Panamint Valley, which preserves numerous high elevation wave-cut shorelines, constructional beach ridges, and sparse delta foresets (Smith, 1976). Older (most likely pre-MIS-6) Pleistocene lacustrine deposits are exposed in outcrops of the PCC, or buried in the basin.

The PCC consists primarily of a coarse-grained facies association (cobble- to boulder-conglomerates and thin sand beds) interpreted as alluvial fan deposits, interbedded with a dominantly fine-grained facies association (silty clay to fine sand) interpreted as pluvial lacustrine deposits. Fine-grained lacustrine facies thicken from ~1.5 m in the northern part of the outcrop to > 5 m in the south, where accommodation was higher due to syn-sedimentary normal faulting and alluvial fan-lobe avulsions that produced some degree of compensational stacking.

Changes in catchment-wide erosion rates over ~$10^{4\text{-}6}$ yr timescales were quantified by measuring concentrations of CRNs in buried alluvium and correcting for post-depositional production and decay. In this case, sampling vertically through strata yields a time-series of catchment-averaged paleo-erosion rates spanning major changes in Pleistocene climate. We sampled medium sized sand from vertical outcrops typically within narrow canyons, and sieved in the field to the desired grain size. CRNs from a total of 15 samples were measured using accelerator mass spectrometry at Purdue's PRIME Lab.

Results of $^{26}Al/^{10}Be$ burial dating show basal units were deposited and buried after ca. 1.4 Ma with continued sedimentation through ca. 0.2 Ma (after Craddock et al., 2010). We document no discernable major increases in paleo-erosion rates since roughly 1.4 Ma in the Panamint Mountains, but do observe some degree of variability. Paleo-erosion rates for the PCC from ca. 1.4 – 0.2 Ma range from ~0.04 – 0.075 mm/yr, while modern catchment-wide erosion rates are ~0.03 mm/yr. Pleasant Canyon catchment represents a tectonically active, high-relief system, yet our results indicate relatively low denudation rates of 0.03 – 0.07 mm/yr since the early Pleistocene. Other studies employing CRN paleo-erosion rate techniques in the Death Valley region document broadly similar rates of erosion and variability over the last ~100 kyr (Machette et al. 2008). To put these results into context, denudation rates less than 0.1 mm/yr and rate variability on the order of ~2 – 3x are similar to studies of denudation in slowly eroding continental interiors (Granger et al., 2001; Anthony and Granger, 2007; Schaller et al., 2004). Paleo-erosion rates in high-relief, tectonically active, (+/-) glaciated catchments are typically higher by an order of magnitude, and can vary by 2 – 10x over million year timescales (Haeuselmann et al., 2007; Cyr and Granger, 2008; Charreau et al., 2011). Another CRN-based study of non-glaciated low relief rivers along the Texas coast was able to documented variability between late Pleistocene glacial-interglacial times, with higher denudation rates correlating to interglacials, likely due to higher temperatures and changes in precipitation patterns (Hidy et al., 2014).

Our paleo-erosion rate data indicate periods of increased sediment transfer from source-to-sink, which we interpret to record increased precipitation in the catchment associated with glacial times. However, the absolute magnitude of denudation rates in Pleasant Canyon catchment during these times were likely limited by aridity associated with the rain shadow of the Sierra Nevada range. This study demonstrates that CRN-derived paleo-erosion rates can be used to quantify the variability of sediment supply to a depositional sink over $10^{4\text{-}6}$ yr timescales. When applied to reactive catchment-fan systems, this sediment supply record is directly related to sediment production in the catchment and, thus, representative of signals that originated in the catchment.

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Long lived isolated Southern Pyrenean foreland source to sink systems: Constrains from detrital zircon double-dating and detrital rutile U-Pb geochronology

Margo Odlum[1], Daniel F. Stockli[1], Kelly Thomson[1], Andrea Fildani[2], Julian Clark[2], Cai Puigdefabregas[3]

[1]University of Texas at Austin, Department of Geological Sciences, Austin TX, USA
[2] Statoil, 6300 Bridge Point Parkway, Austin, TX, USA
3 University of Barcelona, Spain

Many foreland basins in the world are inverted rifts where inheritance (such as structural fabric and basement composition) play an important, but poorly understood, role in basin architecture and sedimentary fill provenance. The Pyrenean orogen is the expression of an inverted hyperextended rift margin generated by changes in motion between the Iberian microplate and European plate from Early Cretaceous extension to Late Cretaceous-Oligocene convergence. The goal of this study is to assess the influence of inherited rift structures and basin geometry on the incipient Southern Pyrenean foreland basin architecture and source-to-sink systems. This study focuses on the Cretaceous through Paleocene strata of the Southern Pyrenees using sediment provenance to understand foreland basin evolution during inversion and early Pyrenean orogenesis.

Novel geo- and thermochronometry on detrital material provides high-resolution constraints on sedimentary provenance to constrain coupled dynamics among pre-orogenic rift, inversion, and foreland basins. High and low temperature detrital geo- and thermochronometers unravel provenance in light of sediment recycling and provide a provenance picture for the early foreland basin deposits. Detrital zircon (DZ) U-Pb and (U-Th)/He provide information on the crystallization and low temperature cooling ages (below ~180°C) of the sediment sources. Detrital rutile U-Pb provides information on the high-temperature cooling age (~450°C) of source terranes. Integrating these different thermochronometers) provides unprecedented fingerprinting of sediment provenance in complex source-to-sink systems.

The Late Cretaceous through Paleocene detrital mineral provenance from samples straddling the southern foreland basin show that the Tremp and western basin have a different sediment provenance than the eastern and Ager basins. Samples from the Cadi thrust sheet and Ager basin show similar DZ U-Pb age spectra. The Tremp basin and Gavarnie Thrust Sheet also show similarities in DZ U-Pb age spectra that are unique from those in the east. Additionally, detrital rutile age spectra from the central and east are unique from one another further supporting that there were two distinct parts of the basin with different sediment provenance.

The Tremp and Western Basins

The Santonian Vallcarga Fm. through the Paleocene Tremp Formation in the Isabena Valley show an upsection trend of recycling Early Cretaceous and Permo-Triassic sandstones. There is an upsection decrease in ~600 Ma Cadomian (~7% less) age component and an increase in ~300

Ma Variscan age components (~33% increase). The zircon U-Pb of the lower Vallcarga Fm. matches Aptian-Albian strata DZ signatures with a large component of ~450Ma Caledonian and ~600 Ma Cadomian. The upper Vallcarga Fm. shows mixing of Aptian-Albian and Triassic rift strata DZ signatures continuing into the Aren Fm. The Paleocene Tremp Fm. age spectra are dominated by ~300 Ma Variscan component, which we interpret to be continued recycling of Permo-Triassic strata. The Aren equivalent Marboré sandstone sampled near Biescas displays age spectra similar to those of the Upper Vallcarga Fm. and Aren sandstone suggesting similar provenance.

The double-dated zircons from all four samples show a dominant cooling age peaks at ~175Ma, ~250Ma and 300Ma with minor peaks ~100 Ma attributed to episodes of Permian volcanism, Triassic-Jurassic rifting, and Early Cretaceous rifting. We interpreted these as the signal of unroofing of early Cretaceous rift basins strata, Triassic and Permo-Triassic red beds, and Permian volcanics.

Detrital rutile U-Pb age spectra from the upper Vallcarga sample has a prominent component of Variscan aged grains, similar to rutile age spectra of Triassic sandstones. The Tremp Fm. sample has a distribution with ~300Ma Variscan, ~600Ma Cadomian, and 1600-2200Ma Paleoproterozoic peaks. There is one grain with a ~105 Ma Albian U-Pb age that is sourced from granulites found in the NPZ massifs. This suggests that there may be a major change in provenance or catchment area in the Paleocene.

The Eastern and Ager Basins

The eastern foreland basin strata show similar upsection trends of recycling Triassic and Early Cretaceous syn-rift strata from the Late Cretaceous through Paleocene, but with an additional sediment source from the Catalan Coastal Ranges. In two Late Cretaceous samples from the Cadi thrust sheet, there is a DZ component with ~80Ma U-Pb ages is interpreted to be sourced from volcanics in the Catalan Coastal Ranges. The Santonian-Paleocene DZ U-Pb age spectra in the east and in the Ager Basin are dominated by Variscan aged zircons. In Cretaceous and Paleocene samples from a previously published section in Baga is a similar upsection trend as observed in the Isabena section, reflecting recycling of Early Cretaceous and Triassic strata. However, there is significantly less Caledonian and Cadomian aged zircons reflecting more input of Variscan aged zircons from the Catalan Coastal Ranges and recycling of Permo-Triassic strata. Detrital rutile from Late Cretaceous sandstones have prominent peaks of ~300 Ma Variscan, ~600 Ma Cadomian, and ~900 Ma Kibaran aged rutile. The lack of Paleoproterozoic rutiles and presence of Kibaran rutiles are distinct differences from the Tremp basin detrital rutile spectra.

Our new detrital zircon double-dates and detrital rutile U-Pb data suggest a partitioned early foreland basin, likely separated by structures along Boixols Thrust and/or the Montsec Thrust. The sediment of the eastern and Ager basins was sourced from the eastern Pyrenees and the Catalan Coastal Ranges with age spectra dominated by Variscan aged component with the presence of ~80Ma volcanic grains. The Tremp and western basin deposits were sourced from the central and eastern Pyrenees and North Pyrenean Zone. These new data show a partitioned southern foreland basin from its inception with distinctive detrital mineral signatures between the eastern and Ager basins and the Tremp and western sector.

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Recognition of shelf-margin clinoforms in outcrops; illustrated from Jurassic Las Lajas – Los Molles formations, S. Neuquen Basin, Argentina

Cornel Olariu[1], Ronald J. Steel[1], Nataleigh K. Vann[1,2], Rene Winter[1,3], Eugen P. Tudor[1,4], Monsoo Shin[1]

[1]University of Texas, Austin, Texas, USA
[2]BHP Billiton, Houston, Texas, USA
[3]BP, Houston, Texas, USA
[4]Hunt Oil, Bucharest, Romania

The source-to-sink concept of erosion, sediment dispersal and deposition was built on modern and recent sedimentary systems where river catchments, alluvial and coastal plain, shoreline, shelf, slope and basin floor deposits can be observed as "linked" parts of an entire erosional to depositional system. However, in ancient systems it can be difficult to observe all parts of the system, though where seismic data or seismic-scale outcrops occur basin margin clinoforms linking alluvial plain to deepwater fans can be mapped. Basin margin clinoforms were not commonly recognized in the past (pre-1970, before seismic data) and stratigraphic successions in many basins were considered as "layer cake". However, when stratigraphy displays deep water, shelf and fluvial deposits from base to top, the simplest initial hypothesis is that they are part of an "entire" laterally connected source-to-sink system, where the alluvial and shallow-marine topsets aggrade and prograde out across the underlying deepwater slope and fan deposits. In this study, an outstanding source-to-sink clinoform succession is recognized in outcrops and specific depositional environments on shelf, slope and basin floor are described.

The Lower to Middle Jurassic deposits of Challaco – Las Lajas – Los Molles formations in the S. Neuquen Basin in Argentina fill the basin from south and east by the means of shelf-slope-basin floor clinoforms. Exceptional outcrops (Fig. 1A) expose 1000s m of stratigraphy along 20 km depositional dip and 10 km depositional strike. The outcropping stratigraphy shows a characteristic large scale (1000 m) tripartite grain-size partitioning with sandy basin floor, muddy slope and sandy topset deposits, betraying the clinoformal basin infilling. Individual clinoforms have been mapped both by following the "flooding surfaces" (continuous muds), and occasional coarse-grained, channelized units that can be walked from the shelf and down through the otherwise muddy slope (Fig. 1B). The unusual aspect of the clinoforms in this area is the coarseness of the deposits (conglomeratic) at times continuous from shelf to basin floor. The depositional elements indicate a shelf dominated by fluvial and tidal processes, a mainly muddy shelf edge penetrated in places by coarse-grained channel belts and delta-front lithosomes, deepwater slope is dominantly muddy but punctuated by coarse grained channel deposits and extremely thick (hundreds of meters) basin-floor fan deposits composed of channelized to unchannelized turbidite lobes (Fig. 1C). The recognition of the Lajas-Los Molles clinoforms show how the coarse deposits extend from the shelf through the shelf-edge, discontinuously down the slope and then onto the basin floor where there are continuous coarse sandstone units (fans).

Comparison of Neuquen Basin clinoforms with other basins where 100s to 1000s m thick tripartite sand-mud-sand successions show how clinoforms fill the basins. Clinoforms can be recognized in outcrops only where the exposures are large and continuous with sandstones punctuating the mud-prone slopes (100s to 1000s m thick) as in Spitsbergen, Neuquen Basin and a few other locations. When outcrops are combined with subsurface data (e.g., in Washakie Basin, Wyoming or Dacian Basin, Romania) the clinoformal interpretation becomes more obvious in the light of subsurface geometries. However, in the cases of limited subsurface data despite large outcrops such as in Karoo Basin, South Africa, Tyee Basin, Oregon, Fish Creek – Valecito Basin, California or Magallanes Basin, Chile the interpretation of clinoforms and "linked systems" is more difficult and requires the use of a model as proposed here.

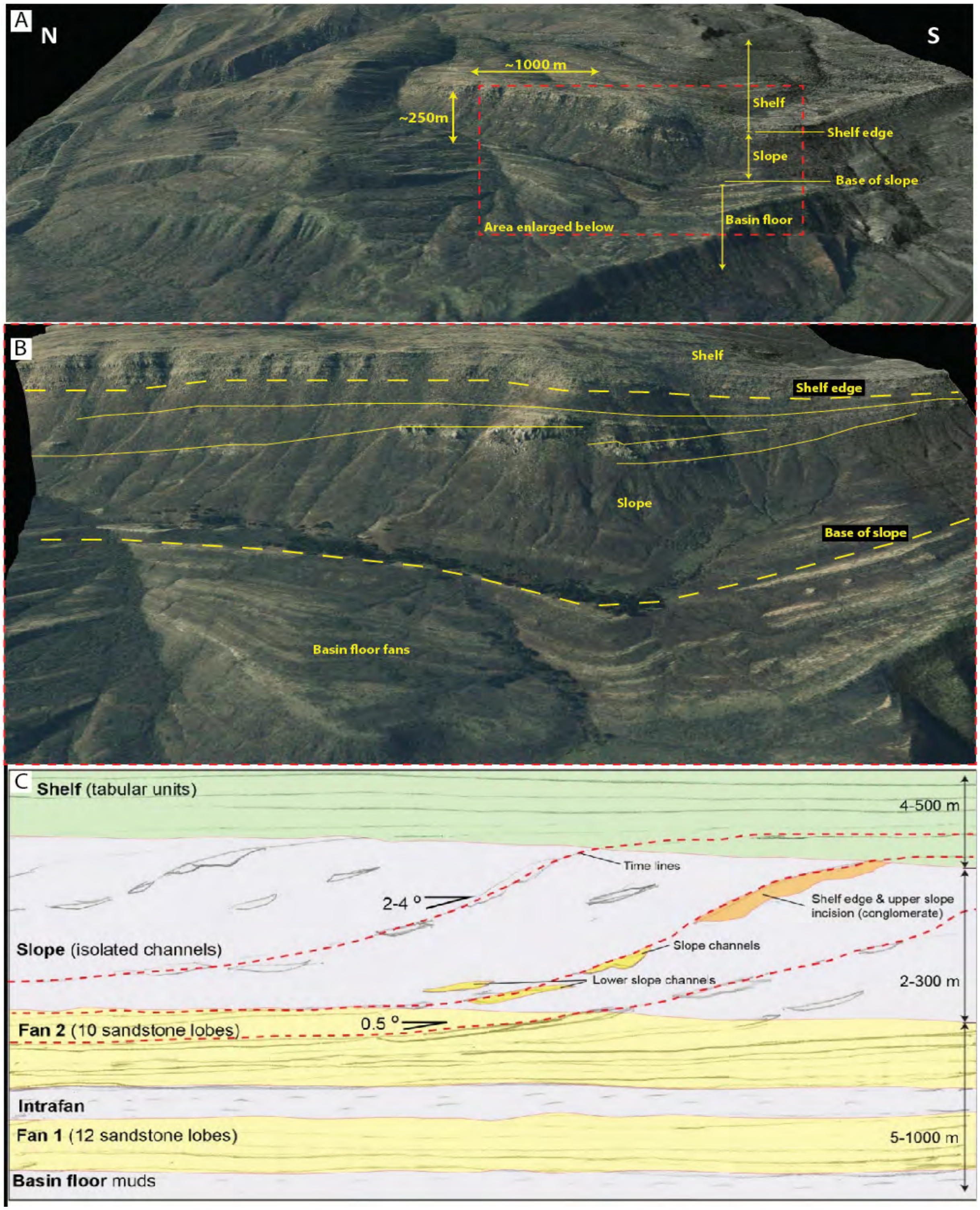

Figure 1. Jurassic clinoforms in Neuquen Basin. A – Dip oriented outcrop belt with continuous sandstone units on shelf, 250 m thick mudstone dominated slope and hundreds of meters basin floor fans. B – close-up birds eye view with diverging sandstone units form shelf into the slope. Progradation direction is to the right. C – Sketch with the geometry and main depositional elements of the clinoforms.

Source-to-sink analysis in an active extensional setting: Holocene erosion and deposition in the Sperchios rift, central Greece

Sofia Pechlivanidou[1], Patience Cowie[1], Robert Gawthorpe[1], Alexander C. Whittaker[2], Bjarte Hannisdal[1], Christos Pennos[3]

[1]Department of Earth Science, Bergen, Norway
[2]Department of Earth Science and Engineering, Royal School of Mines, Imperial College, London, UK
[3]Department of Physical Geography, School of Geology, Aristotle University of Thessaloniki, Greece

We present a fully integrated source-to-sink analysis to explain key controls on surface processes within a tectonically active rift setting. We study a well-constrained natural example of a complete source-to-sink system from the Sperchios rift basin, Central Greece to demonstrate how the characteristics of the sediment supply, the rate of accommodation creation and pre-rift topography, control depositional patterns and facies development during the Holocene. We implement a combination of methodologies that have been separately applied in source-to-sink studies and evaluate our modelling results against independent field observations from different segments of the Sperchios erosional-depositional system.

The Sperchios rift forms an asymmetric half-graben basin, bounded along the south side by several major NW–SE striking high angle normal fault segments. The rift morphology dies out to the west but towards the east, fault offsets gradually increase and the rift becomes less asymmetric as antithetic faults develop along the northern margin of the graben. The source-to-sink system is characterized by a major axial river approximately 80 km long, which drains the upland basin from west to east and supplies sediment to a fine-grained deltaic succession. Over the first ~ 50 km of downstream distance, the axial river migrates across a ~1 km wide braid plain. There is a downstream transition to a meandering channel that continues to the shoreline and terminates in a bird's foot delta (Fig. 1).

We use a published numerical model (Syvitski and Hutton, 2001; Hutton and Syvitski, 2008) to quantify Holocene-averaged sediment load supplied to the delta and validate our results by comparing the model output with the observed deltaic stratigraphy. To constrain the Holocene depositional volumes along the transport system, as well as to analyse the dynamics of the sediment routing system, we quantify the present-day grain size distributions for the axial river and the major transverse alluvial fans that supply sediment to the axial system. In addition, we apply the stream power model to estimate the volume of sediment released from upland areas, and 'χ analysis' (Willett et al., 2014; Mudd et al., 2014) to reveal spatial variations in erosion rates as well as to investigate the stability of drainage divides. Combining all of this information allows us to calculate the sediment budget for the offshore and onshore depositional system and to perform a mass-balance analysis for the Sperchios rift over the Holocene.

