Sediment Provenance Studies in Hydrocarbon Exploration & Production

5 - 7 December 2011

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Monday 5 December

Keynote Speaker: Pragmatic Strategies for Provenance Analysis in Hydrocarbon Exploration

William A. Heins, *ExxonMobil Production Deutschland, Hannover, Germany*

The last decade has witnessed an explosion of mechanical, statistical, and conceptual tools to relate environmental parameters associated with sediment generation (such as provenance lithotype, climate, transportation history, etc.) with physical parameters of the generated sediments (such as mineralogy and grain-size distribution). The successful application of these tools to hydrocarbon exploration requires a consistent and comprehensive intellectual framework, which focuses on play element prediction.

Any successful analysis starts with standard journalistic questions: who, what, when, where, why and how:

- ***For whom is the analysis conducted?*** All the other answers depend on this one; corporate shareholders, government funding agencies, and academic reviewers all have different goals, which require different approaches;
- ***What properties must be predicted? On what rock?*** Oil-company shareholders want to know, for example, about the presence and quality of reservoirs and seals. In that context, the genetic history of the sediments only matters to the extent that it affects the play elements. All the other questions must be posed regarding a very specific body of sediments, which has distinct stratigraphic and lateral limits.
- ***Where did the sediments come from?*** Usually the goal of the analysis is to predict properties that cannot be directly observed, typically in a reservoir that has rarely or never been drilled. Rather than trying to infer the genetic conditions from physical properties of the sediment, which might be typical in an academic study, we must reason the other way around. In this case, we can only select the appropriate set of environmental parameters if we know where the sediment was born. In most cases, knowing the provenance lithotype, the transport distance to the basin, and a crude paleo latitude is sufficient for a first-order approximation of all relevant physical parameters of the sediment.
- ***When were the sediments born and buried?*** Often "when" is more important for choosing among alternate scenarios of "where" than for any other purpose. However "when" can also be useful for making fine distinctions among climatic conditions.
- ***Why is the analysis necessary?*** Provenance analysis makes sense in hydrocarbon exploration when it helps predict the spatial distribution of play-element characteristics that cannot be observed directly, or not at an appropriately fine resolution. The case must always be made why inferences from provenance/paleogeography are better than direct measurements.
- ***How did provenance influence the play elements?*** The focus of the analysis must always remain on play-element distribution. Insight into the genetic history of the sediments can yield important, and otherwise unobtainable, inferences about sediment phyiscal properties that can be used for play-element prediction. Moreover, much of the work that goes into answering the question "where" the sediment came from, for example paleogeographic reconstruction and structural restoration, may also do double duty for understanding the burial-thermal history that drives source-rock maturation and reservoir diagenesis.

Provenance analysis tools can be useful in hydrocarbon exploration (for many play elements), but only if they are deliberately applied in a thoughtfully constructed framework.

NOTES

Heavy Mineral Signatures along the Northern South America and Trinidad Active Margin

Hasley Vincent[1], Yawooz Kettanah[2], **Grant Wach**

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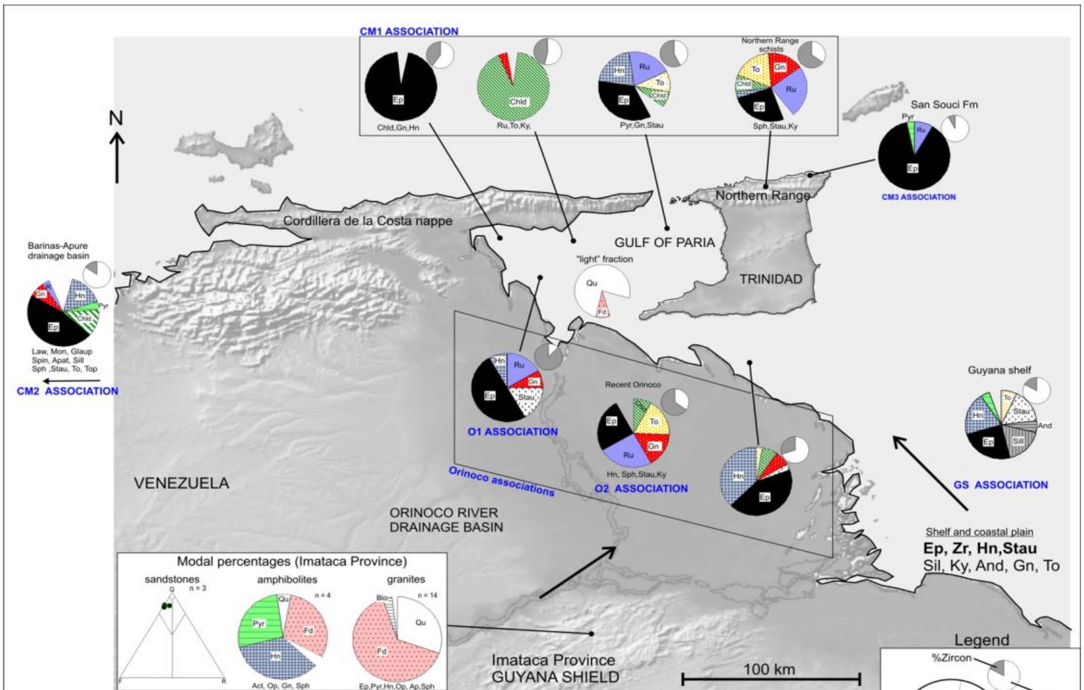
Cenozoic sediments in Trinidad record elements of pre- and syn-orogenic siliciclastic deposition related to the advance of the Caribbean Plate with its 'bulldozing' effect along the northern South American margin. Interpretations regarding timing of this change in tectonic regime vary from Late Cretaceous to Neogene. Integrated analyses of heavy minerals and process sedimentology were conducted to refine the timing of active margin deformation and understand the distribution and quality of known hydrocarbon reservoirs. The relative uniformity of deepwater sedimentological processes from Late Cretaceous through most of the Cenozoic meant process sedimentology could not be used exclusively to discern changes in tectonic-sedimentary signatures, and this was further hampered by poor and segmented outcrop exposures. However, changing tectonic regimes and provenance domains were recorded in the sandstone composition.

At least three associations of heavy mineral assemblages were compiled from the heavy mineral literature of modern sands within and around Trinidad basins. The Guyana Shield Association is characterized by high grade metamorphic minerals such as sillimanite and staurolite, derived from the Guyana Shield and mountain belts such as the Merida Andes. The Caribbean Mountain Association, derived from the rising Caribbean Mountain belt, comprise minerals more typical of low temperature, high pressure metamorphism inclusive of epidote, chloritoid and rare glaucophane. The Orinoco Association comprises an ultrastable mineral assemblage that is almost entirely zircons, and is interpreted to represent the effects of extreme chemical weathering within the Orinoco fluvial belt of the Andean foreland basin. The recognition of these Associations provided the basis to deduce the changing tectonic regimes in Trinidad basins and effectively map the migration of active tectonism across the margin.

The Late Cretaceous and most of the Paleogene (Paleocene to Early Oligocene) were associated with the delivery of coarse-grained, mature quartz arenites with a heavy mineral assemblage of the Orinoco Association. The source of these mature siliciclastics was the South American foreland basin. Changing heavy mineral character suggests the incipient input of syn-orogenic sediments into the basin as early as the Eocene, although the onset of active syn-orogenic sedimentation is clearly recorded in the mineralogy of Late Oligocene to Early Miocene sands of the Nariva and Cipero formations. That heavy mineral assemblage is more typical of the Caribbean Mountain Association with a significant input of chloritoid and detrital chlorite. This was the dominant source by the Pliocene with a flood of epidotes and further abundances in chloritoid and chlorite. This was mixed with rare occurrences of andalusite-sillimanite suggesting input from high grade metamorphic sources (Guyana Shield Association).

The Cenozoic sandstones evolved from mature Paleocene-Eocene quartz arenites sourced from continental lowlands, into immature litharenites sourced primarily from the uplifted Caribbean Mountains. The changing heavy mineral associations mirror changes in the lithic component of the detrital framework with the most notable increase in metamorphic schist fragments coincident with the occurrence of the Caribbean Mountain Association in the Late Oligocene sandstones. This represents a significant departure from the siliciclastic-dominated rock fragments of earlier sandstones. The modal detrital framework shows a clear "recycled orogen" signature on Dickinson compositional plots. Sediment dispersal patterns gradually became south and east directed during the later Cenozoic.

The results from this study do not support inferences for a northern source of clastics during the Paleocene-Eocene, and a southern Guyana Shield was not the dominant source for Pliocene sands. Changes in sediment dispersal patterns in the Trinidad basins were consistent with changes across northern South America related to the uplift of the northern Andean mountains, including the Caribbean Mountains. The results suggest that most of Trinidad's hydrocarbon reservoirs were sourced along active margins with greater lithic input and detrital clays. It is interesting that no hydrocarbons have yet been found within the clean, quartzose Paleogene passive margin sandstones.



Source		Heavy minerals
Caribbean Mountain Associaiton	**CM1**	Epidote+Chloritoid+Hornblende
	CM2	Epidote+Chloritoid+Hornblende+Glaucophane/Lawsonite
	CM3	Epidote+Pyroxene
Orinoco Association	**O1**	Zircon
	O2	Epidote+Rutile+Hornblende
Guyana Shield Association	**GS**	Sillimanite+Epidote+Hornblende+Staurolite

Figure 1 Compilation of modal framework and heavy mineral percentages from modern sands and ancient sandstones in north-eastern South America, into heavy mineral associations representative of different provenance domains. Note the separation of zircon from the main graph as depicted in the legend. Arrows indicate sediment transport direction.

NOTES

Composition and Provenance of Cenozoic Siliciclastic Depositional Systems Supplying the Eastern Black Sea

Stephen J. Vincent[1], Andrew C. Morton[1,2], Fiona Hyden[3], Bill Braham[4]

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[2]*HM Research*
[3]*Oil Quest Ltd*
[4]*Consultant stratigrapher*

Reservoir quality is a key uncertainty for hydrocarbon geologists in the Black Sea. Petrographic data from the proximal, onshore components of depositional systems that supplied the Eastern Black Sea have been analysed in Georgia, Russia and Ukraine. Sandstone compositions vary from quartz arenites with ~95% quartz to lithic arenites with up to 90% volcanic rock fragments. These data can help delineate depositional systems with differing reservoir potentials, although it is only when they are integrated with sediment provenance studies that a thorough assessment can be made. For instance, once the sediment source area for a particular depositional system has been established, field observations and analysis can constrain likely variations in sediment flux from this source area and thus its relative importance within the Eastern Black Sea basin fill through time.

In the Eastern Black Sea region, three main source areas have been identified that were capable of supplying quartz-rich sediments during the Cenozoic; the Russian Platform, western Greater Caucasus and Dziruli Massif. These have been distinguished by field mapping and sedimentological analysis, standard heavy mineral analysis, single mineral grain geochemistry and U-Pb zircon dating. Furthermore, the controls on variations in sediment composition derived from the western Greater Caucasus have been investigated through the analysis of reworked palynomorphs. This indicates that different stratigraphic units were reworked along the length of the range during Greater Caucasus Basin inversion.

Provenance work is ongoing in Turkey, Bulgaria and Romania in order to expand the geographic scope of this research.

NOTES

Keynote Speaker: A Geochronological Perspective of the Temporal Sensitivity of Detrital Archives.

Andrew Carter, *Department of Earth and Planetary Sciences*, *Birkbeck, University of London*

Geochronology and thermochronology studies of basin sedimentary rocks are increasingly used to understand sediment provenance and the connections and feedbacks between tectonics and surface processes that drive and moderate particulate fluxes, useful for predicting reservoir extent and quality. Such approaches can only work if the original chronological fingerprint has been preserved and there is no significant lag between perturbation and response. Hence interpretations depend on understanding the sediment routing system, transport times and how erosional systems respond to variations in climate or tectonics. Sediment flux can rapidly adapt to changes in precipitation rates driven by climate changes due to isostasy but theoretical considerations based on simplifying diffusion models show that only short (< 300km) transfer systems will produce a sediment record in tune with the changes. Landscape responses to tectonic perturbations mostly take longer and are therefore less likely to be in equilibrium even for 100 ka timescales. Indeed for large orogenic belts sediment flux rates can take several million years to stabilise following a shift in tectonic accretion rate. Such issues present a challenge to reading basin sediment flux changes and requires the application of a range of techniques and research strategies that enable comparison between basin sediment provenance and hinterland erosion histories. Examples from basin studies in Europe and Asia will be used to illustrate different influences on basin sediment flux and provenance signals.

NOTES

3D Stratigraphic Modeling and Sensitivity Analysis of Climatic and Tectonic Forcings in a Coupled Catchment – Fan System

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The link between basinal sedimentation and hinterland tectonics is a key question for both academic (e.g. climate record in sedimentary basin) and industrial purposes (e.g. sediment dispersal patterns and reservoir distribution). Because of their location at catchment outlets, alluvial fans represent a good potential record of the erosional dynamics of the landscape as well as their tectonic or climatic perturbation. They are thus the first key milestone to characterize for understanding the relationship between sedimentary basin and hinterland dynamics.

Recently, coupled catchment-fan systems have been studied using many approaches such as fieldwork (e.g. Whittaker et al., 2010), experimental modelling (e.g. Rohais et al., 2011) or numerical modelling (e.g. Armitage et al., 2011), proposing key results and concepts in the comprehension of stratigraphic record of a climatic or tectonic perturbation in sedimentary architectures. They highlighted questions such as – How can we transpose experimental and numerical results to natural alluvial fan? – What is the sensitivity of the coupled catchment-fan system to a forcing, in nature, in amplitude, in duration? We address these questions using a new workflow based on industrial software widely use in petroleum exploration.

Based on present day alluvial fan examples (China, Spain) we design all the input parameters for 3D stratigraphic modelling such as the rainfall rate, uplift rate, grain size, erosion rate, diffusion coefficient, scale. Starting from dynamic equilibrium, when sediment supply and fan slope are almost constant, we study the impact of tectonic and climatic changes within the catchment in terms of sediment supply and related fan dynamics by varying either the uplift rate or rainfall rate to a new value. The erosional perturbation induces characteristic dynamics of both the sediment supply (Qs) and the ratio between the sediment (Qs) to water (Qw) supply, which has a direct impact on the transport capacity. This results in univocal fan dynamics with regard to the forcings.

We then characterized the response of the coupled catchment-fan system using sensitivity analysis software, for several model sizes, amplitude and duration of the forcing. It provides simple laws that can be adjusted to one particular example, and tested for inverting the stratigraphic record.

NOTES

Single Grain Rutile and Zircon U-Pb Geochronology in Sedimentary Provenance Research - Analytical Advances and its Applications to Sedimentary Basin Evolution

Randall R. Parrish[1,2], Laura Bracciali[2,3], Yani Najman[3]

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[3]*Lancaster Environment Centre, Lancaster University, Lancaster, UK*

Single grain zircon geochronology is a powerful tool that has provided a rich dimension to the study of sediment provenance in fields as diverse as Precambrian sedimentary rock dating, reconstruction of orogens and continental configuration, sedimentary basin evolution and stratigraphic correlation, orogen exhumation studies, and even sourcing windblown dust or ice rafted debris of ocean sediments. Because of zircon's refractory characteristics, it often preserves multiple age zones that can only be observed by electron microscopy and which can complicate the interpretation of standard single grain zircon U-Pb data. In addition, zircon can survive metamorphism and melting, and multiple sedimentary erosion and deposition cycles; therefore its interpretation as a fingerprint of sediment source can be ambiguous, especially if that source consists of a complex assemblage of polygenetic continental rocks. The ability to confidently identify a source of sediment relies critically upon a set of source characteristics preserved in the single detrital mineral grains. The isotopic U-Pb age of zircon alone, however, is often not a diagnostic proxy or fingerprint of source regions.

In order to more confidently identify sources regions and assist in the reconstruction of a basin's depositional history, one needs to go beyond the standard method of zircon dating and use a more effective approach that includes other detrital minerals. We have developed an approach of imaging (using cathodoluminescence SEM methods) and subsequently dating the multiple zones of zircon, in particular any very thin external growth rims – which are most likely to record the most recent events in the orogen from which the zircon was eroded. In addition to zircon, we have developed the rapid U-Pb dating of single grains of rutile (TiO_2) from the heavy mineral suite to complement zircon. Rutile U-Pb ages primarily indicate the time since the last significant metamorphism or cooling below ~500^{o}C within the orogen that generated the rutile-bearing rocks. Rutile therefore adds an important lower-temperature complement to zircon ages, and together comprises a much more unique isotope fingerprint of the source region than standard zircon data. This approach should allow more confident interpretations of sedimentary provenance signals, and permit more sophisticated basin reconstructions.