Our analysis demonstrates that the Sperchios rift comprises a 'closed' system at least over the Holocene, so that the sum of the sediment volumes deposited at the delta and along the routing system balances the sediment volumes released from the upland source areas. We show that more than 40% of the total sediment that builds the Holocene delta is produced by less than 22% of the upland drainage (see Fig. 1). We explain how this feature of the source to sink system can be attributed to the combination of the pre-existing topography, high erodibility of the bedrock lithology, active normal faulting and a long-term (~10^6 years) transient landscape response to fault segment linkage.

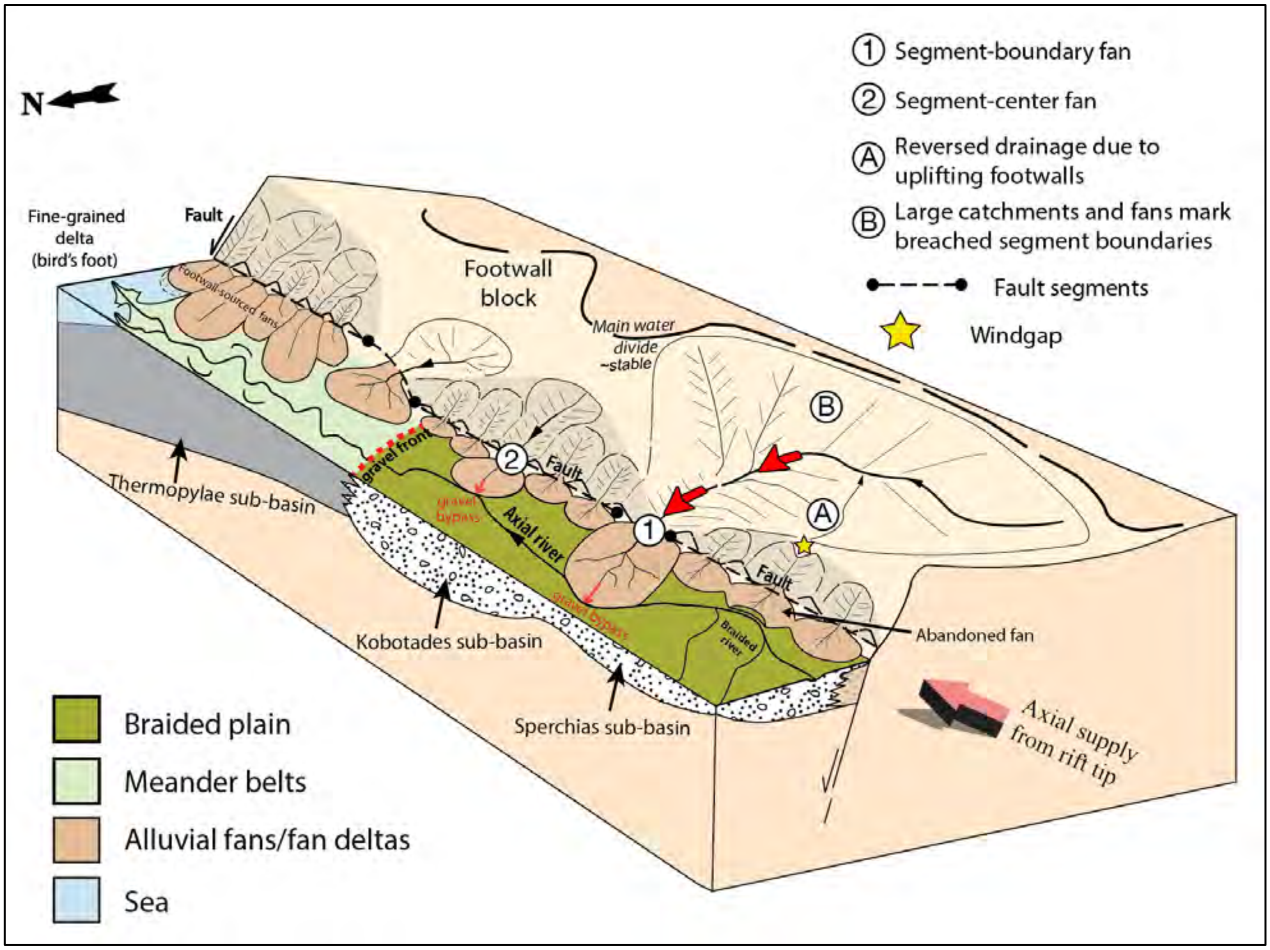

Figure 1: Schematic summary of the Sperchios source-to-sink system. River capture events (see A) lead to the development of a large catchment (see B) in the footwall of active normal faults. Thick red arrows indicate high sediment supply from this catchment. Axial supply from the rift tip due to high relief pre-existing topography is shown with a thick pink arrow. Grain-size fines down the axial river, which changes from a braided to a meandering channel downstream. The entire amount of coarse fraction is extracted in to stratigraphy leaving a fine-grained delta at the eastern part of the rift. The position of the gravel front is indicated with a red dashed line. Small red arrows show transverse gravel supply from fault segment-boundary and fault segment-center fans and indicate where transverse sediment supply enters the axial system.

We show how the location of transverse fluvial systems relative to fault segmentation, and the associated variations in relative tectonic uplift/subsidence, influences gravel delivery to hanging wall depositional systems. Furthermore, using the grain-size fining model of Fedele and Paola (2007), we demonstrate that a linear increase in the rate of hanging wall accommodation creation from west to east along the rift axis explains the observed grain-size variation and the formation of the extensive meandering belt and fine-grained delta at the eastern part of the rift (Fig. 1).

Finally, we compare long-term depositional volumes, derived from geophysical constraints on the hanging-wall stratigraphic fill thicknesses and the age of the rift, to short-term depositional volumes obtained from modelling downstream fining rates along the axial and the major transverse systems. The rates are in close agreement near the tip of the rift where fluvial processes dominate but differ significantly along axis where both sea-level variations and tectonic subsidence control accommodation creation.

This study shows, in a robust way, the link between sediment supply variations and depositional patterns in an active rift basin and the power of integrating different data types and modelling approaches with field observations in order to understand how complex source-to-sink systems function.

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Significance of river hydrological regime in source to sink analyses

Piret Plink-Björklund[1], Evan Jones[1], and Mark Hansford[1]

[1]Colorado School of Mines, Golden, CO, USA

We typically utilize average values in source to sink analyses. For example, we calculate average paleo-discharge using paleo-channel dimensions, and then paleo-drainage basin size or sediment yields using these average paleo-discharge values (see e.g. the widely used BQART scaling relationships; Syvitski and Milliman, 2007).

Based on global modern river discharge analyses, we show that such average discharge (Q_{ave}) values represent discharge events of very different frequency and magnitude in rivers with different hydrological regimes (see Jones et al., submitted). Thus, applying Q_{avg} in source-to-sink analysis may cause an error of multiple magnitudes in drainage basin and sediment yield estimates.

Only in rivers with normally distributed discharge do the Q_{ave} values approach the 50th percentile occurrence (the highest frequency of occurrence; Q_{50}) (Fig. 1) and can be assigned a specific frequency and magnitude. It is rivers with extremely persistent hydrology that have hydrographs with approximately normal distributions. In such rivers both low and high magnitude discharge events are rare occurrences, and their differences are small relative to Q_{ave}. Such persistent discharge is largely a function of perennial precipitation style that provides a year-round surface water supply, and lacks extreme wet- or dry-seasons (Fig. 2a).

A B

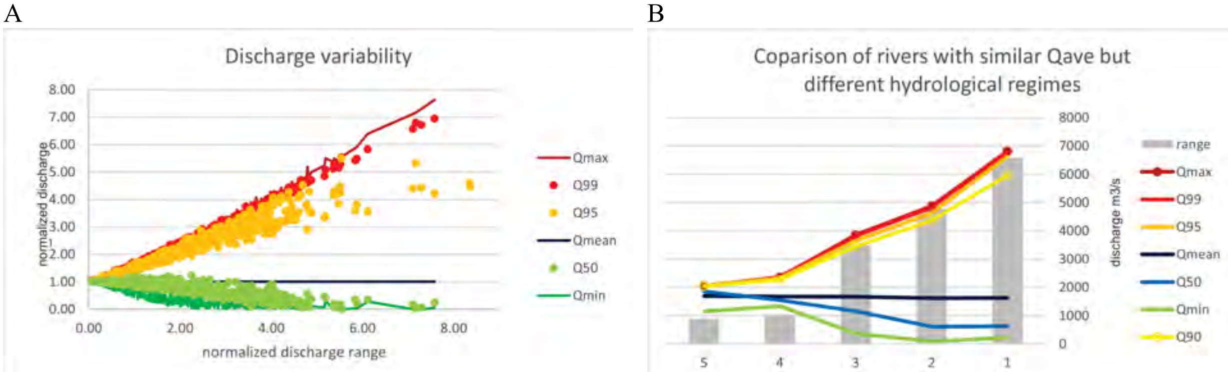

Figure 1. (A) Average discharge is a value that represents most common discharge only in rivers with very persistent discharge (left side of diagram with normalized discharge range values <2). In rivers with highly seasonal or erratic hydrology, average discharge does not represent either the low base flow, or the efficient discharge of the floods (data from Global river database http://nelson.wisc.edu/sage/data-and-models/riverdata/index.php) (B) Comparison of hydrology in rivers with variable hydrology but the same average discharge. Examples 5 and 4 illustrate persistent discharge, whereas 3 – 1 increasingly variable discharge (data from the Global Runoff Data Centre (GRDC), Germany).

Rivers with variable hydrology have hydrographs that deviate from normal distribution and are best fitted with log- normal or exponential distributions (Figs. 1, 2b). These rivers have seasonally low base flow conditions that are interrupted by a strong wet-seasons that make higher magnitude flow events more likely, giving the hydrograph a positive skew, a longer right tail, and a high magnitude excursion from base flow. Because of the positive skewedness of these distributions Q_{ave} is a higher magnitude of flow than base flow or Q_{50} conditions (Figs 1 and 2b). Even more erratic, ephemeral rivers with extremely low or lack of base discharge and intermittent flooding events have extremely positively skewed discharge frequency distributions. These hydrographs are best fit with highly asymmetric log-normal distributions or in some examples approach exponential distributions with very high frequency of low-magnitude discharge events and increasingly infrequent high-magnitude discharge events (Fig. 1). Q_{ave} in such rivers is also inflated by the positive skew of the distribution such that it is higher than the base flow condition (no flow) and higher than Q_{50}, but not high enough to reflect discharge during floods. Thus Q_{ave} rather represents a flow event that likely only occurs momentarily as a flood surge is waxing or waning, and is a transient flow state that inadequately characterizes either base-flow or flood conditions.

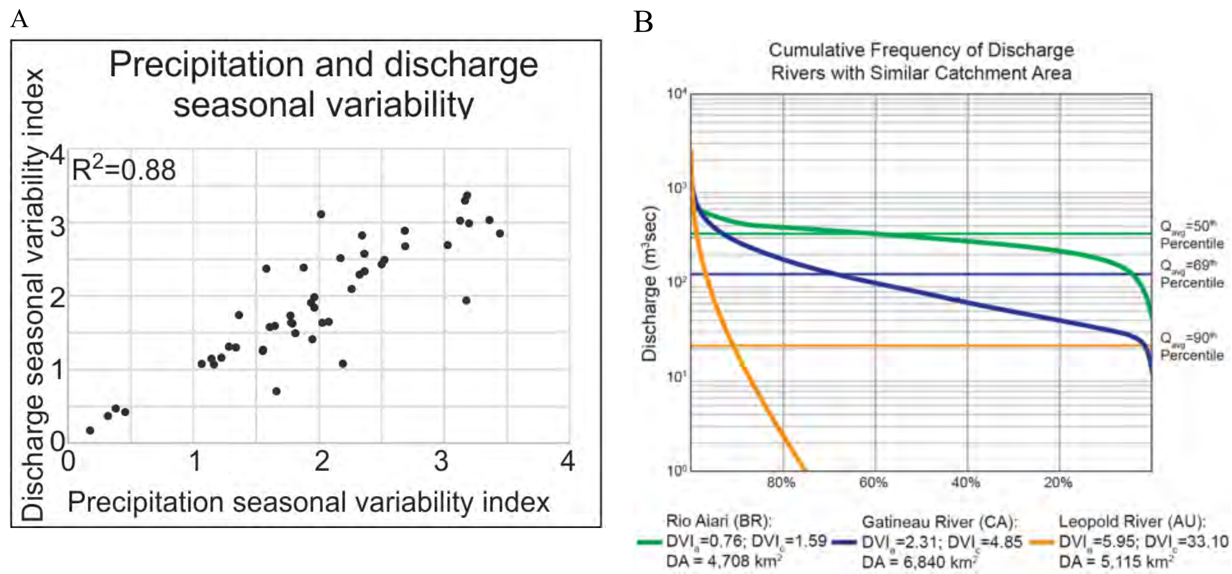

Figure 2. (A) River discharge variability has a positive correlation with precipitation variability as low base flow is a function of sustained dry periods and high-magnitude floods of intense wet seasons (Data from Leier et al., 2005). (B) A comparison of the cumulative frequency of discharge for three rivers with similar drainage basin size (approximately 5,000 km^2) and variable hydrological regime. While the average discharge of the persistent Rio Aiari is more than one hundred times larger than the erratic Leopold River, the separation in discharge magnitude is reduced at higher percentile discharge events (data from the Global Runoff Data Centre (GRDC), Germany).

Comparing the hydrographs of modern rivers with similar drainage basin size but variable hydrological regimes illustrates the large differences in the magnitude and frequency of Q_{ave} conditions (Fig. 2b). Q_{ave} in a river with persistent hydrology can be 100 times larger as compared to a river with erratic hydrology with the same drainage basin size. This implies that using Q_{ave} we are highly likely to consistently underestimate the drainage basin size, as well as the efficient discharge (discharge that transports most of the sediment), and thus also the rivers capacity of sediment yield in rivers with erratic and highly seasonal hydrology.

Moreover, this efficient discharge is also the channel forming discharge and thus determines channel dimensions that we utilize in the ancient record as a key parameter in drainage basin or sediment yield estimates. Based on the above analyses, channel-forming discharges and thus channel dimensions are values close to Q_{ave} only in rivers with persistent hydrological regime (normal distribution) (Fig. 1). In rivers with highly seasonal and erratic hydrology, the efficient channel forming discharge (bankful flow) is a considerably higher magnitude flow and is likely close to Q_{99} rather than Q_{ave} (see Jones et al., submitted).

The latter is clearly demonstrated by an analyses of modern fluvial fan systems where channel dimensions characteristically decrease downfan. Our analyses shows that using Q_{ave} values, the drainage basin size scales with the size of channels in the toes of the fans, rather than with the larger channel in the fan apex that would be recognized in the geological record as trunk channels. If used as a measure of flood discharge (Q_{99} or higher), the trunk channel size scales with the drainage basin size, as demonstrated by our new regressions for scaling of drainage area (see Jones et al., submitted). The global river data analyses shows that at such flood discharges the hydrological regime of the river does not have a strong impact on predicting runoff yields.

River hydrology is largely driven by climatic conditions, and thus a function of precipitation and snowmelt, and aided by hydrological connectivity and groundwater flow. Accordingly, we commonly assign documented increases and decreases in riverine sediment supply to changes in precipitation and climate. Also here, we commonly utilize average values in our interpretations of environmental drivers, and there is a tendency to interpret lower sediment yields as a result of lower average precipitation (increased aridity). However, rivers with highly seasonal or erratic hydrology are common in dry climates and produce efficient discharges that may be multiple orders of magnitude higher than their $Q_{ave.,}$ and are thus likely to have high sediment yields, especially when paired with increased hydrological connectivity (e.g. due to reduced vegetation cover). Furthermore, sediment transport in suspension is elevated in variable discharge rivers due to high magnitude floods and increased flow velocities, and downstream sediment transport rates are thus likely to be increased.

Sediment routing and fluvial architecture in the Ypresian-Lutetian Corçà Fm. (Àger sub-basin, south-central Pyrenees, Spain)

Poyatos-Moré, M.[1*], Roigé, M.[2], Gómez-Gras, D.[2], Solé, X.[3], Duller, R.A.[4] and Boya, S.[2]

[1]School of Earth and Environmental Sciences, University of Manchester, M13 9PL, United Kingdom
[2]Departament de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[3]Carrer Catalunya 23, 08552 Taradell, Spain
[4]Department of Earth, Ocean & Ecological Sciences, University of Liverpool, L69 3GP, United Kingdom
*corresponding author: miquel.poyatos@gmail.com

The Corçà Fm. is a lower Eocene fluvial succession that overlies the transitional marine Ametlla Fm. in the Àger sub-basin (south-central Pyrenees, Spain). The Corçà Fm. has received relative little scientific attention, which is surprising since it offers key information into: (1) fluvial depositional environment and architecture development in a diachronously subsiding basin; and (2) development, linkage and time-correlation of mid-late Eocene sediment routing systems. Here, sedimentary, architectural and provenance data are presented and used to determine the evolution of depositional systems and sediment transport pathways through time, which allow to provide a chrono-tectono-stratigraphic framework between the Àger and Tremp-Graus sub-basins.

A NW-SE basin axis orientation is indicated by onlap geometries of the Corçà Fm. strata onto the Ametlla Fm. (south) and the Montsec thrust (north). A series of north-striking extensional syn-sedimentary structures are observed to the south of the study area, where deposits display subtle fanning geometries interpreted as growth strata. These structures therefore affected deposition of the lower Corçà Fm. acting as topographic hindrances to sediment transport pathways in the southern limb of the Àger syncline. Facies and sedimentary structures of the Corçà Fm. indicate an overall NW palaeo-transport, with a shift towards the N in the western part of the area, where an increase of gravel facies is observed.

Palaeontological, sedimentary and provenance data together with correlative surface mapping suggests that the Corçà Fm. is equivalent to the Montanyana deltaic complex, located ~15 km basinward (NW) and linked with the Hecho Group turbidites. According to pebble composition and sandstone petrography the Corçà Fm. derives from a highly weathered source area which provided significant amounts of quartz pebbles and a matrix rich in K-feldspar grains. Therefore the combination of petrofacies and palaeoflow analysis does not suggest a major Pyrenean source and points towards a dominant southern source area, identified here as the Ebro Massif.

The equivalence in facies characteristics, petrology and dominant paleocurrent directions of the Corçà Fm. and the fluvial Castissent Fm. (Tremp-Graus sub-basin) indicate their depositional systems were eventually connected on both sides of the Montsec high. This would suggest a relatively subdued topography in the vicinity of the Montsec thrust at the time. Sedimentary data integrated with the provenance study from these formations suggest an interaction and competition between southern and northern sediment routing systems took place during the mid-upper Ypresian in the south-central Pyrenees, coeval with the development of major tectonic structures. This interaction progressively decreased and during the Lutetian northern-sourced systems became more established. This is also consistent with a stronger Pyrenean provenance signal detected in the younger turbidite systems in the Ainsa and Jaca basins.

This work provides evidence for an important southern feeding system of the South-Pyrenean Foreland Basin acting during the lower Eocene and co-existing with the northern Pyrenean sources. It also cautions against using thermochronologic proxies for regional palaeogeographic reconstructions without integrating a comprehensive sedimentary study with petrographic and provenance analysis.