The analytical measurement of rutile U-Pb ages is routine using LA-ICP-(MC)-MS with high sensitivity instrumentation. It has comparable age precision (~± 2-4% of U-Pb age) to zircon for grains with >20ppm U, a concentration found in >50% of all rutile grains in sediments we have examined. With its simpler geological interpretation, its lack of age and growth zoning, and the rapid analysis by LA-ICP-(MC)-MS, rutile is an ideal but under-exploited mineral in this field of applied research, with considerable potential in the hydrocarbon industry. Examples of this combined approach will be presented in this talk.

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Keynoter Speaker: Provenance Studies in Indonesia and Malaysia

Robert Hall, *SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK*

Sedimentary provenance studies in SE Asia are in their early days and only ten years ago there were very few in Indonesia and Malaysia. Their results are proving very useful for our tectonic understanding of the region. They give information which is otherwise hard to obtain about areas that were emergent, and provide valuable insights into timing and patterns of sediment supply to basins. Both factors are important in hydrocarbon exploration. In addition, provenance work is providing important information about the age and nature of the basement, particularly from studies using zircons.

Most of the provenance studies that have been carried out have are those by the SE Asia Research Group in London, complemented by a small number of others. In such a large region it is not unexpected that it was initially difficult to understand the meaning of all our results, but although there are still many puzzles we are also seeing patterns that can now be interpreted with confidence. These will be highlighted, noting especially surprises and differences from previous ideas about regional development.

Although the region is well-known for its volcanic history the abundance of volcanic quartz has been largely overlooked and there has been a common assumption that quartz-rich sediments indicate a continental provenance. In some areas this is not the case. Light and heavy mineral studies often use models that were developed in temperate climatic settings. These are undoubtedly important but in the tropics different rules apply and conventional models can mislead. Mineral assemblages are modified in tropical settings, but some supposedly unstable minerals are more common than might be expected. In some cases this is the result of high rates of erosion, transport and deposition but it may also reflect a relatively limited understanding of mineral stability in tropical settings.

Zircon dating studies suggest that there is much more continental crust at depth in areas previously identified as accreted arcs, ophiolites and melange, and some is significantly older than expected. Most of this crust came from Gondwana at different times and means that Indonesia provides detrital zircons with ages that resemble those from Australia. In eastern Indonesia this has added to the tectonic confusion. Most Early Archaean zircons originated in West Australia but there are a few areas where an Australian-origin explanation is problematical. Permian and Triassic zircons came mainly from the Tin Belt, but some originated in the Bird's Head of New Guinea, and some probably came from Australian fragments accreted to SE Asia in the Cretaceous. Jurassic zircons, when abundant, generally indicate a Cathaysian origin. Most Cretaceous zircons originated from the Schwaner granites of Borneo, with a contribution from the Malay peninsula and Sunda shelf granites. Cenozoic zircons can usually be matched with known nearby arcs, but in some areas of arc activity expected volcanic detritus is not found, and in other areas zircon ages cannot be matched to known arc activity.

Provenance work has already proved valuable in changing ideas and offering new insights. Many more studies are required because only with a much larger data set will we acquire a good understanding of the emergent terrestrial source areas that leave so little record.

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Recognising Sediment Source Areas of a Transgressive Coastal Plain: The Barito Basin, Southeast Kalimantan, Indonesia.

Duncan Witts, Robert Hall, *Southeast Asia Research Group, Royal Holloway University London, Surrey TW20 0EX.*

The Barito Basin is located in southeast Kalimantan, Indonesia. It contains a thick, and well exposed sedimentary succession that records different processes influencing the basin since its formation in the early Cenozoic, that include changes in climate, tectonics, sea level and sediment source.

Over the past fifty years, the Barito Basin has been the subject of numerous studies as a result of its long history of coal, oil and gas exploitation. However, these previous studies have produced an array of conflicting models for the basin, with considerable disagreement on the age and depositional environments of the sedimentary succession and nomenclature used to describe it. The provenance of sandstones, some of which are proven hydrocarbon reservoirs, has never been investigated, thus sediment source areas have never been identified. A robust stratigraphic framework and a clear understanding of the sedimentary succession and its sources are needed, not only for academic interest, but for effective economic evaluation of subsurface hydrocarbons and associated reservoir potential.

Part of an extensive study of the Barito Basin sedimentary succession is presented, focussing on the Tanjung Formation. Field observations and new biostratigraphic data have provided a robust stratigraphic framework. Depositional environments and sediment dispersal patterns have been determined from facies analysis and palaeocurrent data, and sediment source areas have been identified from detrital modes of light minerals and lithic fragments, heavy mineral assemblages and U-Pb dating of detrital zircons. The data have enabled the succession to be correlated where possible with regional tectonic events and climatic and eustatic fluctuations.

The Tanjung Formation represents the oldest part of the Barito Basin succession and records the earliest stages of basin formation in a largely terrestrial tropical setting, followed by a complete transgression to shallow marine conditions. Palynomorph assemblages have dated the oldest part of the formation as late Middle Eocene, in contrast to some previous estimates that include Late Cretaceous and Paleocene. Foraminiferal assemblages have dated the top of the formation as late Early Oligocene. A significant part of the Tanjung Formation has previously been regarded as deltaic. Field evidence however, conflicts with this interpretation. Twenty lithofacies have been defined, and assembled into four facies associations: TFA1 - alluvial braidplain, TFA2 - fluvio-tidal coastal plain, TFA3 - lower coastal plain and estuarine, and TFA4 - estuarine to shallow marine. The characteristics and stratigraphic organisation of these associations suggest a tidally-influenced fluvio-tidal coastal plain undergoing transgression. Correlation with global sea level curves suggests the transgression was driven largely by eustatic change, with relatively minor tectonic influence.

During the deposition of the Tanjung Formation, the Barito Basin was essentially flat, more or less at sea level, and was affected by tidal processes from a very early stage. This is recognised by the presence of laterally extensive coals, and the abundance of tidal signatures throughout the formation, such as bi-polar palaeocurrents, synaeresis cracks, mud drapes, the presence of *Paleophycus heberti, Teichichnus* and *Psilonichnus upsilon*, and inner neritic larger foraminifera. Palaeocurrent data indicate sediment was being transported into the coastal plain by a river system flowing towards the north. The rivers comprised fluvial channels of low sinuosity and smaller, sinuous tidal channels and estuaries and the fluvial system had a strong flood cycle, as recognised by the thick successions of overbank deposits.

The rivers were transporting sediment from the Schwaner Complex in the west and the Karimunjawa Arch in the southwest, as indicated by provenance work. The sandstones are texturally immature, yet compositionally mature which is relatively unusual. Light minerals other than quartz and quartz-rich lithic fragments are essentially missing from the sandstones, and heavy mineral assemblages are dominantly stable and ultra-stable species such as zircon and rutile. This discordance between texture and composition is interpreted to be the consequence of tropical processes which can strongly alter the composition of sandstones by the systematic removal of unstable minerals and lithic grains. There is no evidence to suggest the sandstones were derived from distant sources. In addition, identifying the Karimunjawa Arch as an important source indicates the arch was elevated during the Eocene and acting as a barrier to transport from inland areas of Sundaland.

These data conflict with previous suggestions of a northwestern source for the Tanjung Formation, and need to be considered in conjunction with facies interpretations when developing regional reconstructions. The data also provide a new insight into hydrocarbon plays and in the prediction of reservoir geometries, compositions and quality.

NOTES

Detrital Zircon from the Banda Arc: Insights into the Palaeogeographic Reconstructions

Inga Sevastjanova, Robert Hall, *SE Asia Research Group, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK*

1. Introduction

The Banda Arc is composed of volcanic inner arc, outer arc islands and a trough parallel to the Australian continental margin which curves in horse-shoe shape around the Banda Sea. Being the source of the latest plate tectonics discoveries and having high hydrocarbon potential, it is the focus of active scientific debate.

2. Geological Background

Most authors agree that in the south, in Timor, the arc was produced by the collision between a volcanic and Australian continental margin. Fragments of continental crust in the Banda arc are unequivocally known to be of Australian origin; however their ages of rifting and collisions remain controversial. Hall (2011) suggested that Jurassic rifting of the Banda and Argo Blocks from the Australian margin produced a continental promontory, the Sula Spur. Fragmentation of this spur in Neogene is responsible for the present day complex distribution of the continental crust in the Banda Arc (Hall, 2011). Hall (2011) suggests that the Banda Block is now in SW Borneo. This interpretation is dramatically different from traditional palaeogeographic reconstructions (e.g. Wakita and Metcalfe, 2005) that treat SW Borneo as a part of Cathaysia (see Table 1).

3. Aims

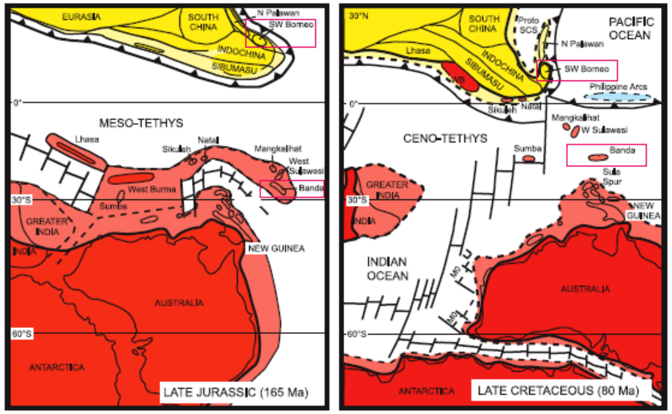
This study aims to provide detrital zircon age data that will help to resolve arguments between the existing models for the Banda Arc. In order to achieve this, U-Pb ages and Hf isotope analyses were collected from two Karimunjawa Arch (SW Borneo Block) and four Seram (the Banda Arc) Permian-Triassic sandstones samples. These data were then compared with published detrital zircon U-Pb ages from Timor and Savu Islands (e.g. Zobell, 2007, Ely, 2009) and potential zircon source areas (e.g. Chen et al., 2011; Neumann and Fraser, 2007, Southgate et al., 2011,van Leuween et al., 2007; Zhu et al.,2011) inferred from the existing reconstructions (Table 1).

4. Preliminary results and Discussion

Analysed samples yield Paleoproterozoic, Mesoproterozoic, Neoproterozoic-Cambrian, minor Ordovician-Silurian, Devonian and Permian-Triassic detrital zircon U-Pb age populations. Zircon U-Pb ages in samples from the Karimunjawa Arch are similar to those from Seram, suggesting derivation from similar source areas. Similar $_{176}Hf/_{177}Hf_i$ ratios of these zircons support this suggestion. Mesoproterozoic zircons present in the Karimunjawa Arch are uncommon on the Cathaysian Blocks (e.g. Chen et al., 2011; Zhu et al., 2011). This provides evidence against the Cathaysian affinity for the SW Borneo Block. Triassic zircons are more abundant in the Karimunjawa Arch. Traditionally Permian-Triassic zircons in SE Asia are interpreted as derived from the Tin Belt granitoids in the Thai-Malay Peninsula. However, this remote source is unlikely for the Banda Arc sandstones. Instead these zircons suggest existence of a local Permian-Triassic zircon source in Eastern Indonesia and/or on the NW Shelf. This suggestion is further reinforced by recent discoveries of Triassic detrital zircons on the Exmouth Plateau (Southgate et al., 2011) and in the Bird's Head region (Gunawan, 2011).

Table 1. Different tectonic models and expected zircon ages for the SW Borneo Block and the Banda Arc.

Reconstruction



Palaeogeographic reconstruction of Wakita and Metcalfe (2005). Note that the SW Borneo Block is regarded as a part of Cathaysia. Figure from Hall

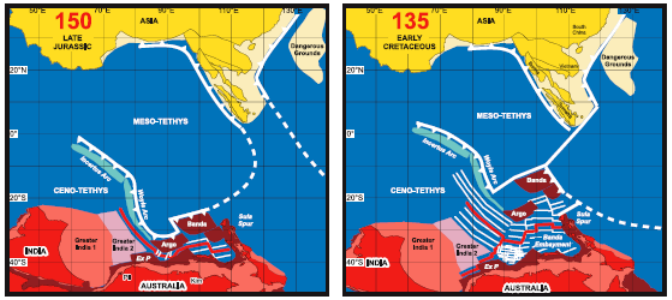


Plate tectonic reconstruction of Hall (2011).

Potential source areas	Expected zircon ages[1]	This Study
SW Borneo		
1) E Malaya-Indochina 2) N Palawan 3) S China	1) Carb., Perm., Trias. 2) Perm. 3) Neoarch.-Prot., Ord.-Sil., Carb., Perm.-Trias.	Abundant Mesoprot. zircons suggest a different source area.
The Banda Arc		
1) NW Shelf 2) W Sulawesi	1) Arch.-Prot., Trias. 2) ?	
SW Borneo and the Banda Arc		
1) Sula Spur 2) N Australia 3) W Australia 4) NW Shelf	1) Prot. (Mesoprot.); Dev. 2) Arch.-Prot. (Mesoprot.) 3) >3 Ga (Pilbarra & Yielgarn); Neoarch. Prot. 4) Arch.-Prot., Trias.	Data suggest a Triassic (volcanic?) source on the NW Shelf and/or in the Sula Spur.
5) Greater India	5) >3 Ga, Neoarch.-Prot.	No zircons >3 Ga.

[1] *zircon ages from Chen et al., 2011; Neumann and Fraser, 2007, Southgate et al., 2011,van Leuween et al., 2007; Zhu et al.,2011*

NOTES

Age, Character and Provenance of the Clastic Tipuma Formation, West Papua, Indonesia: New Insights from Detrital Zircon Dating

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The Tipuma Formation of West Papua, Indonesia is a potentially important reservoir. Its sedimentation may record parts of the region's Mesozoic tectonic history, including several phases of rifting. Little is known about the composition of the formation or variations in lithologies, and nothing is known about its provenance. The Bird's Head region of West Papua is underlain by Australian continental crust and has a relatively complete stratigraphy from Palaeozoic to Recent. The region is surrounded by active or recently active tectonic zones. GPS measurements and seismicity indicate that at present the Bird's Head is moving independently of Australia.

The Tipuma Formation is dominated by red to cream well-bedded mudstone, sandstone and conglomerate. It rests unconformably on the Kemum Formation and is overlain by the Cretaceous Jass Formation, with a total thickness of 90-150 m. The formation was deposited in a terrestrial fluvial system. Sandstones are generally compositionally and texturally immature, dominated by quartz and lithic fragments with angular to sub-rounded shape. Volcanic quartz was also found within the sequence. Overall, the modal composition of the Tipuma Formation shows a transitional recycled orogenic and transitional arc character with only two samples that have a continental character. It is difficult to assess the true age of the Tipuma Formation due to the absence of fossils, and the suggested Triassic age is based solely on its stratigraphic position.

Detrital zircons from nine samples of the Tipuma Formation were dated using Laser Ablation ICPMS to estimate the age of sedimentation and to identify major sediment sources. The formation is divided into Lower, Middle, and Upper Members. The Lower Member has Triassic, Permian, and Carboniferous age populations, and Proterozoic peaks. Phanerozoic ages in the Middle Member are mainly Triassic to Carboniferous with a few Ordovician grains. The most important age populations are Permian and Carboniferous. The Middle Member has an important Precambrian population in the Paleoproterozoic, with a single Archaean zircon (3266±24 Ma), which is the oldest radiometric age ever reported from the Bird's Head. The Upper Member of Tipuma Formation has important Middle Triassic and Late Permian populations, with other significant populations in the Carboniferous, Devonian, Silurian, and Ordovician. Precambrian ages include Neoproterozoic, Mesoproterozoic, and Paleoproterozoic populations. Based on these zircon age data the maximum depositional ages for the Lower, Middle, and Upper members of the Tipuma Formation are *ca.* 214 Ma, 229 Ma, and 205 Ma respectively.

The Tipuma Formation has a complicated history contrary to the popular belief that it was deposited in a simple continental block setting. The geochronological results suggest that the Tipuma Formation was deposited during the Late Triassic. Data show no strong evidence for the rifting event suggested by previous workers. The Upper and Lower Members are dominated by Late Triassic subhedral zircons, overwhelming or masking any older populations, and suggesting volcanic activity in the Bird's Head during the deposition of these units. The absence of Late Triassic zircon ages – and the abundance of older zircons – in the Middle Member suggests there was a cessation in the volcanic activity during its deposition. Local intrusive bodies and volcanic rocks outcropping to the north of the Tipuma Formation represent a possible source of sediment, but there is no provenance work and little geochronological information available for this area. Sediment derived either or indirectly from the Australian continent for the older zircons is another possibility

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Provenance of Neogene Sandstones, Sabah, Northern Borneo

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The Early Miocene Sabah Orogeny uplifted, deformed and exposed pre-Neogene rocks in northern Borneo. Post-TCU (Top Crocker Unconformity) Neogene sedimentary rocks of the Kudat, Tanjong, Sandakan, and Bongaya Formations were deposited in fluvio-deltaic to shallow marine environments in Sabah.

The majority of Neogene sandstones are compositionally and texturally mature, have a quartzose recycled orogenic source, and ultrastable heavy mineral assemblages dominated by zircon, tourmaline and rutile. An exception is the oldest member of the Kudat Formation, which is compositionally and texturally immature, has a mixed and dissected arc provenance, with heavy mineral assemblages dominated by euhedral and subhedral zircons and garnets.

Petrographic data, garnet analyses and U-Pb geochronological studies of the sandstones indicate multiple sediment sources. LA-ICPMS U-Pb ages from detrital zircons reveal a spread of ages from Proterozoic to Early Miocene, with the majority being Mesozoic. The most significant clusters of ages are Cretaceous, Jurassic and Permo-Triassic.

The Rajang and Crocker Groups were the principal sources throughout the Neogene for the Tanjong and Sandakan Formations in eastern Sabah, to the offshore basins in western Sabah, and contributed to the Kudat Formation of northern Sabah. Sediments were derived from recycled pre-Neogene sedimentary rocks which were ultimately derived from the Schwaner Mountains on Borneo and the Malay-Thai Tin Belt Granites, with some input from northern Borneo ophiolitic basement, and Cenozoic volcanic rocks.

In contrast, during the Early Miocene, granites and metamorphic rocks of the Palawan Microcontinental Block contributed significant amounts of sediment to the oldest member of the Kudat Formation. The Jurassic zircon population indicate a South China source. A new garnet compositional database compiled from the literature to help identify the provenance of detrital garnets supports the derivation of garnets from Palawan.

NOTES

An Isotopic and Geochemical Multi-Technique Approach to Provenance Studies; A Case Study in the Bengal Basin, Bangladesh (With Cairn Energy Plc)

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A researcher undertaking a provenance study on a sediment is confronted with a myriad of techniques which may be suitable; isotopic or geochemical based, applied to bulk (whole) rock or single grain, the latter with potential for more than one technique to be applied to the same crystal. Cost and time constraints also need to be factored in when choosing a suitable approach. This presentation illustrates the considerations taken to determine a suitable approach to documenting the first arrival of Himalayan material into the Bengal Basin, a multi-technique provenance study on core and outcrop samples in collaboration with Cairn Energy.

The rationale behind this study is two-fold. From an academic perspective, a knowledge of when Himalayan material was first eroded is critical to understanding crustal deformation processes and to testing the proposed link between Himalayan evolution and changes in global climate ocean geochemistry. Whilst most people are in agreement that the Neogene deposits in the Bengal Basin are Himalayan-derived, the product of deposition from the Ganges-Brahmaputra rivers, the origin of the Palaeogene sediments is disputed, with suggestions of provenance from the Indian craton to the west, the Himalaya to the north, and the Indo-Burman ranges (IBR) to the east all proposed. From an industrial perspective, Cairn Energy are interested in palaeogeographies, in particular sediment pathways and routing.

The first issue considered was whether the potential source terrains which may have contributed detritus to Bengal Basin sediment i.e. the Himalaya, Indian craton and Indo Burman Ranges were adequately characterised and whether their signatures were sufficiently distinct from each other that the material could be recognised and uniquely identified in the sediment. Also, it needed to be considered whether the signatures of the source regions seen today are the same as they would have been at the time the sediment in question was deposited, or whether subsequent metamorphism had altered the signature. If characterisation of source areas was deemed insufficient, this first needs to be rectified. Analysis of modern river sands draining the source areas is an efficient method of gaining representative grains, usually more efficient than analysing numerous bedrock samples, if the source regions are heterogenous. In this project, numerous published Himalayan bedrock data, typified as reflecting largely Proterozoic Indian crust with large parts affected by Cenozoic Himalayan metamorphism, were complemented by additional analyses, where appropriate, from Brahmaputra modern river sand in order to isotopically and geochemically characterise the Himalayan potential source terrain. Due regard was taken of the fact that much of the rock at surface today in the Himalaya has been influenced by Neogene metamorphism which occurred after deposition of the studied Bengal Basin sediment. Indian craton signature is typically considered to reflect Archaean crust, yet our analyses from modern river sand reflected the Proterozoic signature of the Chotanagpur Mobile belt. Published data from bed rock and river sands draining the sedimentary Paleogene Indo-Burman Ranges reflected the IBR's derivation from the Cretaceous Burmese arc to the east.

The isotopic / geochemical characterisation of the three potential source regions then allowed us to choose techniques which permitted maximum discrimination between source signatures. We chose a multi-technique approach since, unless the drainage basin is relatively simple and/or the potential contributing source rocks easily distinguished in terms of composition or age (not the case in this study) application of a single technique often cannot adequately distinguish between all sources. Decisions on whether bulk rock or single grains should be analysed were also taken. Whilst bulk rock analysis, usually of mudstones, provides a good average of what has been contributed to the basin, the signature obtained will likely be an average due to mixing of more than one source, and subordinate contributions may be masked. By contrast, single grain analyses overcome these limitations, and double or triple dating techniques on the same grain allow maximum information to be derived. However, single grain techniques are dependent on the mineral phase analysed actually being present in all the potential source terrains. The number of analyses to be undertaken is always a compromise when time and cost considerations need to be taken into account. How many grains are needed to adequately characterise a sample? Most workers consider 100 grains to be ideal, but 50 grains are often analysed either due to lack of availability of grains, or time / cost considerations. If the presence of a specific signature is needed to determine a provenance, obviously analyses can be terminated once this signature is found and replicated. However, if absence of a signature is required, then considerably more analyses must be undertaken for the interpretation to be robust.

We used a range of techniques to determine the provenance of the sediments, firstly dating them using biostratigraphy, complemented with maximum age constraints gained from detrital mineral isotopic ages. Seismic data helped determine sediment input directions to the basin. Petrography and heavy mineral data allowed first order differentiation between the arkosic signature of a craton vs the metamorphic orogenic signature of the Himalaya, vs an igneous lithics-rich signature of the IBR. U-Pb dating of zircon, Sm-Nd and $^{187}Os/^{188}Os$ isotopic analyses on mudstones did not allow differentiation between the Precambrian Himalaya and the craton of similar age and composition, but did allow distinction between these two sources and IBR material derived from the juvenile Cretaceous Burmese arc. Ar-Ar dating on white micas and zircon fission track dating allowed discrimination between the Indian craton, and the Himalaya which has been metamorphosed during the Cenozoic. Cr-spinel geochemistry allowed determination as to whether the grains had been derived from the Deccan Traps of the craton, or from Himalayan ophiolites.

Finally, the effect of diagenesis needs to be taken into account. Changes seen upsection in a core, or absence of a certain mineral may be the result not of changes in the detritus being contributed to the basin, but post-depositional diagenetic alteration. In this study, detailed examination of grain morphology pointed towards significant diagenetic alteration and preferential dissolution of minerals in this wet and humid environment. Thus petrographic and heavy mineral data were treated with caution.

Combining these techniques, we concluded that the 38 Ma and younger Barail Formation represents the earliest significant input of Himalayan derived material preserved in the Bengal Basin, and lag time data (defined as the difference between a detrital mineral's cooling age and its host sediment depositional age) showed that rapid exhumation of the source region was occurring by 38 Ma. By this time, major sediment routing was therefore from the north, from the rapidly exhuming orogen, rather than from the east or west as also proposed. This is the earliest record of significant erosion from the southern flanks of the eastern Himalaya, 17 My older than previously recorded, in Nepal. Discovery of Himalayan detritus in the Bengal Basin from 38 Ma: 1) resolves the discrepancy between the lack of erosional evidence for Paleogene crustal thickening that is recorded in the hinterland; 2) invalidates those previously proposed evidences of diachronous collision which were based on the tenet that Himalayan-derived sediments were deposited earlier in the west than the east; 3) enables models of Himalayan exhumation (e.g. by mid crustal channel flow) to be revised to reflect vigorous erosion and rapid exhumation by 38 Ma, and 4) provides evidence that rapid erosion in the Himalaya was coincident with the marked rise in marine $^{87}Sr/^{86}Sr$ values since ~40 Ma. Whether 38 Ma represents the actual initial onset of vigorous erosion from the southern flanks of the east-central Himalaya, or whether older material was deposited elsewhere, remains an open question.

Our ongoing studies are now concentrated on the Neogene sediments of the Bengal Basin, using the sediment record to determine the timing of proposed river capture of the Yarlung Tsangpo by the Brahmaputra River, and to constrain the timing of uplift of the Shillong Plateau and the influence of that uplift on palaeodrainage and sediment routing – see conference abstract and poster by Laura Bracciali et al, for more details.

NOTES

Influence of Sediment Provenance and Grain Size on Heavy-Metal Distribution in a Holocene Alluvial and Coastal System (Southern Po Plain, Italy)

Alessandro Amorosi, *Department of Earth and Environmental Sciences, University of Bologna, Italy*

Reliable quantitative estimates of source-to-sink sediment transfer from multi-sourced sedimentary successions require that high-resolution stratigraphic studies be coupled with accurate reconstructions of spatial and temporal variability of the sediment-routing system through time. Source-to-sink patterns from river catchments to the deltaic and coastal system are reconstructed from the Holocene succession of southern Po River Basin on the basis of the natural distribution of trace metals in sediments.

Approximately 700 study sites and 28 distinct river basins south of Po River were subject to integrated sedimentological, geomorphological, soil and geochemical investigation. Two sets of samples were collected for each site, at depths of 20-30 cm and 120-130 cm, respectively, for a total of 1,400 samples. Bulk samples were analyzed by means of both X-ray fluorescence and aqua-regia inductive coupled plasma mass spectrometry. Comparison with hundreds of data from about 20 continuously-cored boreholes, 30 to 170 m deep, allowed precise identification of the background levels of selected potentially toxic metals (Cr, Ni, Zn, Cu and Pb) for each river basin.

Differences in terms of trace-element chemistry between the study samples are primarily related to differences in sediment provenance, and thus can readily be used for discrimination of separate sediment pathways. Sediment supplied to the delta by Po River and four out of its Apenninic tributaries (Trebbia, Nure, Arda and Taro rivers) exhibits very high natural background levels of Cr and Ni, which invariably exceed the threshold limit values for unpolluted sites. These 'anomalously' high metal concentrations are shown to reflect, instead, remarkable sediment contribution from ultramafic parent rocks cropping out in specific catchments of the Western Alps and NW Apennines (ophiolitic complexes known as 'Ligurian units'). In contrast, where the drainage basins are ophiolite-free and consist almost entirely of monotonous turbidite successions (Marnoso-arenacea Formation), significantly lower Cr and Ni contents are recorded at distal locations, within alluvial plain and coastal plain deposits.

Heavy-metal distribution in the study area is not controlled uniquely by source-rock composition, and spatial changes in the proportion of other metals appear to reflect primarily variations in grain size of the host deposit (i.e., depositional facies). For a given provenance domain, each individual facies association is observed to be fingerprinted by peculiar geochemical composition. Specifically, detailed analysis of seven alluvial and coastal facies associations for their heavy-metal contents show consistently distinct, and easily predictable, geochemical properties for each sedimentological unit. Metal concentration in alluvial and deltaic sediments appears to be related with the proportion of clay, fine-grained (floodplain, swamp, interdistributary bay/lagoon) deposits invariably showing higher values than their coarse-grained (fluvial channel, crevasse/levee, distributary channel and delta front) counterparts.

The different hydrodynamic behaviour of suspended versus bedload sediment and, more in general, the effect of hydraulic sorting during transport and deposition are shown to be the dominant factors controlling the natural spatial distribution of other metals, such as Zn. In addition to sediment provenance and grain size, processes of soil formation and development may play a fundamental role in determining the geochemical composition of sediments, through selective metal enrichment or depletion. A mixed influence of grain size and degree of soil weathering is observed to influence the natural distribution of Cu and Pb.

Geochemical characterization of individual sedimentological units in terms of their natural metal contents results in the construction of a new type of (geologically-oriented) geochemical map. This map, which is largely based on the identified sediment pathways and facies associations, offers a more reliable depiction of the spatial distribution of background levels than interpolation techniques based uniquely upon statistical methods.

From a (sequence-) stratigraphic perspective, geochemical fingerprinting of facies associations framed by surfaces of chronostratigraphic significance is shown to represent an invaluable approach towards mass-transfer calculations and the accurate quantitative assessment of sediment storage, as opposed to volumetric reconstructions based on lithological or geometrical criteria alone.

NOTES

Tuesday 6 December

Keynote Speaker: The Ins and Outs of Drainage Basin Provenance and Source-To-Sink Analysis in Sedimentary Basins

Steven Bergman[1], Calum Macaulay[1], Tom Taylor[1], Tim Diggs[1], John Decker[2]

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Sedimentary basins receive sediment from a variety of sources. An understanding of these sources is required for many aspects of resource exploration, including petroleum systems, basin modeling, and depositional systems analysis. Much attention has been devoted to the thermochronology and chemistry of detrital sedimentary rock constituents to constrain the nature and unroofing history of hinterland source regions and their tectonic evolution. Whereas these data provide important constraints for basin evolution and the tectonic evolution of hinterlands, ambiguities may arise if the source complexities are not properly evaluated. Case studies from widely spaced parts of Mesozoic and Cenozoic North American Cordilleran forearc and foreland basins from North and South Alaska to the Gulf of Mexico Coastal Plains will be presented to illustrate these concepts and how valuable provenance information can be extracted from the sedimentary record. The data also provide insights into diverse tectonic events that have impacted North American Cordilleran basins, including magmatic belt, fold and thrust belt, strike slip margin, and accretionary tectonic evolution. The integrated datasets include conventional petrography as well as apatite and zircon fission track, ^{40}Ar-^{39}Ar, U/Pb, Rb/Sr, and other geochemistry and geochronology data.

This talk also aims to separate the relative contributions of detritus internally derived from within the drainage basin from those externally derived from outside the source drainage basin, building on the earlier work of G.G. Zuffa. “Internal” sources include basement rocks and those overlying sedimentary rocks exposed at the surface within the limits of source drainage basins whereas “external” sources were derived from outside of the drainage basin divides and include volcanic ash, eolian and other exotic materials.

NOTES

Mass Balance Interpretation of Nd Isotope Composition of Detrital Sediments in the Lower Cretaceous of the Scotian Basin

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The study of detrital minerals provides good evidence for specific sediment sources and thus transport routes. However, it is difficult to estimate the volumetric proportions of sediment from different sources using mineralogical data, because many source rocks lack abundant diagnostic minerals. We have carried out a scoping study to assess the usefulness of Nd isotope determinations in making semiquantitative estimates of the role of different source terranes in provenance studies.

A GIS geological map of Atlantic Canada was assembled from individual provincial maps. Rock units were characterised by proportions of different lithologies. Nd isotope determinations from the literature were assembled and the Nd isotope composition of each rock unit was estimated. In this manner, the Nd isotope composition of detrital sediment from any designated source area could be calculated.