Spatial-temporal evolution of sedimentary transition zones and stratigraphic sequences in an exhumed basin margin succession

Poyatos-Moré, M.[1*], Gomis-Cartesio, L.E.[1], Brunt, R.L.[1], Brooks, H.L.[2], Harding, R.[1], Hodgson, D.M.[2] and Flint, S.S.[1]

[1]Stratigraphy Group, School of Earth and Environmental Sciences, University of Manchester, United Kingdom
[2] Stratigraphy Group, School of Earth and Environment, University of Leeds, United Kingdom
*corresponding author: miquel.poyatos@gmail.com

The spatial-temporal evolution of basin margins is recorded in the changing nature of depositional systems and their three-dimensional architecture at multiple scales. Therefore, to decipher the allogenic and autogenic signals preserved in sedimentary successions a multi-scale approach is required, which is rarely afforded by subsurface or outcrop datasets.

The Permian Karoo Basin (South Africa) provides system-scale exposures of shelf/shelf-edge deposits passing down dip through slope valleys and channel-levee complexes into basin-floor lobes, offering excellent outcrops that can be analyzed across a range of scales. More than 20 years of field-based research have yielded a large dataset with 200+ km of logged sections, >20 cored research boreholes, and 1000+ km of stratigraphic correlations covering more than 150 km strike width of an exhumed basin margin. This dataset is further complemented by radiometric dates, geochemistry and magnetostratigraphic data.

Outcrop and core observations, combined with geometric analysis from correlation panels, allow identification and positioning of several sedimentary transition zones through time. These are critical physiographic areas that record major changes in transport and depositional processes and/or earth surface gradient. Their positions were used to constrain palaeo-physiographic segments of the Karoo Basin fill. Facies associations and grain-size proportions were obtained for each segment (shelf, slope, basin floor), and compared to examples elsewhere. Results indicate a mixed sand/mud prone basin margin, with a sand-rich basin floor, mud-rich slope and a sand-rich, younger accretionary shelf. Plotting of data in 3D space enabled identification of persistent areas of preferential sediment accumulation. This, combined with field evidence of seabed topography and sediment entry point migration, suggests that regional and dynamic subsidence mechanisms interacted with sedimentation, resulting in differential sediment distribution across the basin margin.

The physical stratigraphy of the ca. 2 km-thick succession is subdivided into 6 composite sequence sets (CSS1-6). CSS1-3 comprise basin floor sand-rich deposits in an area of increased subsidence around Laingsburg, and correlate to a mud-rich succession 40 km along margin in Tanqua; CSS4-5 comprise sand-rich basin floor-to-slope deposits in Tanqua with equivalent mixed sand/mud slope systems in the Laingsburg depocentre. This across-strike variability in sediment distribution was progressively healed by prograding basin-margin clinothems of CSS6, which can be correlated across both depocentres.

Deep-water depositional sequences (10-50 m-thick) are increasingly compensationally stacked and sand-rich down dip. They are much thinner than shelf sequences (>300 m-thick), which show spatial variability in margin progradation, dominant process regime and soft sediment deformation, but their associated slope deposits are sand-poor. An absence of valley systems incising shelf strata is interpreted as a result of intrinsic compensational processes and high accommodation and sediment supply rates in a high-latitude, early greenhouse setting. This contrasts with the underlying slope and basin-floor sequences that show major lateral variability in sediment supply attributed to a different basin margin configuration, icehouse-driven higher amplitude changes in relative sea-level and dominant processes on the coeval shelf. Therefore, the Karoo shelf strata are a poor analogue to the shallow-marine systems (now removed by later uplift) that fed the underlying deep-water succession. This study highlights the importance of spatial-temporal variability in basin margin topography and its controlling effects on sediment distribution, and cautions against applying over-simplified models for reconstructing long-term progradational basin margins.

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Facies analysis and sequence stratigraphic implications of a mixed (clastic-carbonate) depositional system: lower Eocene Castigaleu Fm. (south-central Pyrenees, Spain)

Poyatos-Moré, M.[1*], Honegger, L.[2], Castelltort, S.[2], Serra-Kiel, J.[3], Puigdefàbregas, C.[4] and Midtkandal, I.[5]

[1]School of Earth and Environmental Sciences, University of Manchester, Manchester M13 9PL, United Kingdom
[2]Department of Earth Sciences, University of Geneva, 1205 Geneva, Switzerland
[3]Department of Stratigraphy, Paleontology and Marine Geosciences, University of Barcelona, 08028 Barcelona, Spain
[4]Department of Applied Geophysics and Petroleum Engineering NTNU, Trondheim / Department of Geology and Geophysics, University of Barcelona, 08028 Barcelona, Spain
[5]Department of Geosciences, University of Oslo, 0371 Oslo, Norway
*corresponding author: miquel.poyatos@gmail.com

The resulting facies and stratigraphic architecture of mixed (or hybrid) depositional systems in foreland basin settings can be very complex to predict due to the interplay between different depositional processes and controlling factors (i.e. clastic supply, carbonate production and local/regional tectonic activity). These systems and resulting deposits are still poorly constrained, and very little work has been done on their recorded autogenic/allogenic signals and sequence stratigraphic implications. Therefore, their understanding remains a challenge for the stratigraphic community.

In the Ainsa basin (south-central Pyrenees, Spain), the lower Eocene (Ypresian) strata of the Castigaleu Fm. are represented by a dominantly clastic and bioclastic succession formed in different shallow marine depositional conditions and overlain by the first deep marine sediments of the Hecho Group. This study aims to constrain the development of this mixed clastic-carbonate succession in response to variable tectonic activity and climatic/eustatic cycles.

To accomplish these objectives, fieldwork has included mapping, logging sections, facies analysis and lithostratigraphic and biostratigraphic correlations. These correlations have been used to provide a preliminary sequence stratigraphic interpretation, and further integrated and tested with carbon stable isotopes on bulk rock carbonates to trace the climatic signals recorded during deposition of the Castigaleu interval.

Detailed facies analysis reveals that the succession is dominated by clastic shelf and delta slope sediments, interbedded with carbonate-rich packages with variable lateral continuity, and often associated with macrofossil accumulations. Results of integrating facies analysis and physical stratigraphy suggest that at least two sequences can be recognized; both bounded by marked angular unconformities associated with tectonically-controlled sequence boundaries. However, a strong eustatic influence is still recorded as sequences preserve and can be subdivided into different sub-units: lowstand deposits are generally comprised by tabular and channelized turbidites overlain by a highly regressive set of mouth bars and tidally-influenced channels; overlying these, markedly transgressive landward shifts of the sedimentary systems lead to the development of an extensive shelf with carbonate-rich horizons (rich in fauna), and condensed sections; highstand deposits are again characterized by a clear prograding trend and a progressive downlap of its fluvio-deltaic deposits over the underlying condensed section. In these, several parasequences can be defined, with high frequency regressive cycles interrupted by minor transgressions and their associated flooding surfaces.

The succession is abruptly interrupted and eroded by a large-scale unconformity associated with the formation of a submarine canyon. This again supports the evidence that local/regional tectonic structures were active at the time of deposition and played a significant control on facies changes, accommodation and sequence boundary generation, but still allowing a eustatic and climatic signals to be recorded. This study provides a depositional model for a mixed system in an active compressional setting, and constrains the controls on the stratigraphic architecture and facies development, as well as the implications of the Castigaleu Fm. strata within the basin fill history.

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Structure-stratigraphy interactions, landscape evolution, and internal vs. external sediment sourcing—implications to S2S systems: integrated outcrop study of the Ainsa Basin, Spain

David Pyles[1], Julian Clark[2], Jeremiah Moody[3], Greg Gordon[4], Matt Hoffman[5], Amy Moss-Russell[6], Henri Silalahi[6], Prianto Setiawan[7]

[1]EOG Resources, Denver, Colorado, USA
[2]Statoil, Austin, Texas, USA
[3]Chevron Energy Technology Company, Houston, Texas, USA
[4]Aera Energy, Bakersfield, California USA
[5]Chevron, Houston, Texas, USA
[6]Chevron, Bakersfield, California, USA
[6]Chevron, Jakarta, Indonesia

Eocene strata of the Ainsa Basin (Spain) contain clastic and carbonate strata that were deposited in a relatively small (~100 km^2), piggyback basin in a foreland basin system. The basin is bounded by the Mediano Anticline to the east and the Boltaña Anticline to the west. These structures separate the Ainsa Basin from the adjacent Tremp and Jaca Basins, respectively. Clastic strata in the Ainsa basin were sourced by an eastern fluvial-deltaic system, whereas carbonate strata were sourced from shallow-water carbonate systems that rimmed the southeastern and southwestern margin of the basin. Four time-stratigraphic units, which form an upward transect through the basin-fill succession, were studied in detail: Ainsa, Morillo, Guaso, Sobrarbe-Escanilla. The transect records progressive uplift of the basin-bounding structures, spatial-temporal changes in the amount and location of maximum subsidence, and temporal changes in the landscape/depositional environment as the basin filled.

The Ainsa unit contains submarine channels that entered the basin from the east and exited the basin to the northwest, although some channels locally transfer to lobes near the northwest end of the basin. The Morillo unit contains submarine channels that entered the basin from the east, diverged onto the basin floor, and then converged at the point where they exit the basin to the northwest. The southern margin of the basin was rimmed by shallow-water carbonates, which sourced carbonate-rich debrites and slump blocks that locally interfinger with siliciclastic strata along the southeastern and western margins of the basin. The Guaso unit contains submarine channels that entered the basin from the east, and possibly also from the south, and transferred to a fully confined, distributive submarine fan at the center of the basin. The southern margin of the basin contains shallowing-upward carbonate cycles and large-scale carbonate slumps and debrites that locally interfinger with the siliciclastic strata in the southern part of the basin. The Escanilla-Sobrarbe unit contains a graded shelf-to-basin profile that entered the basin from the south and prograded northward. The eastern margin of the basin contains shallow-water carbonate strata that locally interfinger with deltaic strata, and nummulitic shoals are abundant throughout the unit, indicating a mixed carbonate-clastic source of sediment.

Four lines of evidence support the interpretation that the basin-fill succession was deposited during structural growth. First, the depocenters of the units, which are interpreted to reflect the position of maximum subsidence during deposition, systematically shifted southwestward through time. Second, the up-dip feeder system systematically shifted southward as the basin filled. Third, many of the stratigraphic units are locally separated by progressive unconformities at the Mediano Anticline. Forth, carbonate-rich, sediment-gravity flow deposits and large-scale slump blocks were shed from the actively growing anticlines during deposition. The upward succession generally records a shallowing of the basin through time indicating that sediment supply exceeded the rate at which accommodation was created in the basin.

These results have at least two implications to source-to-sink (S2S) analyses. First, the Ainsa basin, which was one component of the sink, was actively deforming during deposition. As such, the degree of confinement in the Ainsa Basin and adjacent basins changed through time, affecting the sequestering of sediment volumes and grainsizes between the basins. For example, during deposition of the Morillo unit, the Jaca and Ainsa Basins were connected by a deep-water sediment routing system, however, the basins were partitioned during Guaso time, when deposition was restricted to the Ainsa Basin. Second, some of the strata in the studied units are composed of internally (basin) derived carbonate—a sediment source that was decoupled, although coevally active, with the clastic system. As such, the volume of sediment in the basin is not necessarily a reflection of the amount of sediment that entered from the siliciclastic sediment transport system.

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Source to sink of the Miocene Ribe Group, eastern North Sea Basin: the control of climate, tectonism and eustatic sea-level changes on partitioning of lithology.

Erik S. Rasmussen[1], Mette Olivarius[1], Karen Dybkjær[1], Torsten Utescher[2] & Peter Japsen[1]

1) Geological Survey of Denmark and Greenland (GEUS), esr@geus.dk
2) Steinmann Institute, University of Bonn, Nußallee 8, 53115 Bonn and Senckenberg Research Institute, Frankfurt am Main, utescher@geo.uni-bonn.de

Proper studies of source to sink systems needs detailed studies of both areas, but this is rarely seen in the literature (Helland-Hansen et al. 2016). A study of the lower Miocene Ribe Group, Denmark, includes detailed investigations of both source and sink areas; Fennoscandian Shield and Norwegian-Danish Basin.

The study of the source area encompasses investigations of clay minerals and flora (based on the deposited sediments) and fission track data (based on the exposed rocks in Fennoscandian Shield) in order to unravel the climate and uplift history. The climate of the area was generally warm temperate with mean annual temperature in the order of 17 – 19^{o} C with minor, ca 5^{o} C variations during the so-called Mi glacial events (Miller et al 1998). The precipitation was in the range of 1300 to 1500 mm per year. The initial topography of the source area (Fennoscandian Shield) was relatively low, less than 500 m in the earliest early Miocene . The onset of Neogene uplift as detected from fission track data started around 23 Ma (early Miocene; Japsen et al. 2016a, b). Increased relief of the hinterland is revealed from steadily higher contents of mountain elements in the pollenflora (*Abies* and *Picea*) and by the end of the early Miocene, at app. 15 Ma, the highest peaks in the source area likely exceeded 1500 m. The sediment provenance was investigated by comparing radiometric age dating of the sink area to the comprehensive data available from the source area (Olivarius et al. 2014). The basement in southern Norway and southwestern Sweden, and possibly its derived sediments, is the primary source of the Miocene sand. However, smaller age populations show that the rivers had a larger catchment area. Overall, it is the same type of sediment that was fed from source to sink during the Miocene, but heavy mineral analyses show that the maturity of the sediment varies, presumably in response to changes in the erosion rate. The variations in zircon age distributions in the sink area are related to how the sediment was distributed in the basin, i.e. depositional environment, and possibly also to tectonics in the source area.

The sediment flux was relatively stable during the 8 My of deposition, ca 2000 km^3 per My despite the increased relief of the hinterland. The high sediment supply in the early phase of uplift and thus the relatively low relief, is interpreted to be due to easy erodibility of strongly weathered basement exposed in the source area in the early Miocene or to the presence of sediments derived from the basement.

The study of the sink area includes seismic data, biostratigraphy, sequence stratigraphy, sedimentology, palynofacies, and clay mineralogy. The sink area was characterized by deposition in a fluvio-deltaic system in a ramp setting with water depths less than 100 m. There is no indication of deposition of fan systems in the basinal area, but sediment transport along the shoreline is well documented in spit and barrier systems down drift of the main delta complexes. Sediment transport associated with tidal gyres dominated the deeper part of the marine realm resulting of contourite deposition lateral to the main delta. Displacement of the shoreline in the order of 200 km occurred during the Mi events that displays sea-level changes of max 30 m. The deposition of the most sand proven units occurred on the slope of the delta platform during falling sea level and within tectonically over-deepened incised valleys. In the upper part of the Ribe Group, water depths and thus accommodation decreased significantly. This resulted in constant reworking of sand in the coastal zone and enrichment of heavy minerals in both foreshore and offshore–transition zone.

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Evolution of the sediment routing systems in the south-central Pyrenean Basin: Unravelling the interplay between northern (hinterland) and southern (craton) provenance

Marta Roige[1], David Gómez-Gras[1], Eduard Remacha[1], Salvador Boya[1], Antonio Teixell[1]

[1]Dept. de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

The south-central Pyrenean Basin constitutes a good example to tie changes in sediment composition during the evolution of a foreland basin. The Pyrenees are an Alpine mountain belt that developed diachronously, from east to west. Characterization of sediment provenance in the south-central Pyrenees is a challenging issue because of the complex tectonic setting and the interference of various sedimentary systems during the filling of the basin. An important handicap is the absence of enough detailed correlation frameworks between contemporary sedimentary systems to achieve well-constrained detailed paleogeographic reconstructions. A detailed petrological study leads to identify the compositional changes of the clastic systems and therefore to better understand the evolution of the sediment sources throughout the development of the foreland basin. During Late Cretaceous to Middle Eocene times the Ager and Tremp basins accumulated deltaic and fluvial deposits that graded to the basinal time equivalents of the Ainsa-Jaca basins. Our provenance results show that the clastic systems from both Ager and Tremp basins were derived from different source areas in different times. These differences can be clearly identified in the Maastrichtian to Paleocene Garumnian facies, which in the Tremp basin show an interference of two source areas, situated to the east and to the north, whereas the Ager basin shows distinct compositional features that imply a different source, located to the south. According to the petrological composition, we find the Ebro Massif as the most likely source area for the south-derived sediments. This source area was delivering mature detritus to the south-central Pyrenean basin at least since Santonian times. In the Ager basin, supply from the Ebro Massif can be also identified in the Eocene deltaic and fluvial systems, having implications in the final composition of the distal deposits of the Ainsa-Jaca basin. In spite that the Ebro Massif acted as source area only episodically during specific intervals of the basin evolution, its clear provenance signature emphasizes an important role of the cratonic margin of the South Pyrenean foreland basin which has been overlooked up to date.

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Foreland basin emersion and cannibalization: a case study of integrated sandstone petrography and detrital zircon geochronology in the Jaca basin (Middle Eocene-Oligocene, South Pyrenean basin)

Marta Roigé[1], David Gómez-Gras[1], Daniel F. Stockli[2], Antonio Teixell[1], Eduard Remacha[1], Salvador Boya[1]

[1]Dept. de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[2]Jackson School of Geosciences, University of Texas at Austin, 78759, Austin, TX United States

The Eocene to Oligocene clastic systems of the South Pyrenean basin constitute a good natural laboratory to investigate paleoenvironment, source areas and sediment composition changes during the progressive evolution of a foreland basin. We provide new petrographic and detrital zircon (DZ) U-Pb data of the northern Jaca basin in the Southern Pyrenees, whose stratigraphic evolution from mid Lutetian deep-marine to Oligocene alluvial systems records a major tectonic and drainage reorganization in the active Pyrenean pro-wedge. The analyzed succession starts with the upper Hecho Group turbidite systems, from the Roncal-Fiscal megaturbidite (Mt-5) until the top of the Rapitán system (Lutetian-Bartonian) which is recording the last stage of turbidite sedimentation. The latter is replaced by the first deltas in the Jaca basin. The Sabiñánigo Sandstone and Atarés deltas (Bartonian-Priabonian) represent the transitional stage before the alluvial deposits of the Santa Orosia, Canciás, Peña Oroel and San Juan de la Peña fans (Priabonian-Oligocene). The replacement of the deep-marine turbiditic sedimentation by terrestrial environments is accompanied by shifts in the location of the source areas, which were strongly controlled by the uplift of the Lakora/Eaux-Chaudes and Gavarnie thrust sheets in the hinterland. Detrital zircon geochronology results show a clearly different signature between the Hecho Group turbidites and the alluvial fans which can be associated to a major change in source area. Coupling of DZ U-Pb data with petrographic analysis allows a better resolution of the source-area shifts and a better discrimination between first-cycle zircon derived from Paleozoic plutonic rocks and multi-cycle zircon derived from the erosion of intermediate reservoirs (Mesozoic and Cenozoic). In addition, as the Upper Eocene-Oligocene alluvial systems of the Jaca basin are fed from the erosion of the older Hecho Group foredeep turbidites, our study provides valuable insights on the response and propagation of detrital zircon U-Pb signatures during the recycling (cannibalization) of sediment within the basin.

Millennial-scale storage and release in small mountain-to-deep-sea sediment routing systems, southern California

Brian W. Romans[1], Jacob A. Covault[2], Bodo Bookhagen[3], and George E. Hilley[4]

[1]Department of Geosciences, Virginia Tech, Blacksburg, VA 24061
[2]Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78713
[3]Institute of Earth and Environmental Science, University of Potsdam, Germany
[4]Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305

Quantitative characterization of system-scale sediment mass-balance is critical for accurate linkage of the stratigraphic record to climate and/or tectonic forcings that originated in sediment-source areas at centennial to multi-millennial (10^2–10^5 yr) timescales. Small, high-relief sediment-routing systems with active tectonism are ideal systems to understand mass-transfer dynamics because: (1) sediment storage (volumes and residence times) between net-erosional and net-depositional segments is minor to negligible as a result of short fluvial transfer zones; and (2) sediment sinks are confined such that the accounting of accumulated mass is more certain. We determine system-scale sediment budgets at 10^2-10^5 yr timescales by combining cosmogenic radionuclide-derived catchment-integrated denudation rates with radiocarbon age-constrained sediment accumulation rates from offshore depositional basins. We integrate new data from the northern California Continental Borderland with published data from the southern Borderland and determine denudation-accumulation budgets for these two aggregate source-to-sink systems over the past ~10-15 kyr to evaluate sediment and tectono-climatic signal transfer through 'reactive' systems. We find that sediment-transfer budgets differ in absolute magnitude as a result of differences in system morphology (i.e., catchment areas, relief, and offshore basin areas), bedrock lithology, tectonic uplift rates, and precipitation patterns. However, we find that the proportion of surplus mass in offshore sinks is similar for the two aggregate source-to-sink systems (~50-60%). We interpret these results to indicate that small, high-relief source-to-sink systems temporarily store detrital mass in shoreline and shelf segments, which is subsequently redistributed to deep-sea segments in response to sea-level cycles (e.g., transgressive erosion of shelf and shoreline). Our findings highlight that while small systems lack significant sediment storage in fluvial transfer zones, there is storage-and-release in shoreline/shelf segments at the frequency of sea-level cycles, which is important to consider if using stratigraphic records to decipher millennial to multi-millennial climate or tectonic signals.

Cosmogenic-isotope tracking of sediment cycling and erosion-rate changes in the northwestern Himalaya

Dirk Scherler[1], Jason B. Barnes[2], Nadja Insel[3], Alexander L. Densmore[4]

[1]German Research Centre for Geosciences, Potsdam, Germany and Freie University, Berlin, Germany
[2]Landscape Analytics LLC, Seattle, WA, 98115, USA
[3]Department of Earth Science, Northeastern Illinois University, Chicago, IL, USA
[3]Institute of Hazard, Risk, and Resilience and Department of Geography, Durham University, Durham, UK

The effects of Cenozoic cooling and Quaternary glacial cycles on erosion of the Earth's surface remain debated. While some studies support global increases in weathering and erosion over time, others refute such changes. Measurement of cosmogenic nuclides in ancient fluvial deposits of foreland basins is a recent approach to assess landscape-scale erosion rates over different time scales, and thus to test the response of erosion rates to climatic changes. In practice, samples are obtained from discrete layers of known depositional age. However, because isotopic abundances from hillslope erosion that occurred millions-of-years ago are low due to subsequent radioactive decay, it is important to quantify additional production of isotopes during burial and re-exhumation, which can be difficult at the outcrop scale.

Here, we place constraints on million-year trends in erosion rates based on ^{10}Be inventories from uplifting Himalayan foreland deposits in northwestern India. Using a novel modeling approach, we show that long-term (~10 Myr) erosion rates are similar to modern values in the Yamuna River catchment. Instead of sampling individual layers, we collected river sediment samples that integrate ^{10}Be concentrations from longer time periods. While this approach does not allow resolving short-term changes in erosion rates, it allows resolving long-term trends and is less prone to disturbances. Published depositional ages and rock uplift rates across the frontal Mohand Range allow us to partition the sampled ^{10}Be concentrations of the foreland source rocks into components acquired during hinterland erosion, burial, and re-exhumation in the evolving Himalayan thrust belt-foreland basin system. Although measured ^{10}Be abundances in sediments eroded from the Mohand Range are consistent with higher Quaternary erosion rates, this apparent increase could also be explained by an earlier phase of tectonic activity on the Main Boundary Thrust and sub-glacial sediment production during Quaternary glacial erosion of the rapidly uplifting High Himalaya. While erosional variability on orbital timescales remains possible, lack of significant trends in erosion rates during Late Cenozoic cooling suggests either low sensitivity of Himalayan erosion to long-term climatic changes or negative feedbacks that serve to balance long-term erosion rates and tectonic forcing.

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Climatically controlled increase in Quaternary erosion rates: Real and perceived biases from thermochronology data

Taylor F. Schildgen[1,2] and Peter van der Beek[3]

[1] GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[2] Institute for Earth and Environmental Science, University of Potsdam, 14476 Potsdam, Germany
[3] ISTerre, Université Grenoble Alpes, CS 40700, 38058 Grenoble Cedex, France

Testing for an increase of global erosion rates over the last few million years in response to climate change and Quaternary glaciations has been difficult and remains controversial. Such an increase was initially inferred from the sedimentary record, but several authors have argued that this record is biased due to unresolved erosional hiatuses, and therefore the inferred increase in sedimentation rates is an artefact. More recently, the discussion has focused on erosional records from the source areas themselves, in particular records extracted from low-temperature thermochronology data. A global compilation of such data appears to show increasing erosion rates toward the present, but it has been argued that this increase may also be an artefact, for similar reasons that affect the sedimentary record.

Here we assess real and perceived biases in the thermochronological record that might affect the inference of temporal variations in erosion rates from such data. We argue that it is unlikely that erosional hiatuses affect thermochronology data because the temporal and spatial scales at which such hiatuses are likely to occur are significantly smaller than those resolved by the data. Instead, we explore the potential bias introduced by the erosional response time of thermochronological systems (defined as the time required to exhume rocks that are fully reset for the thermochronological system considered, i.e. to attain exhumational steady state). These response times are typically longer than the timescale of Quaternary glacial-interglacial cycles, implying that thermochronological systems are insensitive to such variations. For thermochronological data to record an overall increase in erosion rates, the increase must occur over longer time periods, independent of superimposed shorter-term variations. However, because thermochronological response times depend strongly on the final exhumation rate, it is much easier to detect increases in erosion rates with thermochronological data than to detect decreases, introducing a potential bias when examining a global database. Moreover, the integration time of thermochronological systems, i.e., the timescale over which a particular system averages the exhumational history, is equal to the response time and therefore also strongly dependent on the exhumation rate. This implies that rapid exhumation rates can only be resolved on relatively short timescales, again introducing potential bias toward high recent rates in global databases. We show that such a bias is real when attempting to reconstruct global average erosion histories from spatially uncorrelated thermochronological data, and it persists even when combining multiple thermochronometers.

Protracted sedimentary signals of slab breakoff beneath the European Alps recorded in Oligo/Miocene Molasse deposits

Fritz Schlunegger[1], Sébastien Castelltort[2], Philippos Garefalakis[1]

[1]Institute of Geological Sciences, University of Bern, Switzerland
[2]Department of Earth Sciences, University of Geneva, Switzerland

Interpretations of depocenter progradation in coarse-grained material in foreland basins have remained non-unique, mainly due to a lack of independent chronologies for the driving force in the hinterland where the sediment sources are, and the stratigraphic response in the adjacent sedimentary basin. Here, we use well dated 32-20 Ma-old sedimentary archives encountered at three sections within the Molasse foreland basin, and geochronological constraints from the adjacent European Alps, to document two consecutive sedimentary responses - an immediate and delayed response - to slab breakoff beneath the central Alps c. 32-30 Ma ago.

The Central European Alps comprise a doubly-vergent nappe stack with a crystalline core of European origin that straddles the subducting European plate. The orogen is the consequence of a subduction-collision history, which started with the subduction of the European oceanic lithosphere beneath the Adriatic continental plate and the closure of the Tethys Ocean during the Late Cretaceous (Schmid et al., 1996). At c. 35 Ma, the European continental lithosphere entered the subduction channel, where contrasts in flexural rigidities between the subducted oceanic lithosphere and the continental European plate induced extensional stresses within the slab, with the result that the oceanic lithosphere slab broke off at 30-32 Ma (Davis and von Blanckenburg, 1994). This was accompanied by rapid rock uplift and orogen-parallel extension in the rear of the Alps, accomplished through backthrusting along the Insubric Line. The rise of the Alpine topography continued until c. 25-20 Ma, when the mountain belt reached a cross-sectional width of c. 150 km (Schmid et al., 1996).

The Molasse foreland basin, situated on the northern side of the Alps, hosts the erosional detritus of the evolving orogen. In this basin, slab rebound and related surface uplift in the Alps after removal of the oceanic lithosphere 32-30 Ma ago resulted in a shift from basin underfill to overfill and initiated the build-up of alluvial megafans (Sinclair, 1997). Among these, the Napf, Rigi and Hörnli megafans represented the major systems that captured their waters and clastic material from the back of the central Alpine orogen. Related sedimentary archives are encountered at three sections, situated at the proximal basin border next to the megafan depocenters. We will use these archives to document two consecutive sedimentary responses - an initial and delayed response - to slab break-off beneath the central Alps c. 32-30 Ma ago.

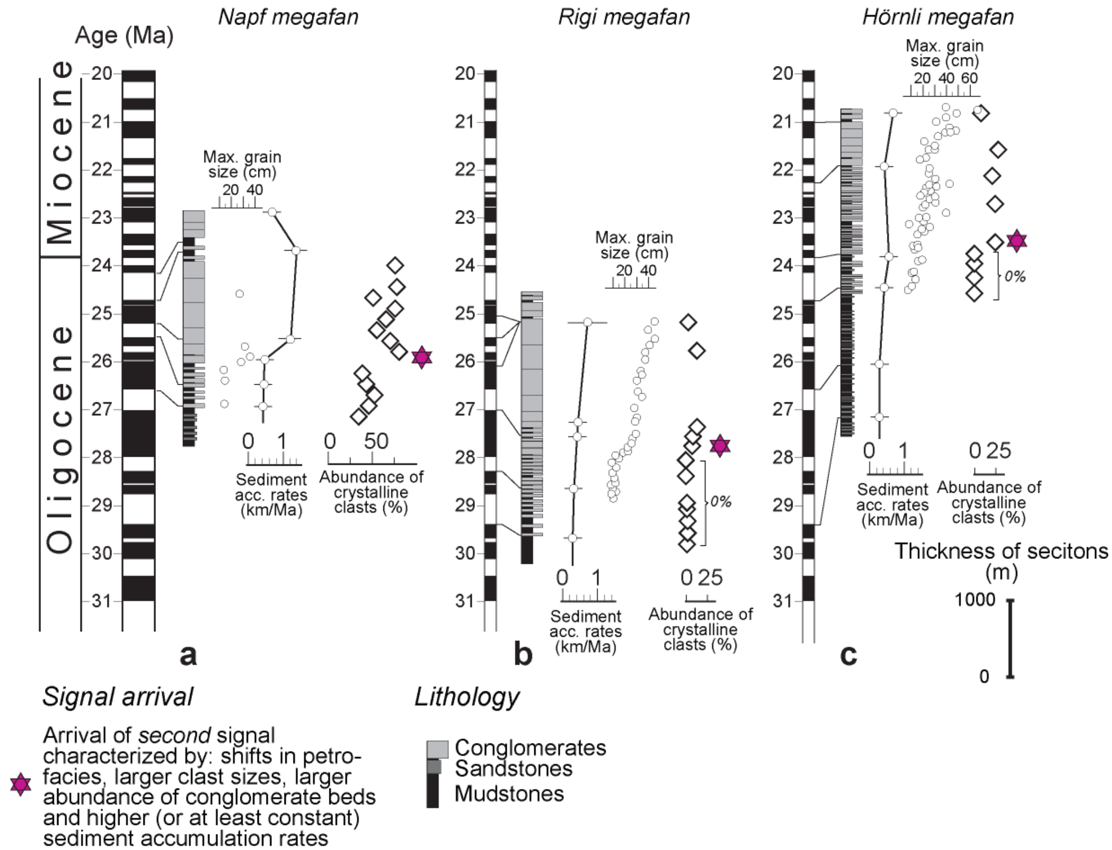

Figure 1: Stratigraphic section of a) the Napf, b) the Rigi and c) the Hörnli megafan. The distances between the drainage divide and the depocenters were c. 80 km for the Rigi, 100 km for the Napf and 120 km for the Hörnli system, respectively. Modified after Schlunegger and Castelltort (2016).

The first section, c. 3600 m thick, is encountered at Rigi (Figure 1), situated at c. 80 km distance from the back of the Alps. The section chronicles a c. 30 and 26-25 Ma-old suite of alternated fluvial conglomerates and mudstones. A remarkable change is recorded in the middle of the section, dated to 27 Ma, with the first arrival of red granite clasts that were derived from the crystalline basement in the back of the Alps (Stürm, 1973). Also at that time, the maximum clast sizes increased from <15 cm to >30 cm, the fan surface steepened from <1° to nearly 2°, the dispersion pattern shifted from a confined to a non-confined braided flow, and sediment accumulation rates increased from <0.4 mm/yr to >0.6 mm/yr. The Napf megafan, which is the second system recording the arrival of the inferred signal, is situated at c. 100 km from the back of the Alps. It comprises a c. 3500 m-thick and 28-24.5 Ma-old succession of alternated marls, sandstones and conglomerates. A remarkable change occurred at 25.5 Ma with shifts in the clast composition of conglomerates and heavy mineral suites, when the abundance of crystalline clasts increased from <50% to >70%, and minerals of the epidote group started to dominate the heavy mineral composition of the detrital sand by c. 80%. This was also the time when the stratigraphic architecture shifted to an amalgamated stack of conglomerate beds, when the largest clasts increased from <15 cm to >30 cm, and when the fan surface steepened to >1.5°. Also at that time, sediment accumulation rates increased from c. 0.4 mm/yr to >1 mm/yr. The third section recording the arrival of the erosional signal is situated at Hörnli at c. 120 km from the back of the Alps (Kempf, 1998). The section is c. 4000 m thick. It is a large-scale coarsening- and thickening upward megasequence deposited by perennial streams with sources in the central Alps. A remarkable change is recorded at 23.8 Ma with the first arrival of crystalline clasts derived from basement nappes in the back of the Alps, and the increase of the largest clasts from <15 cm to >20-30 cm. Also at that time, the abundance of mudstone and sandstone interbeds decreased, while conglomerate units started to dominate the sedimentary suite. Sediment accumulation rates remained nearly constant between c. 0.2 and 0.4 mm/yr, and increased to >0.6 mm/yr at 21.5 Ma. Finally, the Late Oligocene Gonfolite Lombarda Group deposits, situated on the southern side of the Alps, are made up of an amalgamated stack of matrix-supported conglomerates with outsized clasts, which has been interpreted to reflect deposition by debris flows supplied within a submarine canyon (Bernoulli et al., 1991). Embedded granitic clasts that were derived from the Bergell pluton c. 10-20 km farther south imply that the cover rocks of the Alpine pluton had already been removed at that time.

The three sections in the proximal Molasse share the same trends where sections coarsen and thicken upward, and where sediment accumulation rates either increased or remained constant (Figure 1). Thrusting at the range front coupled with northward propagation of the Alpine edifice alone are not capable of explaining the arrival of a substantial proportion of crystalline clasts, particularly because the change in petrofacies invokes more erosion in the back of the Alps and not of the Alpine front. Furthermore, higher sediment accumulation rates would be associated by fining-upward and not coarsening-upward trends if local tectonics alone would be the major driving force. Alternatively, the trends could have occurred in response to a shift towards a more erosive palaeoclimate, yielding larger sediment fluxes, thereby explaining the shift from distal to proximal sedimentation. Although global stable isotope records (Zachos et al., 2001) do suggest that climate conditions did change between the Late Oligocene and the Middle Miocene, it is unlikely that a climate driver alone is capable of explaining the changes within the Molasse sections because identical shifts in stratigraphic records occurred under a cooling (Hörnli) or warming (Napf) palaeoclimate, or are not related to any palaeoclimate shifts (Rigi). We are thus left with a scenario where the changes observed at the proximal Molasse reflect to large extents the arrival, at different locations, of a unique erosional signal characterized by larger grain sizes, larger contributions of crystalline constituents in the clast composition, steeper fan slopes, and more frequent occurrence of conglomerates at constant or increasing sediment accumulation rates. Such a change indicates an augmentation in sediment supply to the basin, rather than an increase of water discharge or a decrease of subsidence. In addition, associated shifts towards predominant occurrence, or first appearance, of material derived from the back of the Alps suggest that the changes in stratigraphic architectures point towards a significant tectonic event at this location. Considering restored

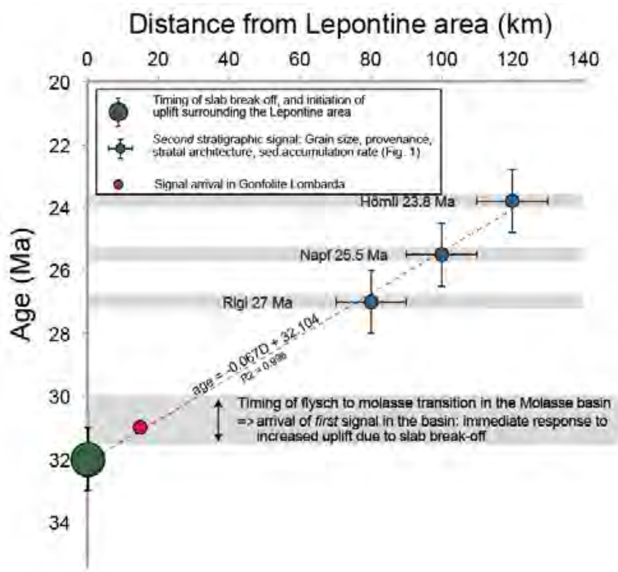

Figure 2: Propagation of erosional signal through the Alpine landscape (Schlunegger and Castelltort, 2016).

distances of 120 km, 100 km, 80 km for the lengths of the streams between the Late Oligocene drainage divide and the points of entry into the basin at Hörnli, Napf and Rigi, a regression analysis on signal arrival time as a function of distance from the back of the Alps yields 29.43-33.43 Ma (Figure 2) for the intercept at origin (R2=0.99). This is in good agreement with the age for the slab-break off and granite emplacement in the Alps (30-32 Ma). The erosional signal in the Como Confolite Lombarda group at ~31Ma is consistent with this picture (red dot on Figure 2). This suggests that slab-breakoff and the related surface uplift 32-30 Ma ago was the initial trigger for the erosional signal recorded at delayed intervals in the different sections of the foreland basin. Accordingly, the general increasing trend in sediment flux during the Late Oligocene (Kuhlemann et al., 2001), paired with continuous megafan progradation would include, at a higher resolution, distinct pulses when the rate of change was accentuated through amplifications of sediment discharge. This most likely reflects a mechanism where incision resulted in a first immediate regional signal at c. 30 Ma contemporaneously with slab-break off and surface uplift, when steeper slopes in the Alps promoted faster erosion and larger sediment fluxes. The results were first a regional and simultaneous switch from basin underfill to overfill at 30 Ma (Sinclair, 1997) paired with shifts to coarse-grained depositional environments in the foreland basin. Several My later, sediment pulses paired with larger grain sizes and provenance change to more crystalline material most likely occurred as the erosional front reached the crystalline core in the back of the Alps. These lithologies offer larger erosional thresholds, thereby retarding surface response to rock uplift until the landscape has sufficiently steepened. Such mechanisms offer suitable conditions for 'whiplash' (Gasparini et al., 2014) effects, when erosion and sediment flux become amplified through positive feedbacks once larger erosional thresholds of crystalline bedrock were exceeded (Schlunegger and Castelltort, 2016).

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Untangling Provenance Signals in Fluvio-Deltaic-Lacustrine Facies, Gale Crater, Mars

Kirsten L. Siebach[1], Michael B. Baker[2], John P. Grotzinger[2], Scott M. McLennan[1], Ralf Gellert[3], Lucy M. Thompson[4], Joel A. Hurowitz[1]

[1]Department of Geosciences, Stony Brook University, Stony Brook, NY, USA
[2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA
[3]Department of Physics, University of Guelph, Guelph, Ontario, Canada
[4]Planetary and Space Science Centre, University of New Brunswick, Fredericton, New Brunswick, Canada

We present a stratigraphic record of basaltic Martian sandstones and conglomerates of the Bradbury group in Gale crater that show a lack of evidence for chemical weathering, but instead have compositional diversity between more felsic and more mafic compositions based on the average grain size of the rocks. We interpret this correlation as reflecting breakdown of plagioclase-phyric subalkaline basalts (in the watershed of Gale crater) and transport and depositional processes that have sorted coarse plagioclase grains from finer mafic minerals [1]. A distinct alkali-feldspar-rich interval within the Bradbury group indicates that at least one additional source rock contributed to sediment diversity, but the majority of the compositional diversity is correlated with transport sorting of mineral grains.