Forty five shale samples and thirty sandstone samples from different parts of the Scotian Basin and at different stratigraphic levels were analysed for Nd isotope composition. In general, adjacent shales and sandstones show similar Nd isotopic composition. Shales with significant content of volcanic ash (based on bulk geochemistry) have relatively high ε_{Nd} values of -5, compared with a range of -6 to -13 for shales lacking abundant ash. Relatively high ε_{Nd} values in some sandstones also correlate with the presence of detrital volcanic clasts, of probable Cretaceous age.

A first order distinction of sources can be made between stratigraphic levels where detrital minerals indicate a predominant source from the outboard Meguma terrane, characterized by strongly negative ε_{Nd} values (-11 to -14), and stratigraphic levels where there is a higher proportion of supply from more inboard Appalachian terranes with more juvenile igneous rock sources (ε_{Nd} values typically -6 to -10). We continue to work on linking the petrography of sandstone samples and the geochemistry of shales to the Nd isotope composition, to understand factors that may perturb the Nd isotope composition.

This approach has already demonstrated that Barremian to Aptian tectonic tilting of the basin margin resulted in uplift of the Meguma Terrane along the Cobequid-Chedabucto fault zone. In the Aptian, sediment supply from inboard terranes was completely cut off, resulting in deposition of a basin-wide shale unit (Naskapi Member) that is an important cap rock.

The presentation at the meeting will explore the promise and pitfalls of the method and provide specific recommendations on how to effectively use Nd isotope data.

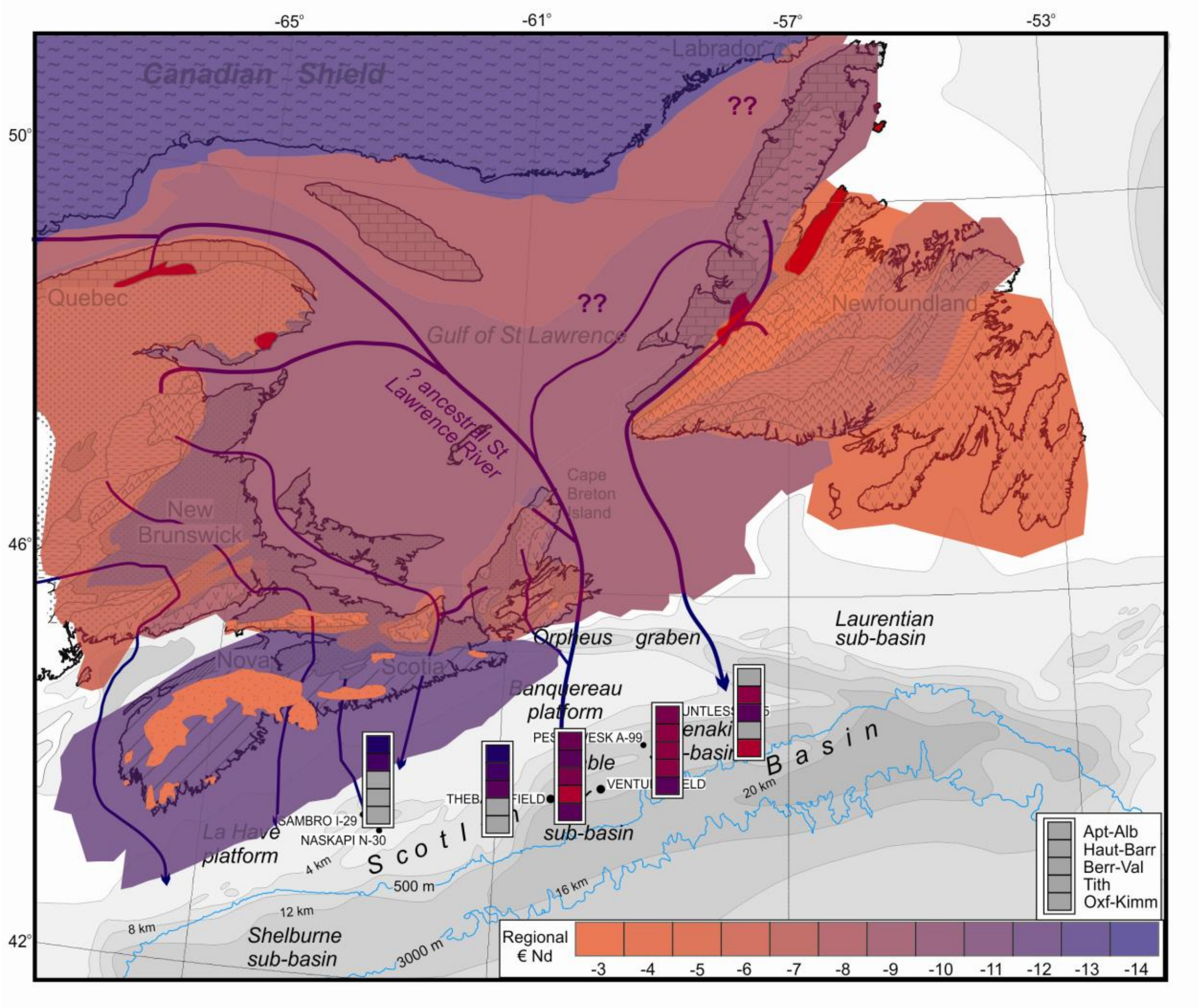

Figure 2 Nd isotopic composition of potential source areas and of samples from the Scotian Basin, arranged stratigraphically and geographically. Positions of rivers schematic, based on interpretation of detrital mineral data.

NOTES

Integrating Geochronology of Muscovite, Monazite and Zircon with Bulk Geochemistry and Varietal Detrital Mineralogy: Application to Cretaceous Reservoir Sandstones of the Scotian Basin, Eastern Canada

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Sandy deltas prograded tens of kilometres seawards in the Early Cretaceous of the passive-margin Scotian Basin, more than 45 million years after the onset of sea-floor spreading. This was a result of increased sand supply compared with the early history of the passive margin. These sandstones are the reservoir rocks for the producing Sable gas fields.

Geochronology of detrital minerals provides a first-order assessment of the source of detrital sediment. The detrital minerals muscovite, monazite and zircon have been dated from different parts of the basin. Much of the stable zircon may be recycled through older sedimentary rocks. Monazite is susceptible to chemical weathering and muscovite to physical abrasion, so that they are preferentially derived from proximal first-cycle sources. Almost all detrital muscovite grains are Late Paleozoic in age, with those of Carboniferous age derived from basement metasedimentary rocks of the inner continental shelf. Mass-balance calculations require a few hundreds of metres of exhumation of the inner continental shelf during the Early Cretaceous. The paucity of older ages results from abrasion during transport from older, more inboard Appalachian terranes.

Most detrital monazite grains are Devonian, but Lower Paleozoic, latest Neoproterozoic, Mesoproterozoic and Paleoproterozoic grains each make up about 10% of the total assemblage. Although monazite is relatively resistant to mechanical abrasion, it is readily broken down chemically under acid conditions. Monazites were classified according to whether they were euhedral, subhedral, rounded or irregular. There is no systematic variation of morphology with age, except that euhedral grains are over-represented in middle Paleozoic ages, characteristic of the outboard Appalachians, and involving short transport distances. This variation indicates that most monazite is of first cycle origin.

Most detrital zircon grains are of Precambrian age, with peaks at 1.0 Ga and 1.7 Ga that are a characteristic of reworked zircons in inboard Appalachian rocks of Laurentian provenance. A few samples show small peaks at 0.6 and 2.0 Ga, characteristic of outboard Appalachian rocks of Gondwanan provenance. All samples have variable but relatively low abundance of 300–550 Ma zircons, representing Appalachian crystalline basement. Comparison between the proportion of monazite and zircon grains of different ages in the same sample provide estimates of the importance of polycyclic reworking of sediment. If samples have a similar age distribution of monazite and zircon, this suggests that a high proportion of the zircons are first cycle; in such samples, only a few zircons are rounded or broken. Samples with many zircons older than the monazites have a high proportion of rounded and broken zircon grains.

In samples with many reworked zircons, bulk chemical analyses show a good correlation between Zr and Cr. These elements are principally in zircon and chromite respectively, derived from quite different rock types, but resistant minerals concentrated by polycyclic reworking. Their co-occurrence indicates that both are concentrated by sedimentary sorting processes. In contrast, Zr correlates with Ti only at low concentrations, above which the abundance of Ti is nearly constant as Zr abundance increases. Ti is transported mainly in ilmenite, a very abundant first-cycle mineral in proximal fluvial sediments, but very susceptible to chemical weathering. There is almost no correlation between Zr and Ce, which is principally present in monazite. On the other hand, Ce correlates well with Ti, suggesting that predominantly first cycle monazite and ilmenite are concentrated together by sedimentary sorting.

Understanding in this way the role of polycyclic reworking of heavy minerals, we were then able to better interpret spatial variation in varietal heavy minerals in the basin. Varieties of minerals such as chrome spinel, tourmaline, garnet and titania (mostly rutile) have been determined both by conventional electron microprobe analysis and by Mineral Liberation Analysis. Polycyclic minerals such as chrome spinel showed little geographic variation in relative varietal abundance. In contrast, some garnet and tourmaline varieties could be use to pin-point particular first-cycle sources. Diagenetic and detrital titania can be distinguished from texture and chemistry.

These multiple sedimentary petrology methods show that the dominant source of the sand was from the local Appalachians, supplied by at least three different rivers. These results clarify why reservoir sand distribution varies along the length of the basin. They also provide insights into tectonics of the hinterland and basin margin at the time that just to the northeast, Iberia was rifting away from the Grand Banks. Variations in detrital petrology in different parts of the basin play a role in variations in diagenesis and hence reservoir quality, although the best predictor of good reservoir sands is local accommodation due to salt withdrawal.

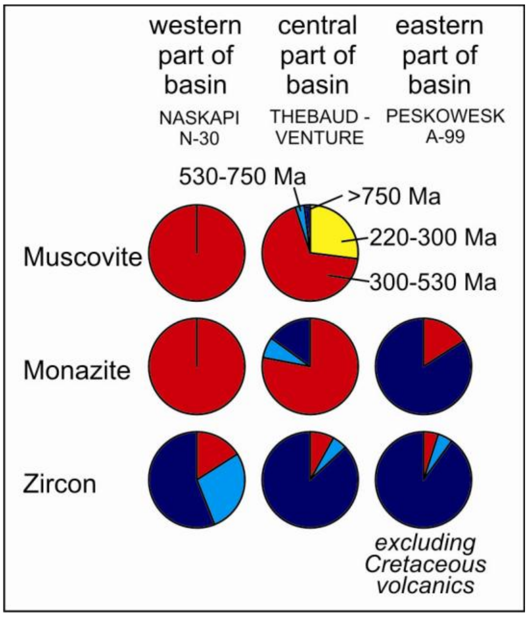

Figure 3. Summary of abundance of different dated detrital minerals in Lower Cretaceous sandstones from different parts of the Scotian Basin

NOTES

Reservoir Quality, Diagenetic History and Provenance of the Late Triassic Sandstones of the Wolfville Formation, Bay of Fundy, Nova Scotia, Canada

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The reservoir characterization and provenance of the Wolfville formation sandstones were investigated using petrography, heavy minerals and microprobe analysis of tourmaline and garnet. These fluvial sandstones are calcite cemented feldspathic litharenites to lithic feldsarenites and consist of quartz, lithics, feldspars, minor amounts of mica and heavy minerals. They are derived from metasedimentary and granitic rocks of the Ordovician Meguma terrane during early stages of rifting along the Minas sub-basin, part of the Fundy Basin rift zone. This postdates earlier Paleozoic collision orogenies which culminated with the Appalachian orogeny. The heavy minerals suites comprise iron oxides (magnetite, hematite, ilmenite and their alteration products) and garnet with minor amounts of apatite, chlorite, zircon, tourmaline, biotite and lesser amounts of rutile, staurolite, hornblende, and rarely epidote. They have a recycled orogenic provenance and the main source of these sediments are the Paleozoic rocks underlying the Wolfville formation dominated by the Meguma supergroup, the South Mountain batholith, Horton and Windsor groups with a possible minor contribution from other Paleozoic formations. The lowermost part of the Wolfville formation has relatively low porosity (~6%). The Wolfville formation has a considerable thickness beneath the Bay of Fundy where it overlies the Horton Bluff formation, Meguma and/or Avalon terranes which should be investigated further to determine the reservoir potential especially where it overlies the organic rich shales of the Horton Bluff formation, a possible source rock.

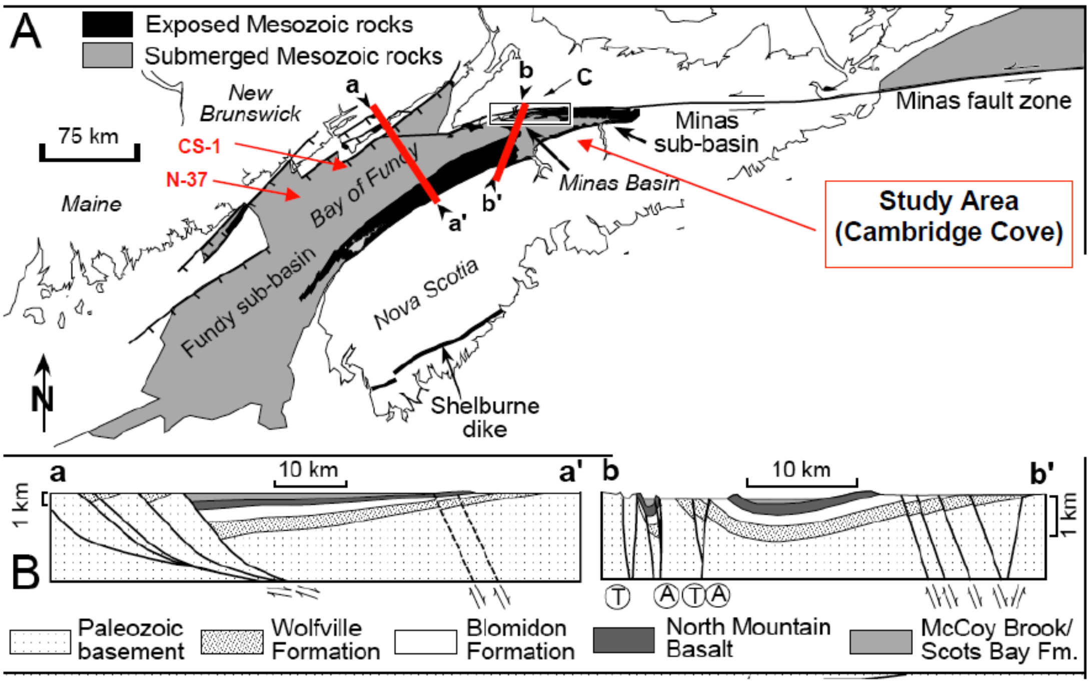

Fig. 1: Map of Fundy basin and a cross section through the Minas Basin showing the stratigraphy of Mesozoic formations beneath the basin and onshore (from Olsen and Schlische 1990). N-37 = Chinampas N-37 well; CS-1 = Cape Spencer No.1 well.