Gale crater is a 154 km diameter crater near the Martian equator that formed ~3.8–3.6 Ga and contains a 5 km tall record of sedimentary rocks exposed along the flanks of a crescent-shaped mound (Aeolis Mons, informally Mount Sharp) preserved around the central peak of the crater. Based on remote sensing data, the near-horizontal sedimentary strata at the base of the mound contain phyllosilicates, which transition upwards to sulfate-rich strata ending in an unconformity ~1.2 km above the modern crater floor, above which the sequence becomes anhydrous [2]. These lower strata likely once filled the crater moat, were later eroded, and are exposed today as the current floor of the crater (named Aeolis Palus, thought to be ~1-2 km stratigraphically above the base of the original crater) and the lower slopes of Mount Sharp [3]. The current surfaces were exposed by ~3.4–3.2 Ga based on crater counting age dates. While some drainage systems leading into the crater are preserved, the source rocks that contributed to the crater-fill sediments presently exposed on the floor of the crater are not well constrained.

The Mars Science Laboratory rover *Curiosity* landed on Aeolis Palus and completed a 9.5-km traverse into the foothills of lower Mount Sharp, while analyzing 65 m of stratigraphy of the Bradbury group during the first two earth years of the mission (Figure 1). The Bradbury group is primarily composed of fluvio-deltaic sediments, fine sandstones to conglomerates, which entered the crater from the north and flowed towards Mount Sharp into shallow lakes based on delta clinoform geometries [3]. Along the traverse, *Curiosity* analyzed the texture and composition of 73 rock targets in the Bradbury group, collecting high-resolution (14–30 µm/pixel) images and using an Alpha-Particle X-ray Spectrometer (APXS) to acquire bulk chemistry of a 1.5-cm diameter surface spot. Additionally, in three locations, drilled rock samples were analyzed with an onboard X-Ray Diffraction (XRD) instrument to acquire mineralogy data.

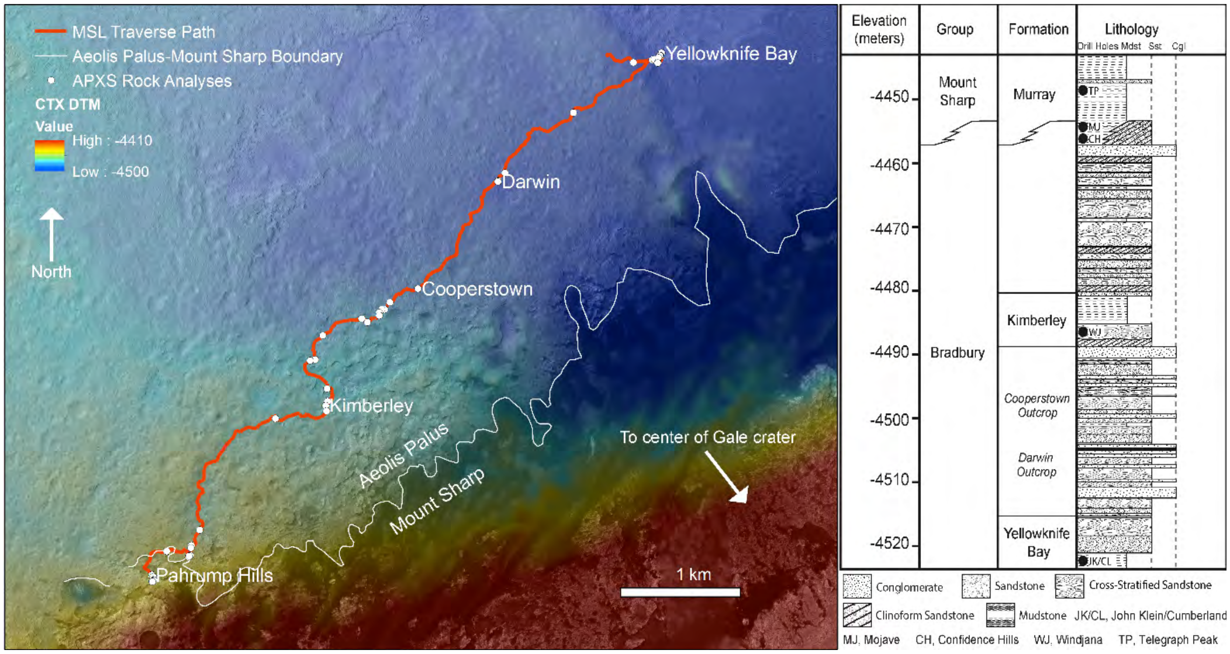

Figure 1. Overhead map and corresponding stratigraphic column for *Curiosity* rover traverse across Aeolis Palus up to Martian day 860. Rover waypoints labeled. The rover landed west of Yellowknife Bay, and this portion of the traverse ended at Pahrump Hills. Locations of APXS bulk chemistry analyses identified with white dots. Modified from [1, 3].

The sedimentary rocks of the Bradbury group have a range of compositions that parallel the feldspar-olivine join on a molar Al_2O_3-$CaO+Na_2O+K_2O$-FeO_T+MgO (A-CNK-FM) ternary, and do not show evidence for chemical weathering of the primary basalt. Uncorrected (minimum) Chemical Index of Alteration (CIA) values, which are based on a molar ratio of Al_2O_3 over the sum of K_2O, CaO, Na_2O, and Al_2O_3 as a proxy for the weathering of feldspars and Ca-bearing pyroxene, range from 30 to 45, within the range for typical fresh terrestrial mafic rocks. The low CIA values of the Bradbury group rocks likely indicate that the climate was cold and water-to-rock ratios were low enough that the minerals did not significantly react during erosion and transport into Gale crater.

While the compositional variability does not reflect chemical weathering, it does correlate with the average grain size of the sedimentary rocks. Although it is often difficult to obtain precise grain size measurements of dusty or homogeneous rock surfaces, it was possible to place the Bradbury rocks in eight textural groups based on grain size and texture: seven groups with increasing apparent grain size, and one group where diagenetic alteration was clearly visible. Relative to average Mars crust, the compositions of the coarsest-grained rocks are enriched in SiO_2, Al_2O_3, and Na_2O, structural components of feldspars, while the finer-grained rocks are enriched in oxides that comprise olivine and pyroxenes (note that CaO is present in both feldspars and Ca-bearing pyroxenes and does not trend with grain size) (Figure 2).

Potassium, notably, does not trend with grain size within the Bradbury group, but is slightly elevated relative to average Mars values throughout the group, and highly elevated in a ~10 m stratigraphic interval. XRD analysis of a rock within the high-potassium interval indicated the presence of 21 wt% orthoclase, which is interpreted as igneous rather than metasomatic based on the presence of olivine and basaltic glass and lack of any other hydrothermal minerals [4]. The significant concentration of orthoclase in a narrow stratigraphic interval indicates input from a distinct igneous source rock—this source may have contributed minor sediment to other portions of the Bradbury group, but was not a significant source for the majority of the rocks.

The enrichment of felsic components in the coarser-grained rocks in the Bradbury group was investigated using multiple geochemical models to constrain source rock characteristics. Geochemical trends parallel those produced by addition and subtraction of $An_{30–40}$ plagioclase to and from average Mars crust compositions. A regression-based model indicates that the felsic endmember composition (at 0 wt% MgO) could be modeled as 87 wt% plagioclase + feldspar, indicating imperfect but significant sorting of these minerals relative to mafic phases (Figure 2). A mass balance model designed to estimate modal mineralogy of the Bradbury compositions indicates that 90% of the non-diagenetic Bradbury group compositions can be reproduced using igneous minerals known to be present at Gale crater [1], and the main compositional variations correlate with the calculated fraction of plagioclase. We conclude that sorting of mineral grains from a plagioclase-phyric basalt during transport of sedimentary grains into Gale crater describes the main compositional diversity within the Bradbury group.

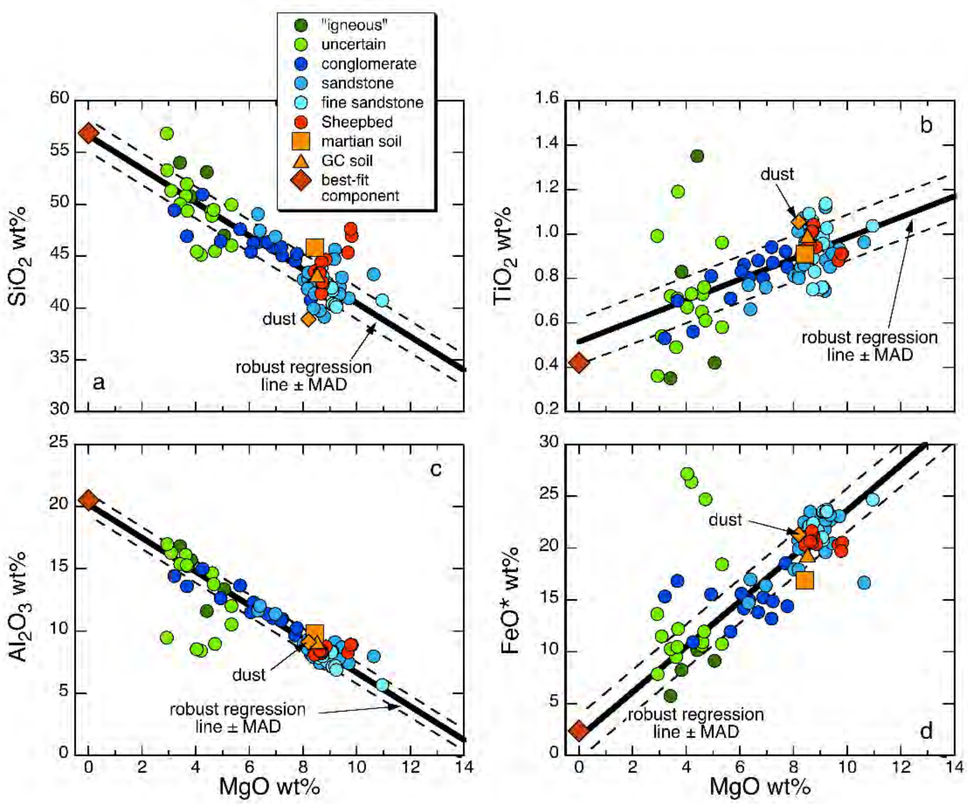

Figure 2. Oxide-MgO plots, (a)SiO_2, (b) TiO_2, (c) Al_2O_3, and (d) FeO* (all Fe as FeO), showing compositions of Bradbury group non-diagenetic rocks colored by grain size class compared to average Martian soil [5] and Martian dust [6]. Dark green "igneous" class represents the coarsest grain sizes, or coarse grains within conglomerates. Uncertain class includes float rocks with ambiguous grain sizes that weather similarly to conglomerates. Conglomerate, sandstone, and fine sandstone categories incorporate fluvio-delatic rocks of decreasing size based on Wentworth scale. Sheepbed class is from a lacustrine mudstone at the base of the Bradbury group. Dark lines are robust fit regression lines, dashed lines are ± the Mean Average Deviation (MAD). Red diamond is the unweighted best fit composition of the felsic endmember (MgO = 0 wt%). Trends are consistent with segregation of coarse-grained feldspar from fine-grained mafic components.

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The role of climatic and physiographic setting in controlling how environmental signals are propagated within coastal systems: Lessons from the Quaternary Gulf of Mexico

Alexander R. Simms[1], Daniel Livsey[2], Johnathan Rice[3], Regina DeWitt[4], Pamela Buzas-Stephens[5]

[1]University of California Santa Barbara, Santa Barbara, CA, USA
[2]USGS, Sacramento, CA, USA
[3]DCOR, Ventura, CA, USA
[2]East Carolina University, Greenville, NC, USA
[3]University of Colorado, Boulder, CO, USA

Recent work has documented the strong role that autogenic processes have on obscuring the propagation of environmental signals such as sea-level, climatic, and tectonic changes within sedimentary systems. These studies have cast doubt into the ability of the sedimentary archives to faithfully resolve past environmental changes. However, most studies documenting the role of autogenic processes are based on numerical models or experimental flume studies and difficulty arises when scaling these results to geological time and spatial scales. The Quaternary record provides an excellent natural laboratory to test if these signals are recorded and how they may be propagated through sedimentary systems because independent records of environmental change are readily available and dating Quaternary sections is relatively easy. In this study we examine how two coastal systems located within different physiographic and climatic settings responded to the same environmental perturbations recorded in independent archives through the Holocene. An extensive array of 36 cores within the Nueces Bayhead Delta of the subtropical subhumid central Texas Coast show that it rapidly (within 100's of years) prograded 10's of km during shifts to wetter climates and retreated similar distances during shifts to drier climates during the Holocene. However, 70 km to the south along the drier subtropical semi-arid Baffin Bay coastline, optically stimulated luminescence ages from beach ridges suggest the shoreline prograded forming well-developed beach ridges during periods of drier climate and underwent retreat and/or no progradation during periods of wetter climate. The difference in responses is attributed to the nature of the systems supplying sediment to the two coasts. The Nueces Delta is feed by a moderate-sized perennial river, which delivered less sediment to the coast during drier time periods, while the Baffin Bay coast experienced enhanced sediment delivery due to dune reactivation along its southern margins during drier periods. Our results suggest that although sedimentary systems do record environmental signals, the nature of how that signal is propagated varies depending on the climatic and physiographic setting of the system.

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Integrating field observations and numerical models to explain complex fluvial system behavior in Sylhet basin, NE Bangladesh

Ryan Sincavage[1], Steven Goodbred[1], Jennifer Pickering[1], Man Liang[2], Michael Diamond[3], Chris Paola[4], Michael Steckler[5]

[1]Department of Earth and Environmental Sciences, Vanderbilt University, Nashville, TN, USA
[2]The Water Institute of the Gulf, Baton Rouge, LA, USA
[3]Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA
[4]National Center for Earth Surface Dynamics, University of Minnesota, Minneapolis, MN, USA
[5]Lamont Doherty Earth Observatory, Columbia University, Palisades, NY, USA

Linking Earth surface processes to the preserved sedimentary record remains a central challenge in the fields of sedimentology and stratigraphy. The problem is often approached by traditional field-based (observational) methods, deterministic and stochastic modeling, and physical experiments. Due to the limitations inherent in each of these methods, process-response relationships are not always clear, leading to misinterpretation of the stratigraphic record. Sylhet basin, a tectonically-influenced sub-basin within the larger Ganges-Brahmaputra-Meghna delta (GBMD), is both actively subsiding and topographically favorable for a major channel avulsion. In spite of these observations, the basin remains underfilled and has only experienced episodic fluvial depositon throughout the Holocene. We attempt to explain this unexpected behavior by informing numerical models with field observations to infer realistic process-based geologic interpretations.

The following observations, developed by interpreting over 400 shallow (up to 90 m) densely-spaced (3-5 km) boreholes, geodetic data, and multichannel seismic data within the GBMD, have been linked form the basis of the unexpected behavior: 1) a planar (10 m thick x 40 km wide) Pleistocene to early Holocene-aged basal gravel-boulder (up to 30 cm diameter) layer underlying the Jamuna (Brahmaputra) valley, 2) a deep (30-40 m) sub-valley that roughly follows the course of the Old Brahmaputra river and has been the site of active deposition of Brahmaputra-sourced sands (based on geochemical provenance signals) as many as three times during the Holocene, 3) relatively rapid (up to 8-10 mm/yr) subsidence of northern and central Sylhet basin, 4) the presence of thick (20-30 m) laterally continuous (20-30 km wide) stacked sand bodies sourced from the Himalayan syntaxis along the primary depositional fairways coincident with the modern Jamuna valley and the Old Brahmaputra river, and 5) the exclusion of large-scale sedimentation to central Sylhet basin (with the exception of 2 lobes dating to the late mid-Holocene) in spite of topographic and tectonic favorability for infilling.

Incision of the main Jamuna paleovalley and adjacent sub-valley was likely initiated by post-MIS 5e lowstands (particularly MIS 2). However, paleodischarges during the last lowstand were insufficient to generate the observed valley geometries or to transport boulder-sized basal gravels found at the base of the Jamuna valley. To address this “paleohydrological conundrum”, estimates of uniform flow properties informed by measured field observations were used to calculate plausible discharge values capable of transporting the observed grain sizes. Similarly, flood height calculations using a range of bed roughness coefficients produce flood heights consistent with observed valley dimensions. These modeling results compare favorably with independently derived discharge estimates of previously documented late Pleistocene to early Holocene megafloods conveyed through the Tsangpo Gorge, implying these events widened the paleovalley network and created the antecedent topography upon which the Holocene sediment dispersal system evolved.

Field evidence suggests up to six Holocene avulsions of the Brahmaputra River between the main Jamuna paleovalley and Sylhet basin, yielding an avulsion period of ~1800 years. A model that incorporated spatially variable subsidence rates, sediment flux, and sea level change produced comparable results, with a mean avulsion period of ~2150 years, indicating tectonic subsidence should be an important control on channel steering in Sylhet basin. However, a detailed analysis of the mid-Holocene occupation reveals that the system operated primarily in a bypass-dominant mode for much of the ~3000 year occupation, with mass extraction to central Sylhet basin limited to the last ~1000 years of the occupation. This time period corresponds to a regional weakening of the Indian summer monsoon as observed in isotopic and geomorphic data, suggesting a link between local hydrology and avulsion behavior. If strong monsoon conditions enhance the persistence of a seasonal lake in Sylhet basin, the subsequent local backwater effect could generate a “hydrologic barrier” to infilling of the basin, removed only when the prevalence of the lake is reduced during weakened monsoon conditions.

To test this “hydrologic barrier” effect, a simple 1-D model using the dimensions of Sylhet basin was created to investigate the influence of varying lake levels on the local backwater effect and topographic favorability for channel steering. The model indicates that lake levels exceeding the physical dimensions of the basin are required to produce a significant effect on channel path selection. 2-D models were also used to test the influence of gradient on individual channel and fan topography. As expected, the steepest topographic slope consistently predicts the favored flow path regardless of whether flow is confined by discrete channel paths or unconfined upon an asymmetric fan. However, including a ~10-15 m incision within the shallower descent path on the topography of the asymmetric fan produced favorability for flow, indicating incipient topography exerts a first order control on channel path selection within Sylhet basin on millennial timescales. Integration of field observations and numerical modeling reduced inherent limitations in both methods and produced realistic predictions of complex Earth surface behaviors in this dynamic system.

Tracing a grain of sand – novel detrital geo- & thermochronometric provenance tools for elucidating source-to-sink dynamics and signal propagation

Daniel F. Stockli

Dept. of Geological Sciences, Jackson School of Geosciences, University of Texas, Austin, TX, USA

Provenance studies have long been used to investigate source-to-sink dynamics, the linkages between hinterland erosion and sediment supply, controlled by tectonics, climate, and intrinsic factors inherent to the local geology, sediment transport and dispersal, sediment storage and recycling from intermediate sinks, as well as deposition in the terminal sink. Many of these relationships and correlations are being used to understand large-scale tectonic, climatic, and source-to-sink dynamics in a predictive fashion, e.g., to predict the size of basin floor fans or fluvial channel thickness as a function of drainage basin area or to predict sandstone reservoir characteristics in the terminal basins.