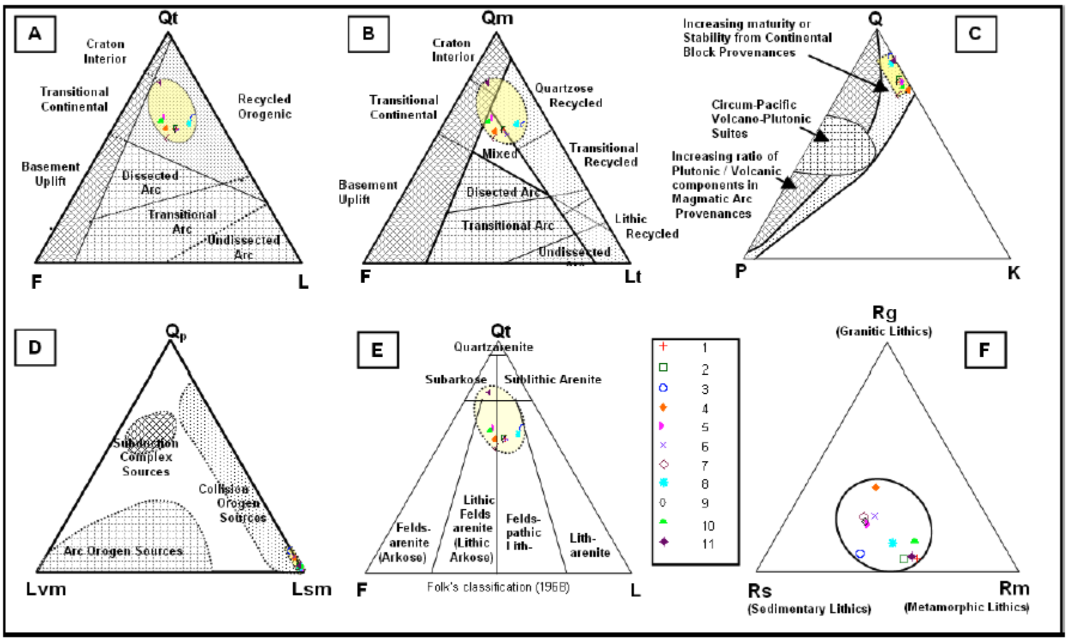

Fig. 2: Detrital constituents of the Wolfville Formation sandstones plotted on the provenance indicator triangular diagrams of Dickinson (1985), and Dickinson and Suczek (1979) (A, B, C, D) and on Folk's (1968) sandstone classification triangle (E). (F) Lithic fragment's triangular diagram; Qm=monocrystalline quartz; Qp=Polycrystalline quartz (chert & quartzite); Qt=Qm+Qp; F=feldspars; L=Lithics; Lt =L+Qp; Lsm=Metasedimentary Lithics; Lvm=Metavolcanic lithics; Rg=Granitic lithics; Rs=Sedimentary lithics;

PARAGENESIS:	**Early**…………………………………..………………**Late**
Source rocks (Meguma terrane)	
Transportation by braided rivers	→→
Deposition in river channels	→→
Primary porosity formation	→→
Early compaction	→→
Iron cementation	→→
Effective calcite cementation	→→
Later compaction	→→
Fracturing of quartz grains	→→
Limited calcite cement dissolution	→→
Alteration of feldspars	→→→→→→→→→→→→→→→→→→→→→→→→
Limited clay cementation	→→→→→→→→→→→
Secondary porosity formation	→→→→→→→→→→→→
Final compaction	→→

Fig. 3: Paragenesis of the diagenetic and related events of the Wolfville Formation sediments.

NOTES

U-Pb Zircon Provenance of Mesozoic Strata from Franz Josef Land

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The opening of the Amerasia Basin in the Arctic is generally considered to have occurred in the late Mesozoic. The tectonic development of the Basin, however, remains problematic because associated sea floor magnetic anomalies are difficult to interpret and the origins of features in and around the Basin are poorly understood. Studies which address these problems will likely lead to an improved understanding of the development of the Amerasia Basin.

Sediment provenance investigations using U-Pb dating of minerals like zircon provide information on the age(s) of source material eroded and incorporated into the sediment. As source regions change due to rifting, uplift/erosion of deeper basement, terrane collision, etc., the age profile preserved in the sediment also changes. In order to identify changes in sedimentary input with time and develop possible links to the tectonic development of the Amerasia Basin, U-Pb zircon provenance investigations were undertaken at the NORDSIM ion microprobe facility in Stockholm, Sweden.

We present U-Pb detrital zircon analyses of Jurassic (and Cretaceous?) sandstones from Franz Josef Land. The data record age peaks at ca. 250, 290, 330, 420-460 Ma, with older (500-2800 Ma) sources also present. The ages are consistent with derivation from local Eurasian sources. In combination with results of late Triassic sandstones (our previous studies), the data document a changing sediment source, particularly between Triassic and Jurassic time. Mesozoic strata from Svedrup basin record a similar change between Traissic/Jurassic time, possibly consistent a large-scale, regional depositional system linking Franz Josef Land and the Svedrup basin.

NOTES

The Subregional Correlation and Provenance Mapping of Triassic / Jurassic Sequences of the Barents Sea using Chemostratigraphic Data

T. J. Pearce, J. H. Martin' *Chemostrat Ltd., Unit 1, Ravenscroft Court, Buttington Cross Enterprise Park, Welshpool, Powys, SY21 8SL*

Triassic to Middle Jurassic deltaic to shallow marine sequences from the Western Barents Sea basin are increasingly being targeted for hydrocarbon exploration. However, reservoir quality is strongly influenced provenance, and the lack of well control, marked lateral facies variations and multiple sediment input points all contribute to the difficulty in correlating and ultimately mapping areas with more favourable reservoir quality.

A major chemostratigraphy study has been undertaken to improve the correlation of the Triassic to Middle Jurassic sequences and to aid in reconstructing the history of sediment input into the basin. The succession has been subdivided into five Chemostratigraphic Megasequences termed BMS0 to BMS4, which are further divided into Chemostratigraphic Sequences BCS0 to BCS10. These sequences are again divided into several packages, which are correlated within individual sub-basins such as the Nordkapp and Hammerfest Basins. The chemostratigraphic zonation is largely based on fluctuations in element concentrations that reflect changes in the abundance of feldspar, clay minerals, heavy minerals and opaque minerals (corroborated by data acquired via mineralogical analyses), which themselves ultimately reflect variations in provenance and palaeoclimate.

The study shows chemostratigraphy is a reliable tool for the regional correlation of the Triassic - Lower to Middle Jurassic sequences of the Western Barents Sea area. Furthermore, the technique can be used to revise the existing lithostratigraphy for this area, despite variations in lithology, facies and depositional environment, which highlights the potential of chemostratigraphy as a standard tool for the correlation of these successions. In addition to chemostratigraphic correlation, the geochemical data and selected mineralogical data are used to assist modelling changes in provenance, palaeoenvironment and facies. Furthermore, by mapping lateral variations in the values of selected element ratios, sediment dispersal patterns can also be developed. When sediment dispersal maps are combined with new isopach data, geochemical / mineralogical provenance indicators and sand:shale ratios, sediment input points along basin margins can be identified and the position of source areas inferred. In addition, this approach could employed on equivalent sequences from Eastern Barents and further into the Russian Arctic, but also similar Triassic sequences in the Canadian Arctic.

NOTES

Constraining Depositional Models in the Barents Sea Using Zircon Provenance Data from Post-Permian Sediments on Svalbard

E. Pózer Bue, A. Andresen, T. Andersen, *Department of Geosciences, University of Oslo, PO Box 1047 Blindern, 0316 Oslo, Norway*

Models of the depositional evolution of the Barents Sea region based on seismic data and drill cores indicate that this epicontinental sea was filled in towards the west and northwest in the Triassic (Glørstad-Clark et al., 2010). These models can be tested and refined by direct sampling and provenance analyses of sediments exposed on Svalbard, the uplifted north-western corner of the Barents Sea shelf. In this study the provenance of Triassic, Jurassic and Tertiary coarse clastic deposits on Svalbard, which are potential reservoir rocks in the Barents Sea, were studied by zircon laser ablation multi collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) U-Pb analyses. The data reveal significant differences in zircon age populations. Early and Middle Triassic sands include large populations of Caledonian (ca. 0.4 Ga) and older zircons compatible with local/nearby source areas on Svalbard and Greenland. In the Late Triassic, sands with significant post-Caledonian populations sourced form the Uralides reach the western margin of the Barents Sea. The zircon age signatures of Jurassic to early Tertiary sands are best explained by renewed deposition of sediments originating in the Greenland and/or the Scandinavian Caledonides. The data demonstrate that the east derived sediments have a distinct and easily identified signature that can be used to test depositional models of the Mesozoic in the Barents Sea.

NOTES

Keynote Speaker: Effects of Sandstone Provenance on Reservoir Quality Preservation in the Deep Subsurface: Experimental Modeling of Gulf of Mexico Deep Water Sand

Rick Tobin, Danny Schwarzer, *Maersk Oil Houston, Inc.*

Deep water turbidite sandstone reservoirs in the Gulf of Mexico have been sourced from a variety of provenance terraines. As a result, the framework composition of each stratigraphic unit in the basin varies widely, including volcanic-rich litharenite (Oligocene Vicksburg), feldspathic-rich lithic arkose (Oligocene Frio), metamorphic-rich feldspathic litharenite (Paleogene Wilcox), lithic-poor quartzarenite (Miocene), and quartz-rich sublitharenite (Cretaceous).

Provenance-driven differences in composition have a complex but critical influence on how each of these reservoirs respond to burial-induced changes in depth, fluid pressure, effective stress and thermal stress. A combination of Petromod and Touchstone modeling simulators are used in this study to document the effects of provenance on the compaction and diagenesis history of the main reservoir types in the Gulf of Mexico. For example, modeling results predict that at higher levels of thermal stress, some lithic-rich sands, although more ductile and highly compacted, will experience less quartz cementation than less ductile, quartz-rich sands, thereby preserving a higher range of porosity and permeability. Further, modeling results predict that temperature / pressure / depth windows for optimal reservoir quality preservation vary widely depending on sandstone provenance.

NOTES

Provenance Controls on Sandstone Diagenesis in a Rifted Basin: The Cameros Basin, N. Spain

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[2]*Dpto. Estratigrafía, Facultad de Ciencias Geológicas, UCM- IGEO (CSIC)*

The Cameros Basin is an intraplate Rift Basin developed from Late Jurassic to Early Albian (i.e., Mas et al., 2011). Its sedimentary fill (more than 6000m thick) has been divided in eight Depositional Sequences (DS) made up mainly by continental sediments, with some marine incursions. These DS consist mainly in alluvial and/or fluvial sandstones that commonly pass upward and laterally into lacustrine deposits, producing considerable recurrence of facies. Lacustrine black-shale deposits (potential oil source-rocks) are frequent throughout the sedimentary record, interbeded with sandstone deposits (potential reservoirs). This architectural disposition of facies and sequences (Omodeo-Salé et al., 2011) promotes the development of potential hydrocarbon systems.

Quantitative petrographic analysis on sandstones evidence the presence of two main petrofacies (Arribas et al., 2003a; Arribas et al., 2007): (1) a quartz-sedimentolithic or quartzolithic petrofacies which provenance is related to recycling processes from the pre-rift sedimentary cover; and (2) a quartzofeldespathic petrofacies related mainly with the erosion of plutonic and metamorphic source areas. Two main provenance cycles (Arribas et al., 2007) has been recognized: Petrofacies A&B from DS1 to DS3, and Petrofacies C&D from DS4 to DS8 (fig.1 and MS1 and 2 in fig.2). Each cycle represents nearly 20 Ma. The transition from one to the other represents the progressive sources erosion typical of a non-volcanic rifted basin.

In addition, framework composition controls the diagenetic evolution of sandstones and hence, their reservoir quality (Arribas et al., 2003b). Quartz-sedimentolithic petrofacies commonly contains intrabasinal and/or extrabasinal carbonate rock fragments. In this petrofacies carbonate cements are very abundant whereas quartz or feldspars cements are scarce (fig.2). Precipitation of early pervasive carbonate cements occludes original porosity during early burial stage, inhibiting compaction and later quartz, feldspar or clay mineral cements (fig.2). Quartzofeldespathic petrofacies shows a more rigid framework, maintaining original pores during burial diagenesis. Quartz and K-feldspar overgrowths are frequent, growing after an important kaolinitization process (epimatrix from feldspars and kaolinite pore filling). Secondary porosity is also observed as a product of feldspar dissolution producing oversize and moldic pores (fig.2). Although rigidity of framework is evidenced, compaction (mechanical and chemical) is the main porosity reduction process during burial. However, primary pores could be preserved (fig.2). Thus, quartzofeldespathic petrofacies offer the best potential reservoir quality in the basin.

Hydrocarbon maturation took place at the end of the rifting due to the progressive burial of the different source rocks (Mas et al., 2011). After hydrocarbon migration, a hydrothermal post-rift low-grade metamorphism destroyed the hydrocarbon charge (Mas et al., 2011). However, diagenetic alteration of sandstones has been preserved. This study corroborates the close relation between provenance (sandstone petrofacies) and diagenesis and reservoir quality in rift basins, and can be of great interest to compare our results with other productive rift basins.

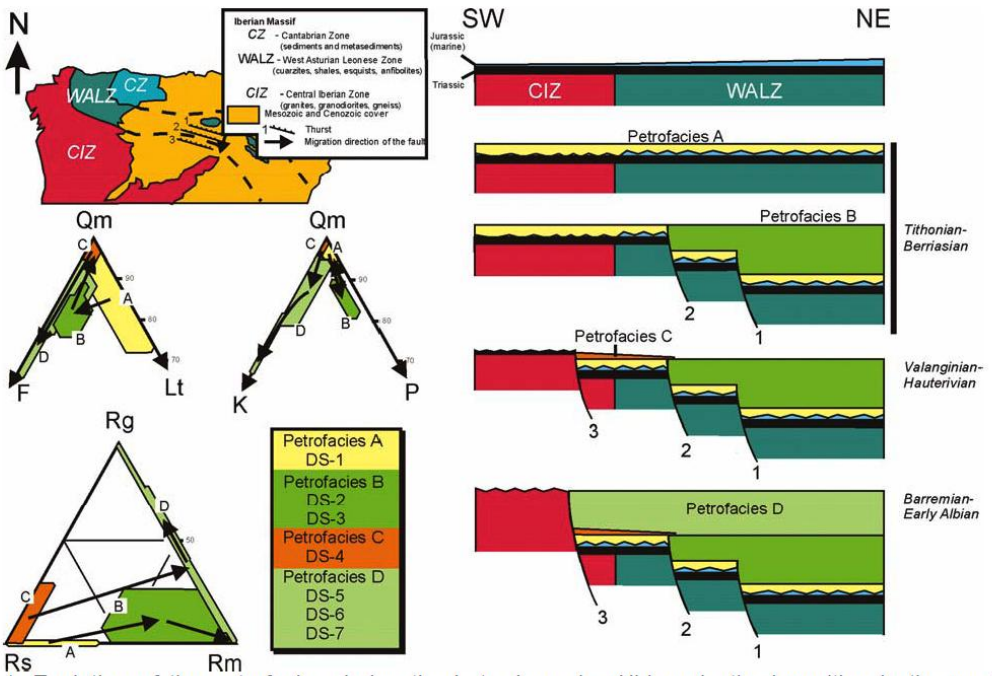

Fig. 1: Evolution of the petrofacies during the Late Jurassic- Albian clastic deposition in the western Cameros Basin and their genetic and tectonic relatioships with the Iberian Massif zones. Both A and B, and C and D represent the petrofacies cycle 1+2 (from Arribas et al. 2003a).

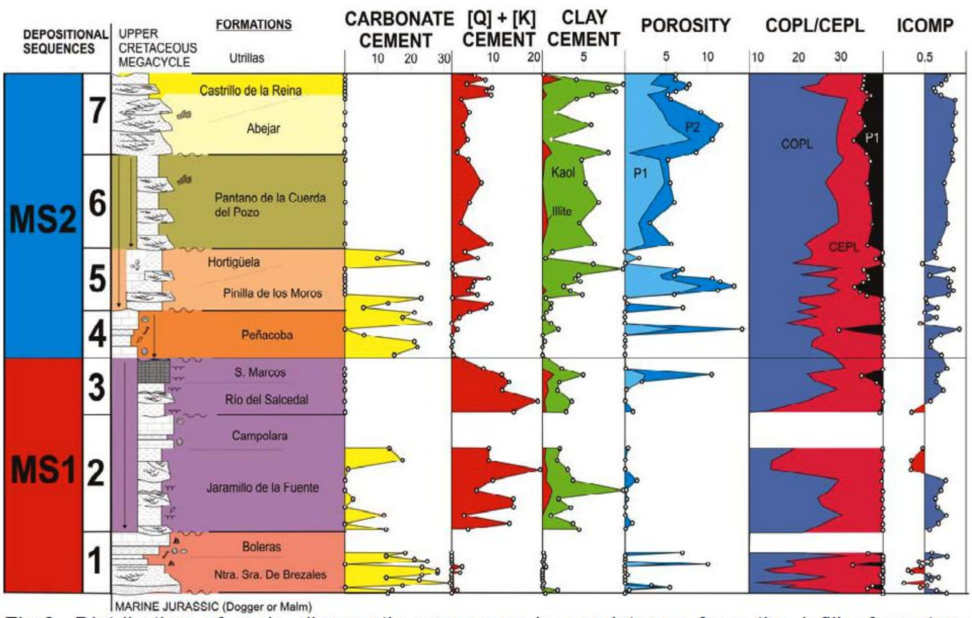

Fig.2. Distribution of main diagenetic processes in sandstones from the infill of western Cameros Basin. MS1 and MS2 represent the two main megacycles (provenance cycles) (from Arribas et al., 2003b).