Modern geo- and thermochronometric dating techniques have become increasingly powerful tools, allowing for both higher-resolution thermal history reconstructions, with a diverse range of applications in quantifying tectonic and sedimentary processes, ranging from exhumation of tectonic provinces, to burial and maturation history in sedimentary basins, to tracking provenance and dispersal in sedimentary systems. This study presents novel analytical approaches to improve the isotopic provenance resolving power, reduce detrital provenance ambiguity, relate sediment supply more effectively to hinterland forcing factors, and expand the applicability of thermochronometers to elucidate hinterland tectonics and sediment production. This is done through detrital zircon U-Pb depth profiling, to recover multiple ages from zircons, split-stream analysis for simultaneous U-Pb and trace element and REE recovery from single grains, through zircon U-Pb-He double dating for integration with hinterland exhumation/tectonic histories and for improved lag time reconstructions, as well as expansion of these same methodologies to other refractory phases such as rutile and apatite.

Detrital zircon U-Pb geochronology has become a very widely used method for isotopic provenance studies of modern rivers to ancient drainage systems. While this rapidly proliferating technique has revolutionized provenance studies, it has its limitations due to inherent ambiguities related to single or multiple recycling events or monotonous or homogenized signatures of U-Pb crystallization ages in the drainage basin. For example, contractional exhumation and unroofing of former rift basins or passive continental margins commonly leads to recycling of detrital zircons that can lead to increasing homogenization and loss of resolving power for provenance studies. Similarly, large tracts with similar U-Pb crystallization ages or pronounced zircon fertility, such as large portions of Pan-African Gondwana or the Grenville belt, respectively, can diminish the power of detrital zircon provenance analysis. U-Pb depth-profile analysis of tape-mounted, unpolished zircon, gives the ability to recover multiple growth ages from individual zircons to constrain detrital provenance more precisely. For example, zircons from magmatic provinces, such as continent arcs, can exhibit cores reflecting the underlying basement or plutonic or magmatic zircon growth might affect rocks in otherwise monotonous basement domains. In the Gulf of Mexico for example, Grenville zircons are ubiquitous in Cenozoic sandstones as the Grenville hinterland spans from Maritime Canada to southern Mexico. However, Permian zircon overgrowth due to arc magmatism is only evident in zircons from central and southern Mexico and is completely absent in Laurentia. Similarly Late Cretaceous magmatic rocks are present in the Cordilleran hinterland both in the USA and in Mexico. Recovery of core ages from such Late Cretaceous zircons through depth profiling has shown the ability to more precisely locate the source terrane as they contain very different Proterozoic aged cores and can be related to the basement underlying these Cretaceous plutons. Lastly, depth profile U-Pb also reliably and effectively recovers the youngest zircon growth mode from detrital zircon populations that can be interpreted as the maximum deposition age (MDA) that commonly places tight constraints on the chronostratigraphic age of a unit – critical for stratigraphic correlations and the establishment of a chronostratigraphic framework for source-to-sink or sequence stratigraphic studies.

Simultaneous recovery of U-Pb ages and trace elements or REE spectra through depth profile laser ablation split-stream (DP-LASS) ICP-MS analysis has been shown to be a powerful tool in both metamorphic rocks and isotopic provenance studies. U-Pb ages can be linked to a petrogenetic context that allows for differentiation between magmatic and metamorphic source rocks, the differentiation of different magmatic affinities (e.g., oceanic vs arc magmatism), or even estimation of the crystallization temperatures. Trace element and REE fingerprinting of detrital zircons can help further reduce source area ambiguity and increase the overall U-Pb provenance resolving power. DP-LASS-ICP-MS to determine REE spectra, common Pb composition, Hf isotopes, and/or Ti thermometry of DZ populations has the capability of providing unprecedented additional provenance characteristics for individual zircons based on growth history, differentiation of magmatic and metamorphic origin, petrologic growth environment and crystallization temperatures. In particular the differentiation of magmatic and metamorphic zircons provide yet more leverage for provenance studies.

Detrital zircon (U-Th)/He (ZHe) dating or detrital U-Pb-He double dating can add an additional facet to reconstructing sedimentary provenance based on cooling/exhumation history of sediment source regions. ZHe ages provide direct information on source area exhumation/tectonics, and thus represent a powerful approach to further refine sediment provenance and the exhumation history of a sediment source region. Detrital thermochronology provides a record of the rate of hinterland exhumation through cooling ages and lag time analysis. U-Pb-He double dating can further refine this approach as one can attempt to reconstruct the cooling and exhumation and hence the tectonic evolution of different basement provinces or even different thrust sheets.

Detrital thermochronometry also adds the potential of constraining lag time – the time required for exhumation, erosion, and deposition in sedimentary basin. This is key to deciphering the temporal and thermal evolution of the source terrane or the basins hinterland, allowing for estimation of erosion and sediment generation mechanisms and rates, coupling of basin evolution (subsidence, sediment supply, etc.) and hinterland dynamics, or reconstructing of provenance and chronostratigraphy. However, in basinal systems that are in part fed by active arcs, it is critical to exclude volcanic zircons that did not adhere to lag time "rules" through U-Pb-He double dating, as these volcanic zircons are characterized by identical U-Pb and ZHe ages.

In addition to zircon, apatite and rutile can be used in a similar fashion through depth-profile, split-stream, or double-dating analysis. Detrital rutile U-Pb and trace element analysis has proven to be particularly useful as it is, similar to zircon, very resistant to weathering, although rutile is significantly less ubiquitous in magmatic rocks. Rutile, with a U-Pb closure temperature of ~500°C and a He closure temperature of ~220°C, commonly occurs in lower-crustal, granulitic rocks and high-pressure metamorphic rocks with very different trace element signatures. In provenance studies, these two petrogenetic environments can thus be easily differentiated. Furthermore, granulitic rutile is useful in provenance studies in orogenic collapse systems or at rifted continental margins signaling the tectonic exhumation and unroofing of lower crustal rocks. Similarly, apatite is a common accessory phase in many igneous and clastic sedimentary rocks and has been widely employed as a low-temperature thermochronometric tool. While apatite U-Pb dating, characterized by grain-size sensitive closure temperatures between 375-550°C, could be a powerful detrital geo- and thermochrometer, the fact it incorporates significant amounts of non-radiogenic common Pb and only modest amounts of U and Th (1-10s of ppm) has traditionally limited its application. Development of a new analytical depth-profiling method allows for intra-grain correction of common Pb in apatite. It allows for the incremental recovery of U-Pb ratios at high spatial resolution (<1 micron depth intervals) during progressive (continuous) laser ablation of tape-mounted unfractured apatite grains. As U concentrations in apatite commonly show significant spatial variability related to growth zonation, depth-profile analysis recovers spatially variable U-Pb ratios that define an intra-grain discordia or radiogenic-common Pb mixing line in Tera-Wasserburg space, allowing for the determination of both the radiogenic lower-intercept and hence the U-Pb age as well as the common Pb composition of individual detrital apatite grains, making it feasible to conduct detrital apatite U-Pb dating in provenance and source-to-sink studies. Case studies from foreland basins have shown that the large majority of the apatites exhibit sufficient internal U variability to allow for robust single apatite intra-grain common Pb corrections and derivations of robust corrected U-Pb ages and common Pb composition by LA-ICP-MS depth profiling. These bedrock and detrital apatite case studies illustrate the power of this new methodology and the intriguing feasibility and applicability of detrital U-Pb dating and U-Pb-He double dating to provenance studies.

The ultimate power and resolution, however, comes from combining geo- and thermochronometric data from single zircon, rutile, or apatite grains and from new analytical capabilities of teasing unprecedented information out of a single accessory phase, such as LA-SS or depth-profiling, to better constrain provenance using the dual criteria of crystallization age and cooling age of any single terrane. Double-dating case studies illustrate the capabilities and resolving power of double dating to elucidate sediment provenance and hinterland influence on sediment supply, dispersal, and stratigraphic correlations, and fundamental aspects of source-to-sink evolution. Cutting-edge detrital geo- and thermochronometry offers exciting new tools for a more detailed and quantitative understanding of tectonic exhumation, basin history, hydrocarbon maturation, detrital provenance, and source-to-sink dynamics.

Provenance Evolution and Detrital Zircon Double Dating Signal Propagation from Fluvial to Deep Marine in the South Central Pyrenean Foreland Basin During the Eocene.

Kelly D Thomson[1], Daniel Stockli[1], Margaret Odlum[1], Julian Clark[2], Cai Puigdefabregas[3], Andrea Fildani[2]

[1]University of Texas at Austin, Department of Geological Sciences, Austin TX, USA
[2] Statoil, 6300 Bridge Point Parkway, Austin, TX, USA
[3] Department of Petroleum Technology and Applied Geophysics, NTNU, Trondheim, Norway

The South Central Pyrenean foreland basin system provides an opportunity to investigate sedimentary processes in response to mountain building during periods of high climatic and eustatic variability. Continuous outcrop exposure allows for investigation of source to sink processes, from fluvial to deep-water environments at high temporal and spatial resolution. This study presents new detrital zircons (DZ) U-Pb and detrital zircon (U-Th)/(He-Pb) double dating (DZDD) ages from the Tremp-Graus, Ager, and Ainsa sub-basins. These new geochronometric and thermochronometric data provide insights into the paleogeography of the Pyrenees during the Eocene and how environmental signals are transmitted and preserved from the fluvial and shallow marine environments into deep marine fans in source to sink systems.

We compare detrital zircon (DZ) U-Pb data from the Ager, Tremp-Graus, and Ainsa sub-basins to investigate changes in sediment provenance in response to tectonic and climatic events and how provenance changes downstream along laterally correlatable units. We then compare DZDD distributions from multiple stratigraphic levels in the South Central Pyrenean foreland basins to investigate how tectonic-induced variations in sediment supply are propagated from fluvial to deep marine and result in the observed stratigraphic architecture. To achieve this, the Eocene Castissent, Güell (lowest Campanué Fm), and Castigaleu sequences in the Tremp-Graus region were examined along with their deep marine lateral equivalents of the Hecho group turbidites in the Ainsa region.

DZDD has the potential to discriminate source regions with non-unique DZ U-Pb ages by measuring both a crystallization age (U-Pb) and cooling age ((U-Th)/He) on a statistically significant population of signal zircon crystals sampled from a detrital population (fig. 1).

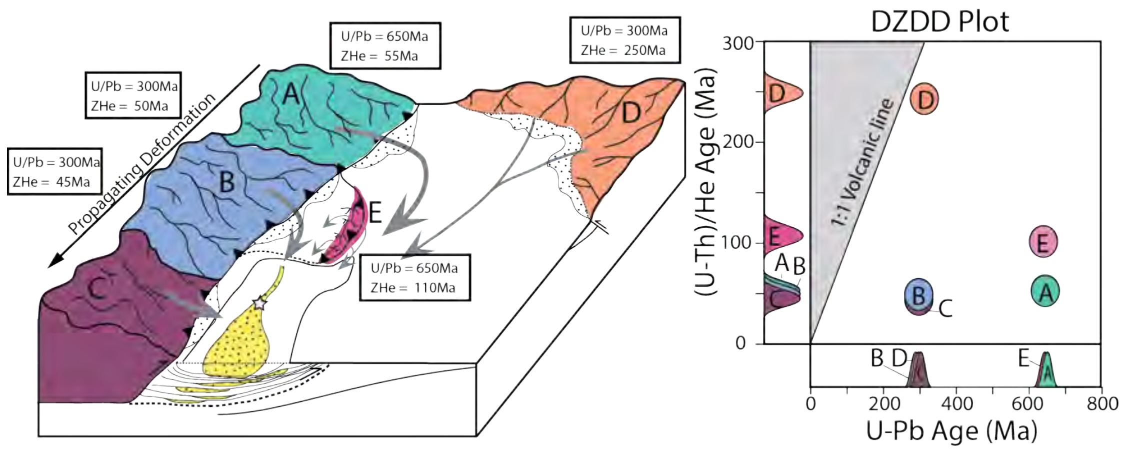

Figure 1. Discrimination of nonunique U-Pb source regions by detrital zircon double dating (DZDD).

DZ U-Pb results reveal four main components contributing to the age distributions: (300 Ma) Variscan aged zircons, (450 Ma) Caledonian ages zircons, (650 Ma) Cadomian aged zircons, and (1100 Ma) Kibaran aged zircons. These age components are attributed to distinct source regions with Caledonian and Cadomian aged zircons sourced from eastern Pyrenean basement and North Pyrenean Zone and Variscan aged zircons sourced from the central Pyrenees, Catalan coastal ranges, and Ebro basement. The overall DZ provenance evolution in the region of Ainsa indicates a progressive shift in sediment source region from Cadomian/Caledonian plutonic and metamorphic rocks of the eastern Pyrenees to Variscan plutonics of the central Pyrenees (fig. 2). Minor sediment contribution from source regions in the Ebro Basement located to the S and SE of the basin are seen throughout the section.

New DZ (U-Th)/He results identify four main cooling components: Pyrenean orogenesis (~56 Ma), initial inversion (~80 Ma), Cretaceous rifting (~100 Ma), and pre-Mesozoic cooling ages related to earlier tectonic phases. In the Ainsa region stratigraphic trends of (U-Th)/He distributions reveal an increase in Pyrenean cooling ages, and a decrease in inversion cooling ages, Cretaceous rift related cooling ages, and pre-Mesozoic cooling ages up section. These trends are interpreted to reflect the westward propagating exhumation of Pyrenean thrust sheets, migration of the flexural profile into the foreland and structural partitioning of the Tremp-Ager-Ainsa sub-basins by the initiation of exhumation along the External Sierras and Sierras Marginales.

These data allow linking fluvial and shallow marine deposits to transitional and deep marine deposits. However, the DZ signals recorded in the sediment of different formations in the Ainsa basin do not match ‘perfectly’ the proposed equivalent fluvial/shallow marine deposits in the Tremp basin, therefore we interpret a degree of sediment mixing between two fluvial networks, one from the Tremp basin and one from the Ager basin. Growth strata along either side of the Montsec Thrust indicates the Tremp-Graus and Ager basins were topographically divided and distinct DZ U-Pb signatures from Eocene deposits in these two basins might have had unique source regions. Axis parallel flow in the Ager and Tremp-Graus systems brought sediment from their respective sources downstream to the west where the rivers met and mixed in the shallow marine and shelf zones before flowing down submarine canyons into the deep marine basin floor of the Ainsa Basin. Unmixing these signals can provide relative sediment discharge estimates for these two delivery networks.

These data have the potential to aid source to sink studies by constraining the extent of the catchment area through time, providing proxies for relief and exhumation rates within the catchments, and tracing sediment fluxes as they are mixed and partitioned downstream. The DZDD approach to sediment provenance not only identifies sediment source regions but also assigns a fingerprint to a sediment mass, which can be used to compare sediment packages through stratigraphy and across laterally correlatable depozones.

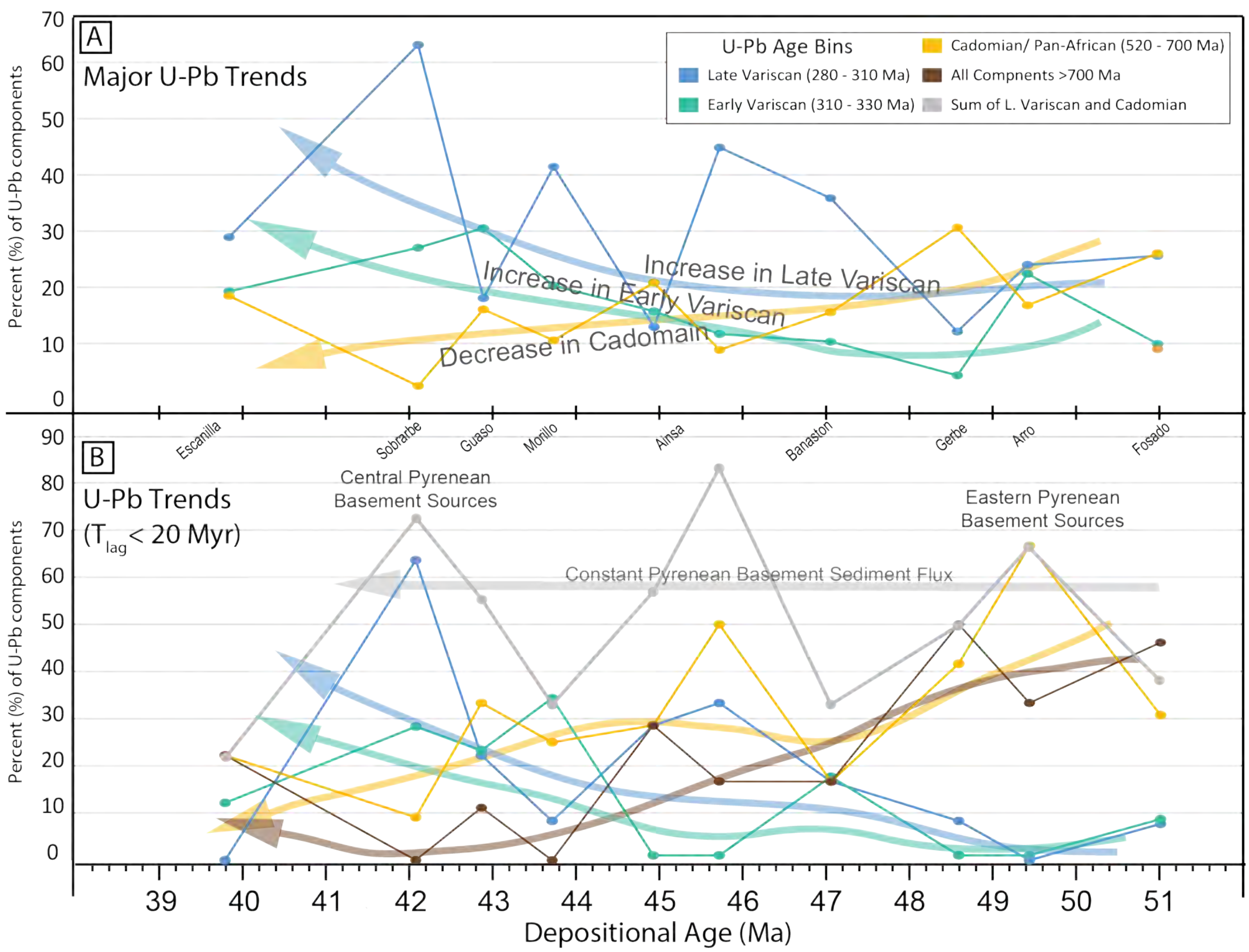

Figure 2. A) Detrital Zircon U-Pb trends for the Hecho Group turbidites and Sobrarbe/Escanilla fluviodeltaics in the Ainsa Basin summarized in terms of component percentage. B) Detrital zircon U-Pb trends from a subset of grains with lag times (lag time = cooling age – depositional age) less than 20 myr.

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Transfer of cyclic sediment supply signals to stratigraphy: experimental test of a theoretical framework for channelized systems

Stephan Toby[1], Rob Duller[1], Silvio De Angelis[1], Kyle Straub[2]

[1]University of Liverpool, Liverpool, UK
[2]Tulane University, New Orleans, Louisiana, USA

The stratigraphic record is a unique physical archive for past climate and tectonic conditions on Earth and other planetary bodies. These forcing and boundary conditions set the rate and volume of sediment delivered to sedimentary basins, which can be, theoretically, linked back to the stratigraphic record. However, for sediment supply signals to make their way through to stratigraphy they must pass through the active layer of the Earth's surface, which is scaled to channel depth. Within this surface layer, temporary deposition and erosion by an autogenically changing network of channels may complicate signal transfer and storage. For the long-term, the likelihood of signal transfer taking place can be evaluated using a vertical time-scale of stochastic autogenics. The current study makes use of physical experiments conducted in the Tulane Delta Basin that differ from each other in their supply rate curve. Using the known boundary conditions of the experiments, we can test whether cyclic sediment supply to an experimental delta will influence morphodynamics and if so, how this can be recovered from synthetic and physical stratigraphic datasets collected during the experiments. Different metrics to analyse the dataset show that supply signals will be modified and can even be destroyed by their interaction with autogenic processes on the delta. Transfer of a supply cycle to stratigraphy depends on the duration and magnitude of the signal and shows different characteristics for short and long period changes, which is predicted by our theoretical framework for channelized systems. The theoretical approach may be applied to field stratigraphy and used to guide more reliable interpretation of ancient sediment supply signals.