NOTES

Source-To-Sink Analysis of the Amur River and North Sakhalin Basin: Implications for Tectonic Setting, Drainage Stability and Reservoir Distribution

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The North Sakhalin Basin in the Russian Far East is one of the world's most prolific hydrocarbon provinces, with more than 6 Bboe discovered to date. The basin covers an area of 84,000 km^2, extending from the Tatar Strait in the west to the Deryugin Basin in the central Sea of Okhotsk Sea in the east. Throughout the Neogene the basin has been supplied with clastic sediment by the Amur River, which has deposited a thick deltaic sequence throughout the basin. Much of this basin is now exposed onshore in the northern part of Sakhalin. These sediments are being actively exhumed and recycled into offshore areas of the basin because of regional transpression along the Sakhalin-Hokkaido Shear Zone.

This paper provides a comprehensive source-to-sink study for the Amur River and its delta in the Russian Far East, including an analysis of the extent and timing of recycling of deltaic deposits from the uplifting island of Sakhalin. We use an extensive dataset from more than 200 samples, including sandstone petrography, heavy mineral data, garnet geochemistry and U-Pb age spectra from zircon grains to constrain the provenance, sediment flux and other processes which have formed the final sediment composition in the basin. These are used to test a number of hypotheses concerning the drainage evolution of the Amur River and the tectonic evolution of the North Sakhalin Basin.

The majority of the sand-sized sediment in the Amur River and its former delta comes from upstream of the Lesser Khingan Ridge, shown by uniformity of sediment composition in the lower 1700 km of the river. The Mid-Amur basin is actively subsiding and it is possible that much of the sediment derived from the Sikhote-Alin Range is trapped within this basin. Alternatively, the volume of sediment coming from the Upper Amur may simply be drowning out any resolvable Sikhote-Alin signature. The sediment composition of the lower Amur River is mineralogically immature, with little evidence for significant weathering of chemically susceptible grains such as apatite, pyroxene and calcic amphibole. The sediment composition of the modern river appears to be identical to the most recent deltaic deposits in the basin, with a progressive decrease in the proportion of unstable grains with increasing depth and stratigraphic age. However, when stable mineral ratios and U-Pb age spectra are assessed, it is clear that there are only minor variations in the palaeo-Amur sediment composition from the Early Miocene to the present day.

The consistency of the petrographic signature in the palaeo-Amur delta renders Miocene-Pliocene drainage capture models involving the Zeya-Bureya Basin and the Upper Amur unlikely. Possible drainage capture of the Sungari River during the Miocene is uncertain, because no samples were available from this river to constrain the characteristics of its sediment load. There is evidence for a minor sediment contribution from local sources on Sakhalin during deposition the Early Miocene and again late in the Early Pliocene. Metamorphic and ultramafic clasts from the East Sakhalin Mountains are present at several sites onshore in Early Pliocene rocks in central Sakhalin, which are age-equivalents to the Amur delta deposits. Reworked sandstone clasts suggest uplift of deltaic sandstones by the end of the Early Pliocene in north Sakhalin. Evidence of sediment recycling is not present in offshore well samples until the Late Pliocene.

A positive correlation between heavy mineral ratios, such as the Garnet-Zircon index (GZi) and horizontal distance from the river mouth is attributed to hydrodynamic sorting laterally across the delta system, with the lighter garnet grains being transported farther than denser zircons. This has negative implications for the use of certain stable mineral ratios as provenance or correlative tools, in particular the GZi and Rutile-Zircon index (RZi) which are commonly used for these purposes. However, intensively weathered heavy mineral zones with low Apatite-Tourmaline index (ATi) and GZi are evident in Miocene deposits encountered in offshore wells. These values may be used as a basis for correlation if they can be linked with sequence stratigraphic systems tracts. This could potentially lead to the development of a high-resolution heavy mineral stratigraphy leading to the possibility of carrying out ‘real-time’ heavy mineral analysis during drilling, provided that the geographic variation in the data is well constrained.

NOTES

Source Areas for Post-Caledonian Sedimentary Basin Deposits in the North Atlantic Region: How Diagnostic Are They?

Arild Andresen*, Nana Yaw Aygei-Dwarko, Lars Augland, Tom Andersen, *Department of Geosciences, University of Oslo, Oslo, NORWAY*

Provenance studies are used extensively to understand pathways for clastic sediments from their source area(s) to their present position as reservoir units in sedimentary basins. Examples of this are represented by the post-Caledonian hydrocarbon-producing basins surrounding the North Atlantic. A prerequisite for successful provenance studies is sufficient knowledge about the geology of likely source areas, which in the “North Atlantic case” are the pre-Devonian rocks in East Greenland and Scandinavia, possibly also Svalbard and Great Britain.

Based on recent geological and geochronological studies in East Greenland and Northern Norway we argue that previous subdivision of Scandinavian(3) and East Greenland (2) into 5 diagnostically different source areas is questionable. Observations supporting our skepticism is based on i) identification of an eclogite bearing gneiss terrane in East Greenland with a Baltican signature (Augland et al. 2011), and ii) the presence of a regionally widespread rocks suite/ exotic terrane in the Uppermost Allochthon of the Scandonavian Caledonides with Mesoproterozoic metasediments (Krummedal Sequence?) intruded by large volumes of c. 950 Ma, c. 470 Ma and c. 430 Ma plutons (Andresen et al. 2011). The latter rock association is characteristic for large areas of the East Greenland Caledonides. Ongoing research combining LA-ICPMS dating of zircons and Hf-isotopes in zircons, and mineral chemical data on other heavy minerals obtained with our electron micro-probe (EMP) will hopefully help us differentiate better between already defined source areas with a diagnostic signature and/or define other smaller areas (e.g. Lofotens) characterized by diagnostic source minerals.

NOTES

Evolving Sand Supply and Dispersal in the Upper Jurassic of the Northern Porcupine Basin: Constraints from the Pb Isotopic Composition of Detrital K-Feldspar

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The Pb isotopic composition of detrital K-feldspar has proved to be a useful tool in provenance characterization. Analyses are carried out *in-situ* using laser ablation multi-collector inductively coupled mass spectrometry (LA-MC-ICPMS). The approach can help overcome some of the inherent limitations with single grain studies using other techniques. As sediment is transferred from source to sink the provenance signal(s) may be masked by mixing of sediment contributed from multiple sources, merging of dispersal systems and incorporation of polycyclic grains recycled from older sedimentary rocks. Improved source discrimination can be achieved by interrogating the provenance signal in more labile mineral grains (e.g. K-feldspar) that are more likely to be first cycle components and derived directly from their source.

There are significant issues in Jurassic basins west of Ireland in relation to sand-entry points, the sediment routing within and between basins and the location of sand-source areas. In addition, the Mesozoic plate configuration, palaeogeography, links between the conjugate Atlantic margins and the regional tectonostratigraphy are particularly important for future hydrocarbon exploration in the Irish offshore. Sand provenance can help constrain many of these issues. The *in-situ* Pb isotopic study of K-feldspar grains reported here focuses on a thick sand-prone interval in well 35/8-2 in the northern Porcupine Basin. The basin lies approximately 100 km west of Ireland (Figure 1) and includes a thick Jurassic syn-rift sequence (Croker & Shannon 1987, Naylor, 2005). The studied succession comprises a series of stacked submarine fan units. Four sandstone intervals are recognised (A, B, C and D from top to bottom), each representing a phase of deep-sea fan activity. Pilot Pb data from <40 K-feldspar analyses identified two distinct Pb isotopic populations (Tyrrell et al. 2007). The small sample number prevented robust statistical analysis of the data or any assessment of temporal changes in sand supply. Tyrrell et al. (2007) interpreted these data to represent hinterland drainage from a northern source, probably from an uplifted Porcupine High with a dispersal distance of c.100 km.

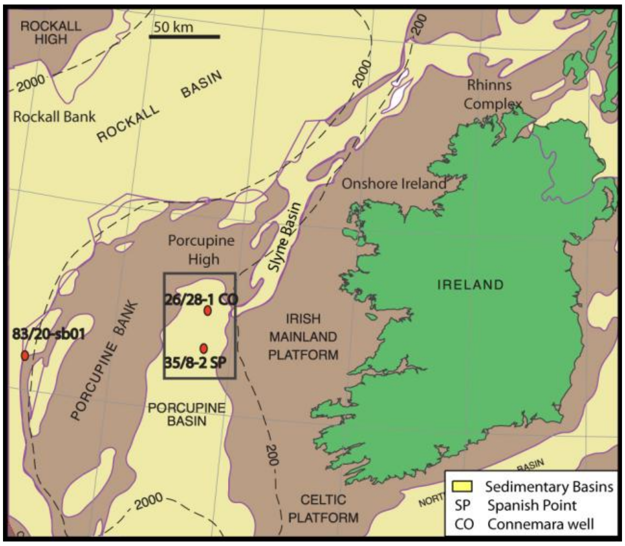
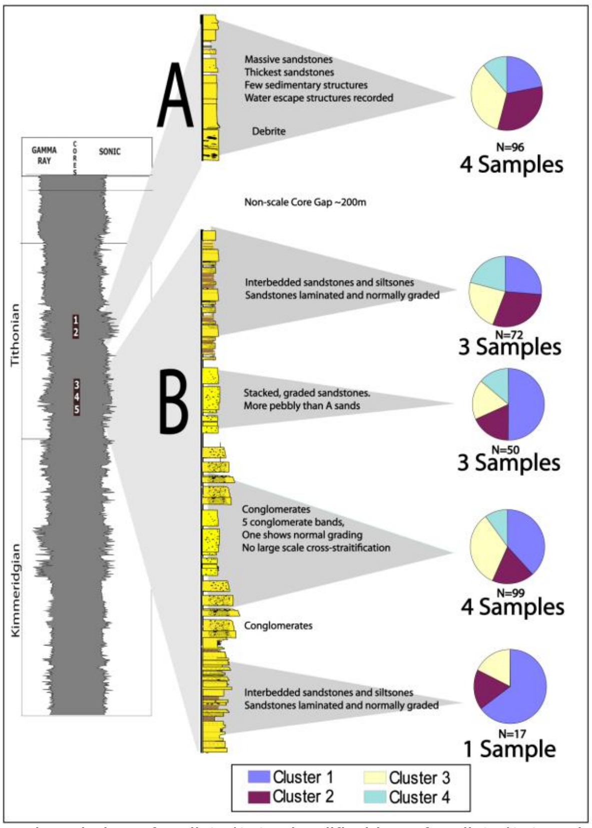


Figure 1 : Location map showing the study area – well 35/8-2 in the northern Porcupine Basin.

The detailed provenance study presented here focuses on the source of the A and B sandstones. The Pb isotope and conventional petrographic data have also been integrated with MLA (Mineral Liberation Analysis) tallies of the grain types to provide a more robust interpretation. The aim of this study is to investigate whether the Pb signal is consistent between different depositional elements recognised in the cores (channels, sheets) and across a wider stratigraphic interval. The latter is important for inferring the continuity of supply during several cycles of deposition, for assessing the potential for multiple sand supply points to the basin, and for constraining hinterland evolution during syn-rift extension. The new data comprise results from 334 K-feldspar grains analysed from 15 samples of fine to medium-grained sandstones. K-means cluster analysis was applied to the Pb dataset to highlight different grain populations and hence source contributions. In order to constrain the potential sources, the clusters are compared to Pb isotopic data from the wider North Atlantic region. Four clusters were identified, each attributed to a discrete basement source and the new data reveal grain populations unrecognised in the previous pilot study.



and sonic log of well 35/8-2, simplified log of well 35/8-2 and summary pie-charts of proportions of clusters in each dominant facies.

These data suggest that four isotopically distinct sources supplied the K-feldspar in the A and B sandstones. The Rockall Bank, Porcupine Bank, Porcupine High and the Irish Massif, or its along strike extension, are identified as likely sources. All of these sources suggest transport distances less than 250 km. There are no far-traveled sand grains from Archaean – Palaeoproterozoic domains to the north or from the Variscides to the south. The vertical distribution of Pb data show the relative contribution from the main sources varied through time (Figure 2) recording the evolution of sediment supply to the deep-water northern Porcupine Basin. Axial derivation, from the north and northwest, seems likely to supply cluster 1 and 2 grains, while lateral input from the basin margins could account for cluster 3 and 4 grains. Cluster 4 is the dominant source in the lower B sands, with clusters 2 and 3 increasing higher in the stratigraphy. This gradual change in provenance may reflect increased lateral input, perhaps linked to local rifting associated with the early formation of the Rockall Basin. This study underscores the potential of the Pb in K-feldspar provenance approach as a useful tool in constraining sediment supply and evolution.

NOTES

High-Resolution Detrital Zircon Stratigraphy of the Kangerlussuaq Basin, East Greenland - Constraints on Cretaceous-Paleocene Sediment Transport Paths and Basin Evolution

D. Frei[1], M. Frei[2], M. Larsen[3], Whitham, A.G.[4], C Knudsen[5]

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As hydrocarbon exploration pushes further westward in the Faroe-Shetland Basin, the questions as to the role that East Greenland has played as a source of sediment to the basin are increasing. The Cretaceous-Early Eocene sediments exposed at Kangerlussuaq, southern East Greenland, are in a position that was adjacent to the Faroe-Shetland region prior to continental breakup in the late Miocene. The 900 m thick succession (Fig.1) provides some of the best exposures of Late Cretaceous-Early Eocene strata in the North Atlantic region and provide a valuable analogue for the Faroe-Shetland basin (Larsen et al. 1999).

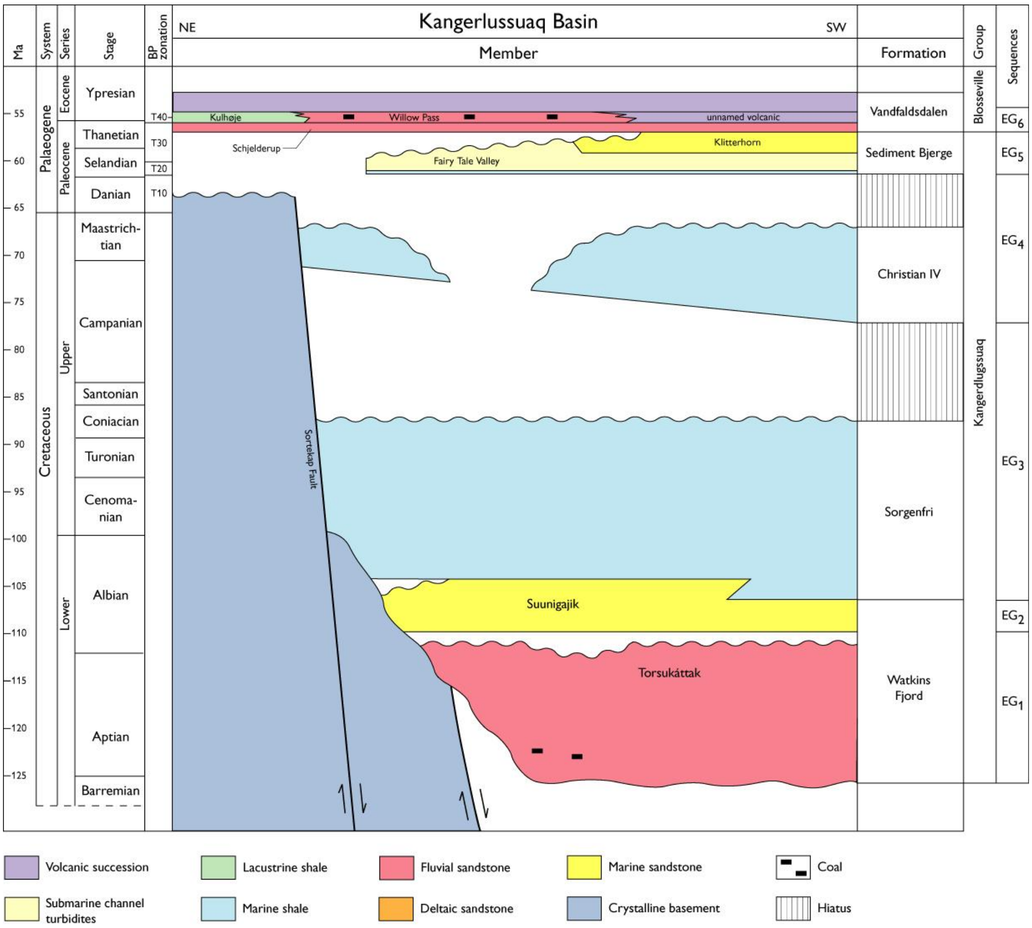

Fig. 1: Litho- and sequence stratigraphy of the Cretaceous-Paleogene succession in Kangerlussuaq, East Greenland.