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100-kyr fluvial fill terrace cycles since the Middle Pleistocene in the southern Central Andes, Toro Basin, NW Argentina

Stefanie Tofelde[1,2], Taylor F. Schildgen[1,2], Bodo Bookhagen[1], Sara Savi[1], Heiko Pingel[1], Andrew D. Wickert[3], Hella Wittmann[2], Ricardo N. Alonso[4], Manfred R. Strecker[1]

[1]Institut für Erd- und Umweltwissenschaften, Universität Potsdam, Potsdam, Germany.
[2] Helmholtz Zentrum Potsdam, GeoForschungsZentrum (GFZ) Potsdam, Potsdam, Germany.
[3]Department of Earth Sciences, University of Minnesota, Minneapolis, MN, USA.
[4]Departmento de Geología, Universidad Nacional de Salta, Salta, Argentina.

Fluvial fill terraces in intermontane basins are valuable sedimentary archives that record tectonic and/or climate- driven changes of river networks and their surrounding hillslopes. However, the rarely complete preservation of such geomorphic features, often combined with large distances from sediment source areas, complicates the identification of causal links between forcing mechanisms and landscape response, especially over timescales of 10^5 to 10^6 years.

The intermontane Quebrada del Toro Basin in the Eastern Cordillera of NW Argentina exhibits at least five fluvial terrace surfaces that have been sculpted into a succession of several-hundred-meter-thick Quaternary gravel conglomerate. These terraces can be followed over several tens of kilometers and are located in the higher part of the basin, close to the sediment source areas. In this study, we determined the onset of multiple river incision phases by dating the abandonment of the three most extensive and best preserved terrace surfaces with nine cosmogenic 10Be-depth profiles. The timing of deposition is based on four cosmogenic ^{26}Al/^{10}Be burial ages and U-Pb zircon age estimates of three volcanic ash deposits that are intercalated into the conglomeratic fill material.

The ^{10}Be depth profile ages suggest a successive abandonment of these terrace surfaces on a 100-kyr-cyclicity between 487±34 ka and 75±7 ka. Depositional ages of the conglomerates, determined by ^{26}Al/^{10}Be burial samples and U-Pb zircon ages, range from 936±170 ka to 18±141ka. They show a clear overlap with the terrace surface abandonment ages and thus indicate the existence of multiple cut-and-fill cycles.

Although the initial onset of aggradation of the Quaternary gravel conglomerate at ~1 Ma and the overall net fluvial incision since ~0.5 Ma can be linked to tectonic processes affecting the narrow basin outlet, the superimposed 100-kyr-cycles of aggradation and incision are best explained by eccentricity-driven climate change. Within these cycles, the onset of river incision can be correlated with global cold periods that are linked with regional humid phases recorded on the Bolivian Altiplano, 1000 km north of the Toro Basin. Deposition, on the other hand, occurs mainly during more arid phases on the Altiplano (regional) and global interglacial periods.

We suggest that enhanced runoff during global cold phases – due to increased regional precipitation rates, reduced evapotranspiration, or both – resulted in increased sediment-transport capacity in the Toro Basin, which outweighed any possible increases in upstream sediment supply and thus triggered incision. On the other hand during arid phases, the river runoff decreases and the still high sediment supply rates result in overall aggradation. Although located far from major ice-sheets, our study shows that global eccentricity-driven glacial-interglacial cycles also result in significant variations in the sediment-transport system in sub-tropical regions.

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The impact of variable sedimentation on reconstructing climate signals in deltaic and shelf deposits: Models and examples from the Paleocene-Eocene Thermal Maximum

Sheila M. Trampush[1] and Elizabeth A. Hajek[1]

[1]The Pennsylvania State University, University Park, Pennsylvania, U.S.A.

The stratigraphic record provides a vital opportunity to investigate how different landscapes and seascapes respond to small and large climatic events. This is especially important in coastal and shallow marine environments, which are likely to be highly sensitive to both the rate and magnitude of climate change. However, the signature of landscape response to climate change may be masked or removed by the highly variable sedimentation that is characteristic of coastal and shallow marine environments. Therefore, climatic events are commonly identified using geochemical proxies, such as carbon and oxygen isotopes. But this approach does not account for the potentially significant variability in deposition and erosion from events like storms, floods, or autogenic processes like channel avulsion or delta lobe switching. In order to explore how geochemical proxy records could be overprinted by landscape dynamics, we use a 3D sedimentation model to build synthetic stratigraphy deposited in a fluvial-dominated marine shelf. The synthetic stratigraphy has a proxy value assigned to each sediment package according to age, which can then be used to create artificial proxy records at random locations through the deposit. We assess the degree to which the magnitude, duration, and shape of an imposed climate change signal can be reconstructed from the synthetic 1D sections. We find that inherent sedimentation variability created by autogenic deltaic processes can overprint the proxy climate signal, regardless of the distance from the sediment source or the magnitude and duration of the climatic event. We then compare our model results to observations of the carbon isotope excursions of the Paleocene Eocene Thermal Maximum (PETM) preserved within shallow marine deposits in the Mid-Atlantic coastal plain. From cores drilled in Maryland, Virginia, and New Jersey across a range of depths, we conclude that although the sedimentary processes change dramatically from the proximal to distal cores, all cores show evidence of variable sedimentation altering the apparent duration and shape of the PETM carbon isotope excursion. Our results suggest that we may be able to use existing geochemical proxy records within well studied, global climatic events such as the PETM, to constrain how sedimentation may have responded to the climatic event in different environments.

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A Tale of Two Megafans: Controls on the Formation and Abandonment of the Tista (West Bengal, India) and Lannemezan (northern Pyrenean foreland, France) Megafans, and their Role as Transient Sediment Traps in Source to Sink Systems

Peter van der Beek[1], Margaux Mouchené[1,2], Rachel Abrahami[1,3]

[1]Université Grenoble Alpes, ISTerre, F38000 Grenoble, France
[2]now at: Tulane University, Dept. of Earth and Environmental Sciences, New Orleans LA 70118, USA
[3]now at: Universidad de Chile, Dept. of Geology, Santiago, Chile

Alluvial megafans occupy a key position in the sediment routing system and, as such, contain a critical record of external forcing on landscape evolution in a variety of settings. Controls on the building and incision of megafans, through alternating phases of aggradation and erosion, have been shown to be related to climatic changes, tectonic activity, base-level oscillations or to a combination of those factors. Both experimental and numerical modelling studies have also shown evidence for autogenic processes that could be of critical importance in (mega)fan evolution. Temporary sediment storage in the fan results in cyclic behaviour, with alternating phases of deposition and incision in the absence of external forcing. An additional level of complexity, often overlooked in previous experiments of alluvial systems, arises due to the strong coupling and feedback between the source catchment and the basin. The specific response time and amplitude of each part of the system to a given forcing may differ and this results in a complex, oscillating erosion signal.

We have studied the controls on formation and abandonment of two megafan systems: the Quaternary Tista Fan in the eastern Himalayan foreland (West Bengal, India) and the Mio-Pliocene Lannemezan megafan in the northwestern Pyrenean foreland (France). Both are anomalous in terms of their size (relative to their catchment area) and both are currently being incised. We estimate the efficiency of these megafans as transient sediment traps by comparing their sediment budget with estimates of the erosional flux from the source area during their time of operation from thermochronological and cosmogenic data. We use cosmogenic data to constrain the timing of abandonment of the fans and use this, together with geomorphic data, to assess the potential abandonment mechanisms. Finally, we employ numerical modelling to identify the possible controls on the evolution of the Lannemezan megafan.

The Himalayan proximal foreland is characterized by a number of Quaternary megafans, of which the formational mechanisms remain debated. The Tista megafan spreads over more than 16,000 km^2 from the mountain front, where it is strongly incised, to the confluence of the Tista River with the Brahmaputra-Jamuna River, and stores sediments produced in the Sikkim Himalaya. We propose a scenario for the formation and abandonment of the Tista megafan based on new ^{10}Be cosmogenic and Infra-Red Stimulated Luminescence (IRSL) age constraints, and discuss the main potential controls on its evolution. We suggest that two distal lobes developed successively downstream from a common proximal lobe. Deposition in the proximal lobe took place since at least ~135 ka and incision began at 4.0±0.5 ka. The western distal lobe of the megafan was deposited early in the history of the megafan, when the Sikkim Himalaya catchment was drained by a tributary of the Ganga River, and was abandoned in the early Holocene (10-11 ka). The eastern, recent (<1 ka), and little incised lobe was built after the main Tista drainage system shifted eastward through nodal avulsions and can be considered still active. Approximately synchronous incision between terraces in the hinterland and megafan surfaces suggests that incision propagated rapidly through the system. Tectonic processes seem to play a minor role in driving incision of the megafan. Aggradation and incision episodes appear more compatible with a climatic control, through changes in monsoon intensity and associated sediment flux. Depositional episodes in the Tista megafan, as elsewhere in the Himalaya and its foreland, appear to correlate with periods of strong monsoon precipitations and associated high sediment flux toward the foreland. Abandonment and incision of megafan surfaces and hinterland terraces appear associated to both the onset and the ending of phases of strong monsoon precipitation, during which the balance between water and sediment discharge changes rapidly. A comparison between present-day sediment flux from the Tista catchment and the sediment volume stored in the megafan suggests that it was an efficient sediment trap during its operation, collecting about half of the sediment flux evacuated from the Sikkim Himalaya.

The Lannemezan megafan in the Northern Pyrenean foreland (SW France) was built during Miocene to Pliocene times and subsequently abandoned as the stream network deeply entrenched the foreland. We report new cosmogenic nuclide (^{10}Be, ^{26}Al) exposure dates for the abandoned fan surface and a series of alluvial terraces along the Neste and Garonne Rivers. Our results show that abandonment of the fan occurred at or before ~300 ka, and we suggest this abandonment is the result of the autogenic dynamics of the river system leading to capture of the feeding Neste River by the Garonne. However, the incision episodes that produced the terrace levels are concomitant to major climatic shifts. We use numerical models to explore the relative roles of autogenic processes and external forcing in the building, abandonment and incision of a foreland megafan, and compare the results with the inferred evolution of the Lannemezan megafan. Autogenic processes are sufficient to explain the building of a megafan and the long-term entrenchment of its feeding river at time and space scales that match the Lannemezan setting. Climate, through temporal variations in precipitation rate, may have played a role in the episodic pattern of incision at a shorter time-scale. In contrast, base-level changes, tectonic activity in the mountain range or tilting of the foreland through flexural isostatic rebound do not appear to have played a role in the abandonment of the megafan. In contrast to the Tista megafan, the Lannemezan megafan only captured a small proportion of the sediments evacuated by its feeder catchment during is time of operation.

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A magnetostratigraphy-based correlation of the middle-late Eocene fluvial to shallow marine units of the Aínsa and Jaca Basins.

Andreu Vinyoles[1], Pau Arbués[1], Miguel López-Blanco[1], Miguel Garcés[1], Luis Valero[2,3], Elisabet Beamud[2], Belén Oliva[4], Patricia Cabello[1].

[1]Dept. of Earth and Ocean Dynamics, Universitat de Barcelona, Spain
[2]Paleomagnetic Laboratory CCiTUB-ICTJA CSIC, Barcelona, Spain
[3]Facultat de Ciències, Universitat Autònoma de Barcelona, Spain
[4] Facultad de Ciencias, Universidad Autónoma de Madrid

The South Pyrenean foreland underwent progressive basin partitioning during the Paleogene due to the emplacement of thrust sheets of the South-Central Unit. Key to this evolution was the growth of the Boltaña anticline, a N-S striking prominent fold which resulted from the combined southwards propagation and clockwise rotation of the Gavarnie-Serres Marginals thrust system. The growth of the Boltaña anticline divided the South-Pyrenean trough into two sub-basins; the Aínsa Basin to the East and the Jaca Basin to the West. The Eocene Aínsa Basin, which evolved from a foredeep into a piggy-back setting, records a thick shallowing sequence from relatively deep-water turdiditic slope to shallow marine deltaic and fluvial-alluvial sedimentation. After palinspastic restoration of the Aínsa Basin, paleocurrent indicators point to a westwards sediment transport direction and deepening of the basin floor in accordance with the distribution of facies belts. Age-equivalent units in the Jaca Basin represent deeper and more distal environments, pointing out the large heterochrony of the sedimentary facies belts between the two limbs of the Boltaña anticline.

A reconstruction of the sedimentary transfer system along the South-Pyrenean foreland requires the construction of an integrated chronostratigraphic framework which allows a correlation to be made between the proximal continental environments and the distal deep marine settings. Pioneering studies provided a magnetostratigraphy-based age constraints that have helped early attempts to correlate the overall sedimentary successions of the different sub-basins. In this study we aim at obtaining a higher-resolution chronostratigraphy for the late Eocene fluvial sediments of the Escanilla Formation in the Aínsa Basin. The new Olsón section was sampled for magnetostratigraphy with 200 sites along a total thickness of 700 meters. The section was sampled along the axis of the Buil syncline in order to minimize hiatuses linked to fold growth. The uppermost 100 meters underlying the contact with the Graus conglomerates could not be sampled due to bad outcrop conditions. Our results suggest a correlation with chrons C18 and C17, thus indicating a Bartonian to lowermost Priabonian age. Despite the sampling gap of the upper Escanilla Fm. prevents us from precise dating of the lower boundary of the Graus conglomerates, it appears that a large portion of the Priabonian is not represented by sediments of the Escanilla Formation. The most plausible interpretation is that this time slice is missing under the Graus conglomerates, its basal unconformity traditionally being interpreted as intra-Oligocene in age.

The fluvial sediments of the Escanilla Fm. are organized in sequences that reveal repeated changes in accommodation space. A correlation with their equivalent sediments in the Jaca Basin will allow us to discuss the relationship between the channel stacking pattern of the fluvial system and the transgressive-regressive sequence arrangement of its laterally equivalent deltaic system of Belsué-Atarés, in the southern flank of the Jaca Basin, and the Santa Orosia fan-delta system, sourced from the northern margin. To achieve this, existing and new magnetostratigraphic data from the southern and northern flanks of the Jaca Basin will be integrated in a revised chronostratigraphic scheme.

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Continental-margin sedimentation in the Waipaoa source-to-sink sedimentary system, New Zealand

J.P. Walsh[1,2], C. Alexander[3], D.R. Corbett[1,2], R. Hale[4], S. Kuehl[5], A. Orpin[6], A. Ogston[7]

[1]Dept. of Geol. Sciences, East Carolina University, Greenville, NC, USA
[2]UNC Coastal Studies Institute, Wanchese, NC, USA
[3]Skidaway Institute of Oceanography, Savannah, GA
[4]Old Dominion University, Norfolk, VA, USA
[5]Virginia Institute of Marine Science, Gloucester, VA, USA
[6]National Institute for Water and Atmospheric Research, Wellington, New Zealand
[7]School of Oceanography, University of Washington, Seattle, WA, USA

Margins with high sediment supply can produce thick sequences that contain detailed information on the controlling sedimentary processes; however, the stratigraphic record must be unraveled to understand the terrestrial and marine processes affecting sedimentation. As part of the U.S. National Science Foundation MARGINS Source-to-Sink program and in collaboration with New Zealand scientists, a comprehensive research program (2004-2012) examined sedimentation on the Waipaoa River continental margin to better understand the modern marine sediment dispersal system. This margin is tectonically active, morphologically complex and oceanographically energetic. It receives a significant sediment supply (~15 Mt/y) because of the erodible, rugged terrain in the catchment. Results show that the Waipaoa fluvial sediment load is stored in shelf depocenters with significant material reaching the outer shelf and slope, filling relict relief and building thick (>40 m) deposits (Fig. 1). Decadal (^{210}Pb) and millennial (seismic-derived) sediment accumulation rates illustrate morphologic evolution of the margin while x-radiograph images provide insight into stratigraphic development. Integration of available data indicates that off-shelf sediment transport and accumulation has occurred throughout the Holocene, but sediment budgets suggest rates of export have increased, likely enhanced by human activities. Time-series measurements of sediment transport conditions and sequential coring at sites around the margin revealed that in addition to bottom-boundary-layer transport, sediment-gravity flows are an important mechanism of sediment transfer. While river flooding is important for sediment supply, marine conditions play a major role in redistribution. Despite a variable pattern of short-term (sub-annual) sedimentation related to river and marine conditions, a persistent pattern of sedimentation is constructed over longer time-scales across the margin.

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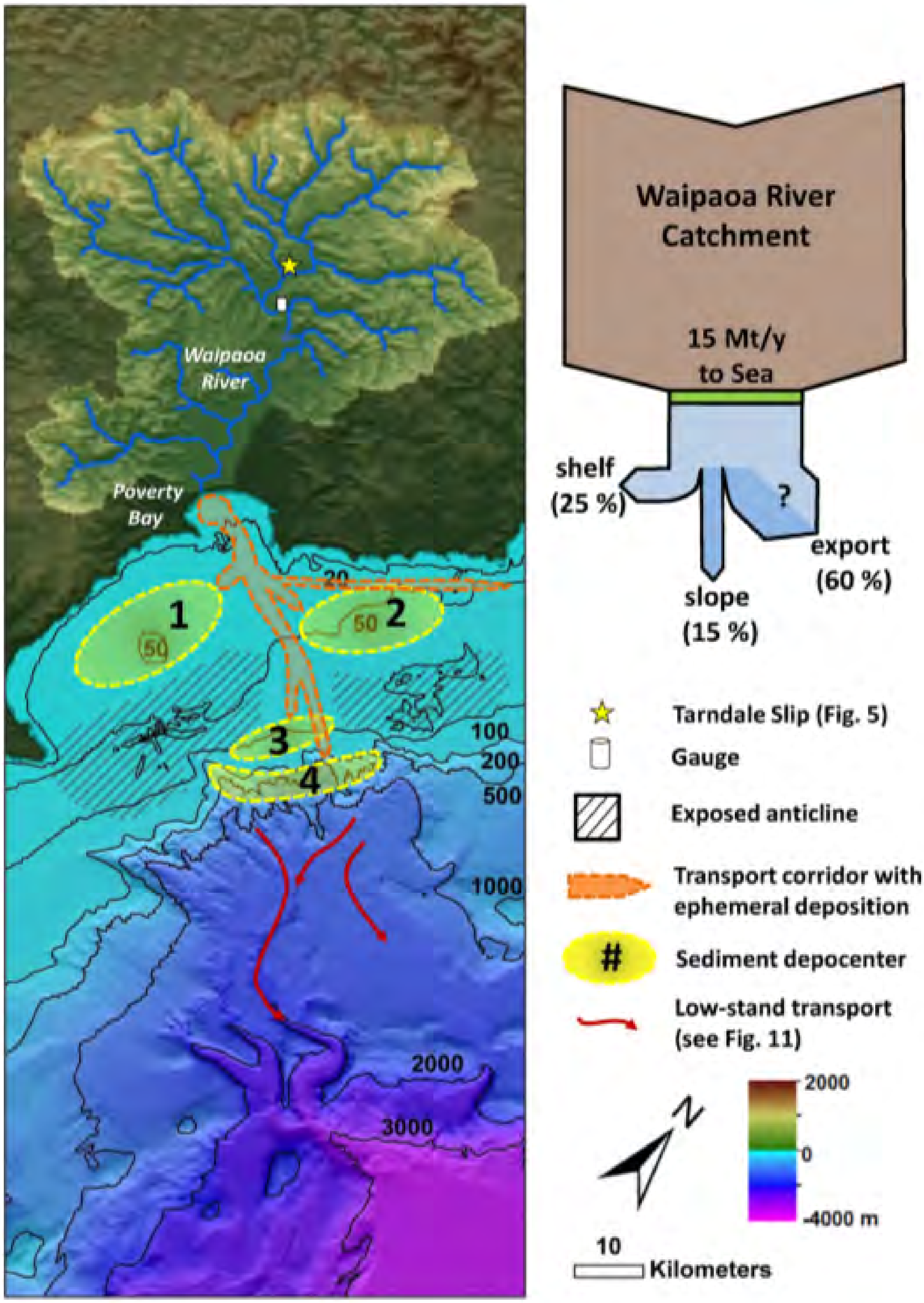

Fig. 1: The Waipaoa River source-to-sink dispersal system. The catchment (sediment source) as well as the primary sediment transport and accumulation area (orange and yellow dashed zones, respectively) in the modern sedimentary sink are shown. Figure is from Kuehl et al., 2014.