Knowledge of the variability of the detrital zircon age spectra of the sedimentary successions exposed at Kangerlussauq is important for (a) the characterisation of sandstones in southern East Greenland in order to provide a framework for the identification of sands in the Faroe-Shetland Basin; (b) identification of major sequence boundaries within the successions; and (c) characterisation of major changes in sediment supply during deposition. To this end, we have conducted a high resolution stratigraphical study based on U-Pb age dates of > 2300 detrital zircons separated from 25 sandstone samples from Kangerlussuaq. All zircons were analysed using LA-ICP-MS techniques (Frei et al. 2005).

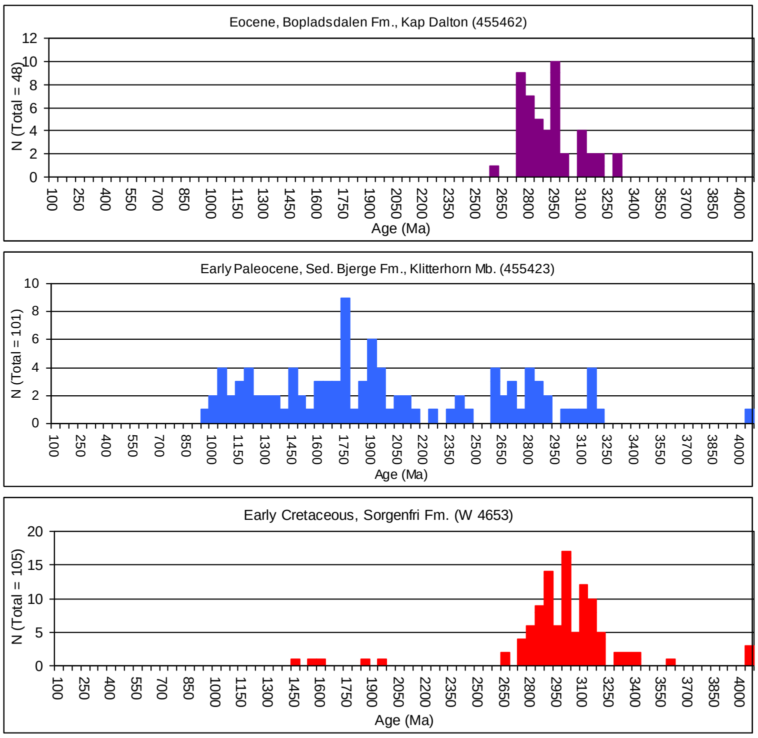

Fig. 2: Binned histograms displaying the detrital zircon age distributions in sandstones from representative stratigraphic profiles through the eastern Kangerlussuaq Basin (with the stratigraphically youngest sample on top).

Prominent changes in the detrital zircon age spectra suggest two major changes in sediment sourcing (Fig. 2). From the Early to Late Cretaceous, Archaean basement sources in the south or southwest have been replaced by sources in the north and northeast that comprise a high proportion of younger material. During the Late Paleocene, sediment supply has changed back to predominantly Archaean basement sources in the south or southwest. The pronounced changes in the observed age spectra from the Early to Late Cretaceous and during the Late Paleocene excludes large-scale reworking of local sediments as a potential sediment source. Within each of the distinct main units, the relative frequency of the main Archaean (i.e. Early, Late and Middle Archaean) and Proterozoic (i.e. Caledonian, Grenvillian, and Early Proterozoic) age groups show clear temporal changes, suggesting that distinctively different age domains in both the Archean and Proterozoic basement have acted as dominant sediment sources. Furthermore, the lack of lateral variations in the age spectra in almost all groups strongly supports the validity of the stratigraphic correlations drawn from litho- and sequence stratigraphic observations.

In conclusion, the U-Pb age analysis of > 2300 detrital zircon grains by LA-ICP-MS from sandstones in Kangerlussuaq, Greenland, allowed to study the evolution of the sand supply to the sedimentary coloumn with hiherto unprecedented detail. Our results clearly demonstrate the benefit of high stratigraphical resolution in provenance studies based on detrital zircon age distributions.

NOTES

Petrography, Geochemistry and Provenance of Cretaceous and Paleocene Sandstones in the Disko Nuussuaq Basin

Christian Knudsen, Anders Scherstén, Martin Sønderholm, *GEUS*

Sandstones of Cretaceous and Paleocene age are potential reservoir rocks offshore Central West Greenland. Their reservoir and provenance characteristics are relevant for the petroleum exploration in the area because the presence of an adequate reservoir rock is one of the main risks in this region. Sandstones from the Nuussuaq Group are well exposed in the Disko Nuussuaq Basin. The Nuussuaq Group is more that 6 km thick and represents a period of deposition from Albian to Paleocene.

Samples from outcrops and shallow wells were analysed for their bulk rock geochemistry and provenance characteristics. In addition, the sandstone petrography has been investigated along the ~1000 m high Itsaku profile in the northern part of the basin. The bulk rock geochemistry includes major (XRF) and trace element (ICP-MS) analyses. The provenance characteristics have been analysed in 65 sediment samples from eight outcrop localities in the Nuussuaq Basin and three exploration wells using the GEUS developed Computer Controlled Scanning Electron Microscopy (CCSEM) of heavy mineral fraction and laser ablation ICP U-Pb dating of zircon (4262 grains).

The age distribution patterns among detrital zircons in the Cretaceous and Paleocene sandstones are compared to the age distribution patterns of zircons recovered from stream sediment samples (~3600 grains) in the potential source area to the east. These samples were collected as part of regional geochemical mapping and represent the geology in West Greenland between 63^{o} N to 72^{o} N. The stream sediment zircons are dominated by one major population with an age of ca. 2.75 Ga and two minor populations that are Early Archean gneisses (~3.6 Ga) and new crust formed during the Nagssugtoqidian orogeny (~1.9 Ga). The Cretaceous sandstones show a similar pattern. However, there are small differences in the pattern with overrepresentation of zircons with ages of 3.2, 3.0, 1.9. 1.5, and 1.1 Ga. compared to the source in West Greenland known from the stream sediment samples. This difference is best explained if the source area included South East Greenland and the Caledonian rocks in Central East Greenland. This suggests that the paleo drainage pattern in the Cretaceous from the Albian to the Campanian was from the east to the west.

On the Itsaku Peninsula in the northern part of the basin, a section from the Albian - Cenomanian Upernivik Næs Fm., the overlying Maastrichtian to Paleocene Kangilia Fm. and the Paleocene Eqululik Fm. shows that there was a complete change in the sediment supply pattern during the Upper Cretaceous. The Upernivik Næs Fm. shows an eastern source as described above whereas the zircon ages in the Maastrichtian and Paleocene sandstones have a unimodal distribution around an age of 1.9 Ga, which is characteristic for the Prøven Granite/Cumberland Batholith to the north and west.

The character of the clastic material also changes from a subarkosic sandstone in the Upernivik Næs Fm., where quartz constitutes 75 - 90 %, K-feldspar 10 - 15 %, albite 3 – 10 % and calcic plagioclase 0 – 8 % of the sand fraction, to the less mature Kangilia Fm. where quartz constitutes 55 - 62 %, K-feldspar 25 - 35 %, albite 3 – 10 % and calcic plagioclase 0 – 7 % of the sand. The overlying Paleocene Eqululik Fm is characterised by influx of mafic volcaniclastic material now preserved as chlorite.

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Wednesday 7 December

Keynote Speaker: Mineral-Chemical Stratigraphy in Sandstone Hydrocarbon Reservoirs

Andrew Hurst, *University of Aberdeen, Department of Geology and Petroleum Geology, King's College, Aberdeen*

Traditionally the application of heavy mineralogy in subsurface applications is a reaction to the difficulty of making robust intra-reservoir correlation using more conventional methods such as biostratigraphy and lithostratigraphy. Numerous applications demonstrate that heavy minerals often provide enhanced lithostratigraphic control in a broad range of clastic sedimentary environments and provide a "fingerprinting" method that supports reservoir-volume correlation. Because common heavy minerals have differing levels of sensitivity to weathering and burial-diagenetic processes, observation and quantification of their presence, abundance and textural character during the routine analysis of mineral extractions from sandstones provides added value. Heavy minerals that are resistant to the effects of weathering and diagenesis and form solid-solution series are particularly useful in lithostratigraphy, and are the basis for varietal studies. These minerals tend to have more and less soluble end members, or have compositions that are dominated by low-mobility cations; the association between specific heavy minerals and their chemistry in lithostratigraphy is termed mineral-chemical stratigraphy. It is important to note that understanding provenance is rarely a primary goal of reservoir-scale heavy-mineral studies and that the sampling density in subsurface-reservoir studies is often far greater than that employed in conventional provenance studies. Consequently when several geographically-focused reservoir heavy-mineral studies are combined they tend to advance the regional understanding of sediment provenance. Applications will be given of mineral-chemical stratigraphy to reservoir zonation and steering of development wells from various depositional environments and stratigraphic sections, which then are amenable to elucidating larger-scale geological processes. Acquiring heavy-mineral data enables or enhances inter-well correlation and invariably adds value to other aspects of reservoir characterization.

NOTES

New Insights into Reservoir Sand Provenance on the North West Shelf, Australia Using Detrital Zircon Geochronology

Keith Sircombe

Abstract TBC

NOTES

Provenance of Devonian-Carboniferous Sandstones from the Clair Basin: New Insights from Detrital Zircon Age Dating

A.S. Schmidt[1], A.C. Morton[2,3], G.J. Nichols[1], C.M. Fanning[4]

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[4]Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia

The Clair Basin, situated about 75 km west of the Shetland Isles, is one of a number of continental basins which formed in the North Atlantic region in response to the Caledonian Orogeny. The basin fill comprises a succession of sediments in red-bed facies, divided into Lower (Units I to VI) and Upper (Units VII to X) Clair Group, directly overlying Archaean basement gneisses ascribed to the Lewisian.

Owing to its importance for petroleum geology, the Clair Basin has been the subject of a number of studies over the last thirty years. However, the provenance of the Devonian to Carboniferous sediments infilling the basin remains unclear. This study presents the results of analyses of detrital zircons from ten sandstone samples by sensitive high resolution ion microprobe (SHRIMP) and shows their significance when discussing potential sources for the Clair Group sediments.

Clast compositions of fan-delta conglomerates in the lower part of Unit I together with heavy mineral data from their matrix are consistent with derivation from local Lewisian basement. However, zircons in the upper part of Unit I are predominantly Proterozoic (*c.* 60 %). Therefore, the catchment seems to have expanded to include low-grade metasedimentary (as indicated by heavy mineral data) Proterozoic rocks shortly after deposition of the locally-supplied conglomerates. Zircon ages, as shown by the age spectra of units IIIa, IIIc, V and VIa, and heavy mineral assemblages throughout most of the succeeding Lower Clair Group also imply a combination of a local Archaean and a more distal Proterozoic source. Strong similarities between detrital zircon age spectra from the NE Greenland continental margin and the Clair succession argue for a derivation of at least some of these sediments from the NE Greenland continental margin.

Samples from units IVb and VIb are notable exceptions from the pattern described above as they are dominated by Archaean zircons. Subunit IVb represents an atypical zone with very low apatite roundness and very high abundances of high-Mg, low-Ca garnets. The low apatite roundness suggests relatively short transportation, implying local sourcing and the garnet geochemistry suggests derivation from high-grade metasedimentary rocks. In Subunit VIb, there is a trend of increasing zircon relative to garnet concurrent with an increase in abundance of high-Mn garnet, suggesting increasing supply from intermediate-acidic gneisses and granites. These two samples are interpreted to represent periods within which the supply of low-grade metasedimentary Proterozoic rocks was cut off by tectonic rejuvenation of the adjacent hinterland. The basal sandstones of the Upper Clair Group (Subunit VIc) yield similar heavy mineral characteristics and detrital zircon ages to the underlying Subunit VIb but are interpreted as representing Lower Clair Group reworking.

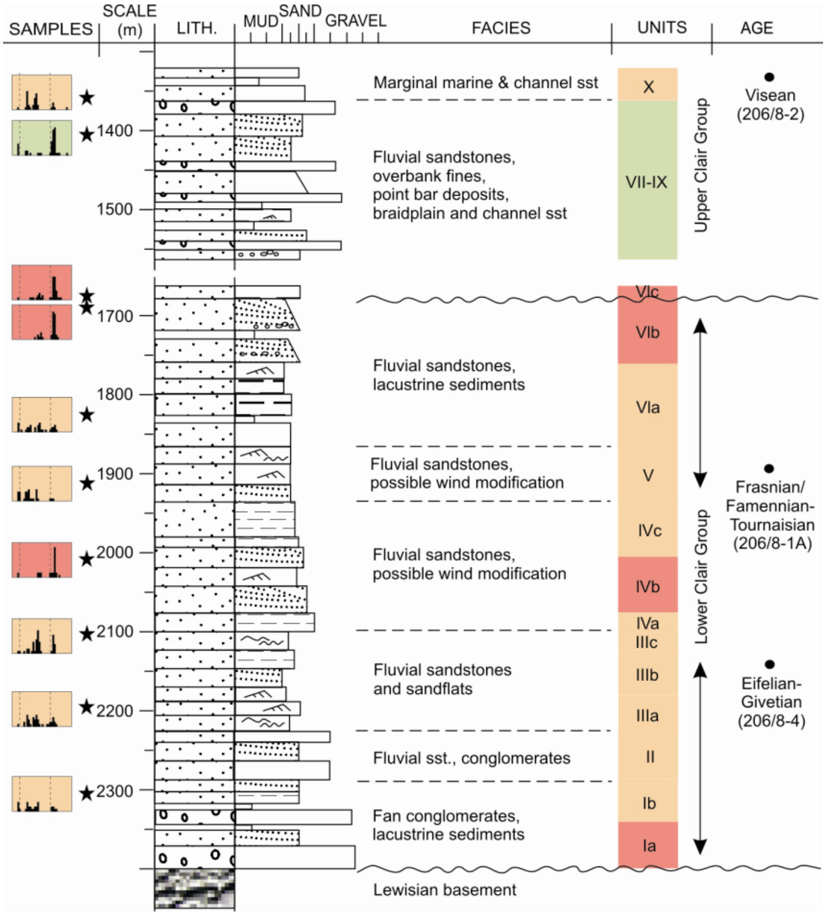

Fig.1. Simplified stratigraphic column for the Clair Group. Stars indicate sample depths for SHRIMP. Orange units represent samples dominated by Proterozoic zircons probably derived from Greenland. Red units contain mainly Archaean zircons derived from local basement. Unit VII-IX (green) comprises Archaean zircons in combination with a medium- to high-grade meta-sedimentary heavy mineral assemblage.

Zircons from Unit VII-IX are also dominated by Archaean ages between 2500 and 3700 Ma (*c.* 70 %). However, in contrast to samples described above, the heavy mineral assemblage indicates derivation from moderate- to high-grade staurolite- and garnet-rich metasedimentary lithologies. Such lithologies occur in the Neoproterozoic to Early Palaeozoic Moine and Dalradian successions of Scotland and their equivalents in East Greenland and Scandinavia. However, the abundance of Archaean zircon suggests that the metasedimentary source was itself supplied from an Archaean terrane.

The Unit X zircon population has much more abundant Proterozoic zircons (*c.* 80 %) compared with the Unit VII-IX sample. This change in zircon ages is accompanied by sharp decreases in staurolite:zircon, garnet:zircon and apatite:tourmaline ratios. The change to a staurolite-poor heavy mineral assemblage and a Proterozoic-dominated zircon spectrum suggests that the sample has a similar provenance to the majority of the Lower Clair Group. The low apatite:tourmaline and garnet:zircon ratios in the Unit X sample are interpreted as the result of weathering during alluvial storage in the humid tropical Carboniferous depositional environment.