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Are landscapes buffered to high-frequency climate change? A comparison of sediment fluxes and depositional volumes in the Corinth rift, central Greece, over the past 130 kyrs

Stephen E. Watkins[1], Alexander C. Whittaker[1], Rebecca E. Bell[1], Lisa C. McNeill[2], Robert L. Gawthorpe[3]

[1] Department of Earth Science & Engineering, Imperial College, London, SW7 2AZ, United Kingdom
[2]Ocean and Earth Science, National Oceanography Centre, Southampton, SO14 3ZH
[3] Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway

Sediment supply is a fundamental control on the stratigraphic record. However, a key question is the extent to which tectonics and climate affect sediment fluxes in time and space. To address this question, estimates of sediment fluxes must be compared with measured sediment volumes within a closed basin, for which the tectonic and climatic boundary conditions are constrained.

The Corinth rift, Greece is one of the most actively extending basins on Earth, with modern day extension rates of up to 15 mm/yr. The Gulf of Corinth is a closed system and has periodically become a lake during marine lowstands over the late Pleistocene. We estimated suspended sediment fluxes through time for rivers draining into the Gulf of Corinth using an empirically-derived BQART method. WorldClim climate data, palaeoclimate models and palaeoclimate proxies were used to estimate discharges and temperatures over the last 130 ky. We used high-resolution 2D seismic surveys to interpret three seismic units over this period and we used this data to derive independent time series of basin sedimentary volumes to compare with our sediment input flux estimates.

Our results predict total Holocene sediment fluxes into the Corinth Gulf of 20 km^3, within a factor of 2 of the measured sediment volume in the central depocentres over this timescale. Sediment fluxes vary spatially around the Gulf, but imply catchment-averaged erosion rates of 0.2 to 0.4 mm/yr. Moreover, BQART predicted sediment fluxes and sedimentation rate measurements both indicate a 25% reduction during the last glacial period compared to the Holocene. At the last glacial maximum mean annual temperatures were lower by 5 degrees, although precipitation was similar, or lower, than present. Consequently, our results demonstrate that sediment export to the basin is sensitive to glacial-interglacial cycles. However, precipitation constraints alone are insufficient to understand sediment flux sensitivity to climate change.

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Straight from the source's mouth; a quantitative study of grain-size export for an entire active rift, the Corinth Rift, central Greece

Stephen E. Watkins[1], Alexander C. Whittaker[1], Rebecca E. Bell[1], Sam A.S. Brooke[1], Lisa C. McNeill[2], Robert L. Gawthorpe[3]

[1] Department of Earth Science & Engineering, Imperial College, London, SW7 2AZ, United Kingdom.
[2]Ocean and Earth Science, National Oceanography Centre, Southampton, SO14 3ZH
[3]Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway

The volumes, grain sizes and characteristics of sediment supplied from source catchments fundamentally controls basin stratigraphy. However, to date, few studies have constrained sediment budgets, including grain size, released into an active rift basin at a regional scale.

The Gulf of Corinth, central Greece, is one of the most rapidly extending rifts in the world, with geodetic measurements of 5 mm/yr in the East to 15 mm/yr in the West. It has well-constrained climatic and tectonic boundary conditions and bedrock lithologies are well-characterised. It is therefore an ideal natural laboratory to study the grain-size export for a rift.

In the field, we visited the river mouths of 49 catchments draining into the Corinth Gulf, which in total drain 83% of the rift. At each site, hydraulic geometries, surface grain-size of channel bars and full-weighted grain-size distributions of river sediment were obtained. The surface grain-size was measured using the Wolman point count method and the full-weighted grain-size distribution of the bedload by in-situ sieving. In total, approximately 17,000 point counts and 3 tonnes of sediment were processed.

The grain-size distributions show an overall increase from east to west on the southern coast of the gulf, with largest grain-sizes exported from the Western rift catchments. D_{84} ranges from 20 to 110 mm, however 50% of D_{84} grain-sizes are less than 40 mm. Subsequently, we derived the full Holocene sediment budget for the Corinth Gulf by combining our grain size data with catchment sediment fluxes, constrained using the BQART model and calibrated to known Holocene sediment volumes in the basin from seismic data (c.f. Watkins et al., in review). This is the first time such a budget has been derived for the Corinth rift. Finally, our estimates of sediment budgets and grain sizes were compared to regional uplift constraints, fault distributions, slip rates and lithology to identify the relative importance of these controls on sediment supply to the basin.

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Fine-sediment mineralogy of the Gulf of Papua shelf deposits: Implications for fluvial storage and sediment dispersal to the clinoform

Emily A. Wei[1], Neal W. Driscoll[1], John D. Milliman[2], Rudy L. Slingerland[3], Larry C. Peterson[4]

[1]Scripps Institution of Oceanography, University of California San Diego, San Diego, CA, USA
[2]Virginia Institute of Marine Science, College of William & Mary, Gloucester, VA, USA
[3]Pennsylvania State University, University Park, PA, USA
[4]Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA

Contributions from the Fly River and four small mountainous rivers to the Gulf of Papua (GoP) clinoform have constructed a mid-shelf clinoform composed of four distinct sediment packages. Geomorphic studies of the Fly and Strickland Rivers in Papua New Guinea have suggested that sediment accumulation in the Fly River has varied throughout sea level cycles, thus potentially impacting the style and geometry of clinoform deposits. The Fly River has significant storage for sediment, especially during transgressions and early highstands, due to its large floodplain and depositional web that introduces a lag in sediment discharge to the shelf. Conversely, we hypothesize that the small mountainous rivers with narrow floodplains have fairly uniform sediment discharge to the shelf over the Quarternary. Near-bed currents that advect sediment to the northeast further complicate this signal. To investigate the contribution of contrasting river systems to the clinoform throughout sea level cycles, we imaged clinoform architecture with CHIRP seismic profiles, identified clinoform sediment provenance, and constrained depositional timing with radiocarbon dates.

Clay mineralogy was used to identify the contributions of river systems to the GoP clinoform, since the Fly River sediment has higher illite:smectite ratios than that from small mountainous rivers draining volcanoclastics. Illite:smectite ratios are likely reflective of increasing maturity of sediment discharged from the Fly River, as its wide floodplain and depositional web cause sediment in the Fly River to have a longer residence time than sediment in the small mountainous rivers.

XRD analysis on the fine fraction (<2 µm) shows along margin variability in surficial mineralogy, with high illite:smectite ratios proximal to the Fly River delta that decrease towards the east (Fig. 1). Downcore sediment mineralogy paired with ^{14}C dates reveal how mineralogy has changed through time, with the biggest shifts in mineralogical composition corresponding to changes in sediment packages. The older relict clinoform emplaced during Marine Isotope Stage (MIS) 3 has lower illite:smectite ratios than the modern clinoform that has been building since the past 2000 years. Principal component analysis was used to test the significance of varying downcore composition. A biplot of the first two principal components shows two clusters: the first cluster contains modern clinoform sediment with high illite:smectite ratios and surficial sediment proximal to the Fly River Delta. The second cluster contains sediment from the MIS 3 clinoform with low illite:smectite as well as surficial sediment proximal to the mouths of the small mountainous rivers. The downcore increase in smectite and decrease in illite suggests that sediment deposited during MIS 3 received less sediment input from the Fly River and more contributions from the small mountainous rivers to the north.

A likely explanation for varying contributions of rivers to the clinoform is different sediment pathways for the Fly River sediment during MIS 3. Sediment from the Fly River could have bypassed the shelf through three submarine valleys incised in the shelf south of the Fly River delta. These valleys could have served as conduits for Fly River sediment to travel to the outer shelf, or Pandora Trough. To test this hypothesis, we examined the clay mineralogical signature of four cores in Pandora Trough cores, which show high illite:smectite ratios during MIS 3 that decrease over the past 10 kyr. This suggests that Fly River sediment likely bypassed the shelf to Pandora Trough during MIS 3; however, the Fly River sediment became increasingly stored on the shelf since the post-LGM transgression.

This work has implications for floodplain storage and sediment bypass throughout sea level cycles and suggests that sediment discharge to the clinoform should not be assumed to be consistent throughout sea level cycles.

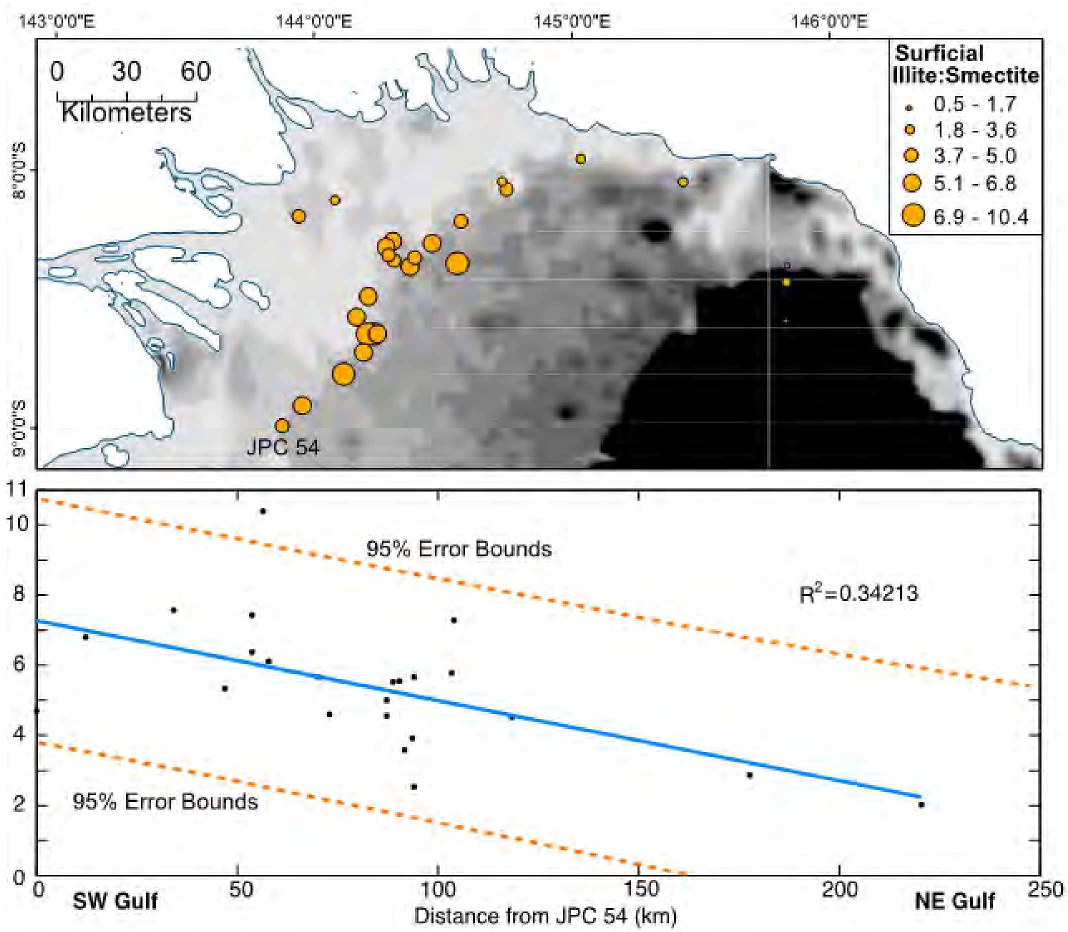

Figure 1: Surficial sediment samples along the Gulf of Papua shelf display a trend of increasing illite:smectite ratios towards the southwest gulf. The bottom plot shows the same ratios but plotted against the distance from JPC 54, the southwestern-most core.

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Controls on the behaviour of sediment routing systems using a mass balance approach

Alexander C. Whittaker[1], Nikolas Michael[2], Sam Brooke[3], Robert Duller[4], Philip Allen[5]

[1]Department of Earth Science and Engineering, Imperial College London, London, UK
[2]EXPEC ARC, Saudi Aramco, Abqaiq, Saudi Arabia
[3]Department of Earth Science and Engineering, Imperial College London, London, UK
[4]Department of Earth, Ocean & Ecological Sciences, University of Liverpool, Liverpool, UK
[5]Department of Earth Science and Engineering, Imperial College London, London, UK

Sediment routing systems link source regions undergoing erosion with depositional sinks and involve a volumetric or mass budget. Understanding how these source-to-sink systems function is important for stratigraphic prediction, but estimation of their surface sediment discharges and depositional fluxes on geological time scales is a challenging problem. Moreover, resolving the extent to which tectono-climatic boundary conditions determine the temporal and spatial distribution of sediment characteristics remains contentious. In particular the rate of down-system fining of grain size, percentages of grain size fractions in preserved stratigraphy, position of moving boundaries, and evolution of gross depositional environments can all be related to variations in the volume of sediment supplied, the grain-size mix of the supply, and the spatial distribution of tectonic subsidence generating the accommodation. Deciphering how these factors interact to produce stratigraphy is a key challenge in the Earth Sciences.

Here we compare detailed reconstructions of both large-scale palaeo-sediment routing systems and small-scale catchment-fan systems within a mass balance framework, and we evaluate the extent to which self-similarity-based grain size fining models effectively reproduce observed trends in sediment caliber. The large scale sediment routing systems comprise the mid-late Eocene Escanilla Formation and its time-equivalents, Spanish Pyrenees, and the Mio-Pliocene sediment routing systems draining the Great Plains, central USA while the catchment-fan systems comprise well-dated Pleistocene to Recent alluvial fans in Death Valley, USA. In each case, rates of grain size fining along time-lines in stratigraphy are reconstructed as a function of down-system distance and cumulative sediment volume in time and space, and are contrasted within a dimensionless mass balance framework that accounts for sediment extraction as a function of sediment volume. Our results demonstrate that the position of key stratigraphic observables, such as the gravel front and rate of grain size fining, are similarly controlled by mass extraction across systems that differ in size and extent, but that selective extraction of particular size classes (e.g. gravel, sand or fines) is more clearly related to the cumulative volume of that fraction available, rather than the total quantify of sediment supplied. We conclude that a mass-balance framework does allow for consistent, quantitative comparison across sediment routing systems of varying scales and shapes.

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Dynamics of River Networks in Eroding Catchments at the Continental Scale

Sean D. Willett

Dept of Earth Sciences, ETH-Zurich

Geomorphology and sedimentology come together around the question of drainage basin geometry, structure, longevity and surface process influence on sediment supply and provenance. Sedimentary archives record changes in erosion rates and drainage area from upstream catchments in the classic source to sink relationship. The quantity and characteristics of sediment derived from a catchment depends on tectonic and climatic conditions within that catchment, but also on the geometry of its river channel network. Changes in channel network geometry include topologic change by river capture and geometric changes that occur by progressive water divide migration, both of which lead to spatial variance in erosion rate. Although river piracy and reorganization have long been noted anecdotally, systematic assessment of the rates and frequency of channel network reorganization under tectonic forcing or autocyclic processes is still lacking. In this presentation, I summarize recent work on theoretical channel network dynamics through two approaches: assessment of geomorphic characteristics of modern river channel networks and through numerical modeling of landscape evolution based on process-based physical models.

One of the fundamental characteristics of river networks, potentially serving as the basis for an interpretative framework, is the observation that drainage area and channel slope tend to scale at all points in a river network. If this condition represents an equilibrium state of a river network, deviations from this state can be interpreted in terms of tectonic or climatic perturbation, or intrinsic instability of a network. This can be visualized through the integral form of this relationship, which predicts a linear relationship between elevation of a point in a channel network and the downstream integral of the inverse drainage area, a quantity now commonly referred to as x. A spatial map of x shows patterns that can be interpreted in terms of landscape disequilibrium, demonstrating where and how the geometry and topology of a river network is adjusting through divide migration. Maps of x are easily constructed using modern GIS methods and commonly available digital elevation models. Patterns and processes can be verified through other geomorphic parameters such as channel steepness, hillslope angles, and symmetry of divides.

I present several examples to demonstrate how modern river systems can be assessed for their transient states. First, I show how the central European river system is dominated by disequilibrium of the Danube River, which is erosionally disadvantaged with respect to its neighbors and thus losing drainage area from several sides. The Danube represents the last vestiges of the Tethys Ocean, north of the Alps, and its successor, the North Alpine foreland basin. The closure of the Tethys is continuing into the modern era with the drainage basin of the Danube showing collapse and the loss of drainage area to the Rhine and Adriatic drainages We interpret this as the response to retreat of baselevel for the Alpine rivers from the former marine foredeep to the modern Black Sea. A second example is presented from the Great Plains of North America, where the mid-continent seaway retreated at the end of the Cretaceous leaving the Mississippi river basin between the Rockies and the Appalachian

Mountains. In the late Miocene, the Rockies experienced a new period of dynamic uplift related to the motion of North America over a mantle upwelling north of the East Pacific Rise. Uplift drove sedimentation into the Rockies' foreland completely resurfacing the High Plains physiographic province and, at its peak extent, covered more than half a million square kilometers with sediment. Today we are witnessing the establishment of a new river network incising into these Miocene alluvial fan surface, producing the escarpments and badlands of the Great Plains. Although this is an internal basin re-organization, without large changes in source area, it demonstrates how drainage basins are disrupted by depositional events, as well as tectonics.

The second means of investigation of drainage basin stability is through numerical models of landscape evolution. Erosion laws based on physical models such as incisional stream power and threshold hillslope failure can be used to investigate river network stability, provided that numerical methods are used that can accurately track discrete boundaries such as water divides. Landscape evolution models driven by purely vertical motion (uplift) quickly develop true steady state topography with static rivers and erosion rates balanced to uplift rates. However, the inclusion of any horizontal motion through tectonic displacement or strain destroys the ability of a landscape to attain steady state. This is demonstrated though a model of orogenic wedge formation as occurs with small collisional orogens such as the Alps. Although a growing wedge reaches a steady long-wavelength size, small drainage basins are constantly shifting shape and size. This is also evident at a continental scale as demonstrated by an example from the eastern syntaxis of the India-Asia collision, where indentation of the Indian continent into southern China has deformed the pre-existing river network leading to a number of large river captures, for example into the modern Yangtze, and the close juxtaposition of the Salween, Mekong and Yangtze Rivers. The large strains in response to continental collision also lead to large variance in erosion rates as drainage area is exchanged between basins. The result is a landscape with disparate morphology and erosion rate, even in the presence of constant tectonic forcing.