The integration of the new detrital zircon age data with published heavy mineral data for the Clair Basin not only allows the identification of ages and lithologies of the source rocks but also enables one to newly interpret and evaluate potential source areas for the Clair succession.

NOTES

Provenance of K-Feldspar in Upper Jurassic Reservoir Sandstones in the Northern North Sea: Implications for Sand Sourcing, Sedimentary Recycling and Well Correlation

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The Pb isotopic composition of detrital K-feldspar has proven to be a powerful indicator of sand provenance (e.g. Clift *et al.*, 2008; Tyrrell *et al.*, 2010). Feldspar is often a significant framework grain component in sandstones and, as a labile phase, is more likely of first-cycle origin than robust minerals commonly utilised in provenance studies. Furthermore, as Pb isotopes vary in the crust at a sub-orogenic scale, potential sources can be characterised and distinguished at a scale appropriate to that of major drainage systems. The Pb isotopic signature of individual K-feldspar sand grains can be measured *in situ* using laser ablation multi-collector inductively-couple plasma mass spectrometry (LA-MC-ICPMS) such that areas of alteration or heterogeneities that may compromise the analysis can be avoided. For these reasons, this approach is particular useful for constraining palaeodrainage and sediment dispersal. With high-resolution sampling, the data can produce a correlateable 'fingerprint' within sandstone sequences, whilst also providing insights into reservoir sandstone distribution and quality.

The Pb-in-K-feldspar tool has been applied to Upper Jurassic reservoir sandstones in the northern North Sea in order to test a sand sourcing and sediment input model. The Kimmeridgian Magnus sandstones in East Shetland Basin (the UK sector of the northern Viking Graben) have been subdivided in to 3 distinct "lobes" (1, 2 & 3) which are biostratigraphically calibrated. The textural uniformity and maturity of the Magnus sandstones suggests a significant shelf where sands were held and winnowed prior to transport into their eventual deep water setting. The most logical local source area is the Manet Ridge / Margarita Spur area to the north (Figure 1), where, it is envisaged, extensive Triassic was exposed. However, the Magnus sandstones contain no obvious Triassic clasts and are typically fine-medium grained micaceous massive amalgamated sandstones. These contrast strongly with Cretaceous Devils Hole Formation, which occurs at depth north of the End of the World Fault within the Magnus Basin, is reddened and contains granitic and sedimentary lithic clasts throughout the cored sections.

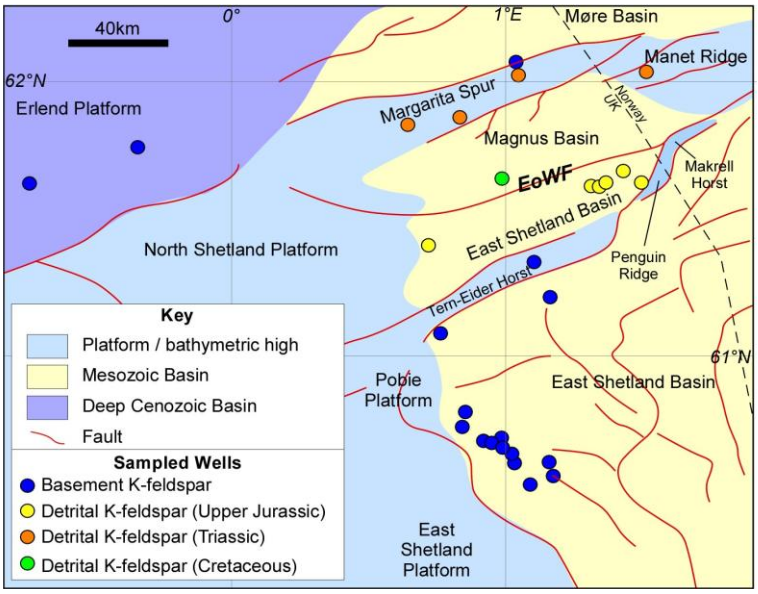

Figure 1: Simplified map of the study area showing the location of sampled wells. EoWF = End of the World Fault.

Pb analysis has been carried out on <750 K-feldspar grains from five wells containing Magnus sandstones and equivalents. Results reveal four Pb grain populations. Populations 1 and 2 form linear arrays, comprising broad trends of $^{206}Pb/^{204}Pb$ of potentially overlapping compositions, whereas populations 3 and 4 form distinct clusters with a narrower range of $^{206}Pb/^{204}Pb$ (Figure 2). These populations are mixed within the sampled sandstones at the scale of individual thin sections. However, when the population abundance is summed for each lobe element, the grain distributions show distinct patterns or fingerprints which appear to correlate across four of the five sampled wells. The upper lobes in the western-most well appear to have a different provenance to the others, with population 4 dominant over all others combined.

In order to constrain the source/s of the K-feldspar sand grains, detrital Pb data are compared to 1) new K-feldspar Pb isotopic data from a broad range of basement in the northern North Sea; 2) new Pb isotopic data from K-feldspars in Triassic sandstones on the Manet Ridge / Margarita Spur; and 3) published Pb isotopic data from the wider North Atlantic region. Populations 1 and 2 appear to correspond to Archaean - Palaeoproterozoic sources, specifically the Nagssugtoqidian Mobile Belt (NMB) of eastern Greenland or an equivalent. There is little correspondence with the more proximal Archaean - Palaeoproterozoic rocks of the Lewisian of NW Scotland or its offshore equivalents. Population 4 grains correspond with granitic crust north and west of the Magnus Basin, such as that encountered in wells on and around the Manet Ridge / Margarita Spur. The definitive source of Population 3 grains remains unclear. Southern sources for K-feldspar in the Magnus sandstones, such as those adjacent to the Pobie and East Shetland platforms, can be ruled out.

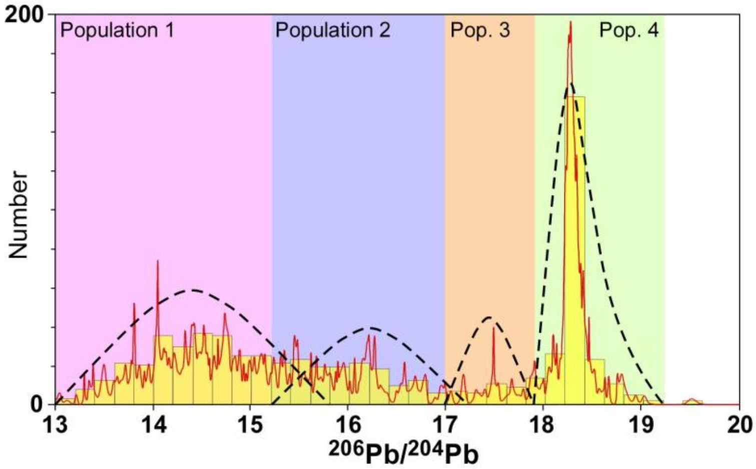

Figure 2: Histogram and relative probability density (red curve) plot showing the distribution of $^{206}Pb/^{204}Pb$ composition in detrital feldspar from all sampled Magnus sandstones and the 4 populations.

This presentation aims to illustrate how these data, when integrated with well and seismic information, provide constraints on the dispersal of sand into the basin and the likely orientation of sediment pathways. There will be specific focus on the potential for feldspar recycling, as similar grain populations are encountered within the Triassic rocks on the Manet Ridge / Margarita Spur. Although it is feasible to produce the K-feldspar populations observed in the Magnus sandstones by recycling and mixing the Triassic sandstones, there is strong petrographic and geochemical evidence against this. The presentation will also demonstrate how feldspar provenance information can feed into, and further inform, palaeogeographic reconstructions.

NOTES

Raman Spectroscopy in Heavy-Mineral Studies

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Raman spectroscopy is a powerful tool to confidently identify dubious grains independently of their size and orientation, and thus to efficiently solve thorny long-standing problems in provenance studies. During counting of heavy-mineral mounts, grain types that cannot be specifically determined are usually assigned to generic groups (i.e., opaques, turbids) and neglected in provenance considerations, which may result in a seriously biased description of the heavy-mineral assemblage.

Raman spectroscopy allows reliable distinction of:
- single phases and solid solutions of opaque Fe-Ti-Cr oxide grains (Wang et al., 2004; Garzanti et al., 2010), which may be strongly concentrated in placer deposits of economic interest, and are particularly relevant for both provenance (Basu and Molinaroli, 1989) and settling-equivalence studies (Garzanti et al., 2008);
- unidentified altered minerals, particularly common in sediments derived from very low-grade metasedimentary source rocks;
- authigenic minerals (e.g., Ti-oxide polymorphs);
- tectosilicates, phyllosilicates and carbonates, commonly found in heavy-mineral mounts (e.g., because of dense inclusions or imperfect separation).

Even identification of unaltered transparent heavy minerals is not invariably univocal under the optical microscope (Mange and Maurer, 1992). This is particularly true for colourless grains that cannot be easily oriented because they lack cleavage and evident crystal faces, or for rounded high-relief and high-birefringence grains. Orientation problems are most serious in provenance studies of eolian sands, where detrital minerals are commonly transformed into perfect spheres.

With Raman spectroscopy we can distinguish:
- colourless zircon versus titanite, monazite, or xenotime;
- metamictic zircon versus cassiterite, sphalerite, or rutile;
- epidote versus clinozoisite or pale-green augite;
- apatite versus sillimanite or topaz;
- enstatite versus prismatic olivine or prismatic sillimanite;
- fibrolitic sillimanite versus anthophillite;
- allanite versus brown hornblende;
- kyanite versus barite.

Raman spectroscopy represents a complementary time-saving technique in varietal studies (Morton, 1985; Mange and Wright, 2007), because precious chemical information can be obtained rapidly, on many grains, and directly on heavy-mineral mounts without further preparation. The technique allows us to quantitatively or semi-quantitatively analyse the chemistry of solid solutions and isomorphic series (e.g., spinels, olivines, garnets; Wang et al. 2004; Kübler et al. 2006; Bersani et al., 2009), and to identify varieties of silicates such as sodic amphiboles or clinopyroxenes.

Moreover, Raman spectroscopy offers an opportunity to:
1) identify rare grains occasionally encountered in heavy-mineral slides or thin sections;
2) investigate gaseous, liquid and solid inclusions in single detrital minerals (e.g., apatite, zircon, micas);
3) calibrate apatite crystallographic structure for fission-track analysis (Zattin et al., 2007);

4) assess degree of metamitictization in zircon (Balan et al., 2001; Nasdala et al. 2001);
5) assess varieties in REE-bearing minerals (e.g., titanite, allanite);
6) investigate anisotropic crystal behaviour to physical or chemical processes (e.g., weathering, diagenetic dissolution) by comparing morphological features observed on different crystal faces.

Last but not least, Raman spectroscopy allows routine identification of minerals as fine grained as fine silt (Garzanti et al., 2011), and it is consequently an unrivalled tool for heavy-mineral analysis of silt and siltstone. Although they represent a huge fraction of fluvial, turbiditic and eolian transport, provenance analysis of fine-grained sediments has been seldom carried out because of operational difficulties (Blatt, 1985; Totten and Hanan, 2007). A whole frontier is thus opening up for provenance studies, considering that mudrocks represent most of the stratigraphic record (Blatt and Jones 1975), and better preserve detrital minerals from diagenetic dissolution (Blatt and Sutherland, 1969).

NOTES

Cathodoluminescence Spectra of Quartz as Provenance Indicators Revisited

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We present a discrimination scheme for cathodoluminescence (CL) spectra of quartz as a tool in provenance studies. We analysed 393 quartz crystals from 45 samples of different plutonic, volcanic, metamorphic, and pegmatitic rocks. The technique is based on the measurement of the relative intensity of the two main emission centres in visible light, for quartz typically at 470-490 nm and 600-640 nm. The results confirm a red, violet or middle to bright blue luminescence for volcanic phenocrysts, mainly bright blue colours for felsic plutonic and high-temperature metamorphic quartz, as well as brown to dark blue CL for quartz of low-temperature metamorphic origin. These and additional results for mafic plutonic (dark blue) and pegmatitic quartz (bright blue) lead to a possible discrimination with the following rock grouping: (1) volcanic quartz, (2) low-temperature metamorphic and mafic plutonic quartz, and (3) felsic plutonic, high-temperature metamorphic, and pegmatitic quartz. In the proposed scheme, 87 % of the spectra were classified correctly. The three quartz groups can be used as an estimate for the amount of volcanic, metamorphic, and plutonic quartz in sediments because commonly most plutonic quartz detritus is transported from felsic rocks and low-temperature metamorphic rocks are the major sources for metamorphic quartz. Hence, despite criticism within the literature during the last decades, the CL colours of detrital quartz still can be used as provenance indicators. We finally conclude that the measurement of wavelength spectra is a fast and straightforward method to determine quartz-bearing source rocks of siliciclastic sediments.

NOTES

Provenance of Palaeozoic Terrestrial Sediments in the Proto-Central Graben, Mid North Sea High: Detrital Zircon Geochronology and Rutile Geochemical Constraints

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Famennian alkaline volcanism and marine deposits on the northern flank of the Mid North Sea High indicates late Devonian rifting in a proto-Central Graben (Lundmark et al. in press). Zircon U-Pb and rutile trace element data from late Devonian to early Permian terrestrial sediments in the graben are used to investigate the sediment provenance and the potential of heavy mineral data for correlations in the Embla oil field.

One group of Old Red Sandstone samples is interpreted to be derived from recycling of Scottish low- to medium grade sediments ultimately originating in the Grenville orogen. A second group of Old Red Sandstone samples contains high grade rutile traceable north-eastwards via the Outer Moray Firth to east Greenland. Both groups likely contain locally sourced detritus from the proto-Central Graben rift flanks.

Mid Westphalian C – Stephanian Upper Flora Sandstone and early Permian sandstone in the Flora and Embla oil fields, respectively, yield heavy mineral signatures compatible with recycling of Palaeozoic sediments to the north of the Southern Uplands.

The study indicates a late Devonian - early Carboniferous switch in the regional drainage system that constrains possible correlations in the Embla oil field, and suggests that Old Red Sandstone lacking a significant high grade rutile component represent the oldest sediments.

NOTES

Keynote Speaker: The Nile Sediment-Routing System

Eduardo Garzanti, Sergio Andò, Marta Padoan, Giovanni Vezzoli, Igor Villa, *Laboratory for Provenance studies, Earth Science and Geotechnology Department, Milano-Bicocca University*, 20126 Milano, Italy

The Nile River flows for ~ 6700 km, from Burundi and Rwanda highlands south of the Equator to the Mediterranean Sea at northern subtropical latitudes. In such a unique natural laboratory, we are carrying out a continuing research project to investigate changes in sediment composition associated with diverse chemical and physical processes, including weathering in equatorial climate and hydraulic sorting during transport and deposition. Petrographic, mineralogical, chemical, and isotopic fingerprints of sand and mud have been monitored along all Nile branches, from the Kagera and White Nile chiefly draining Mesoproterozoic to Archean rocks uplifted along the western branch of the East African rift, to the Blue Nile and Atbara Rivers largely draining Tertiary basalts of the Ethiopian plateau.

Downstream of the Atbara confluence, the Nile receives no significant tributary water and hardly any rainfall across the Sahara. After construction of the Aswan High Dam in 1964, the Nile ceased to be an active conveyor-belt in Egypt, where the mighty river has been tamed to a water canal; transported sediments are thus chiefly reworked from older deposits, with minor contributions from widyan sourced in the Red Sea Hills and wind-blown desert sand and dust. Extensive dam construction has determined a dramatic sediment deficit at the mouth, where deltaic cusps are undergoing ravaging erosion. Nile delta sediments are thus recycled under the effect of dominant waves from the northwest, the longest Mediterranean fetch, and carried eastward and northward to as far as Akko Bay in northern Israel; along the coasts of Egypt and Palestine, sand is progressively enriched in minerals such as quartz and amphiboles relative to volcanic rock fragments and pyroxene.

A better knowledge of the Nile system not only has wide implications on paleoclimatic, paleoceanographic and archeological topics, including Quaternary environmental changes in northern Africa, water circulation and sapropel development in the Mediterranean Sea, and the rise and fall of the Egyptian civilization, but is also needed to mitigate undesirable impacts of human activities on natural equilibria and to improve watershed, reservoir and coastal management.

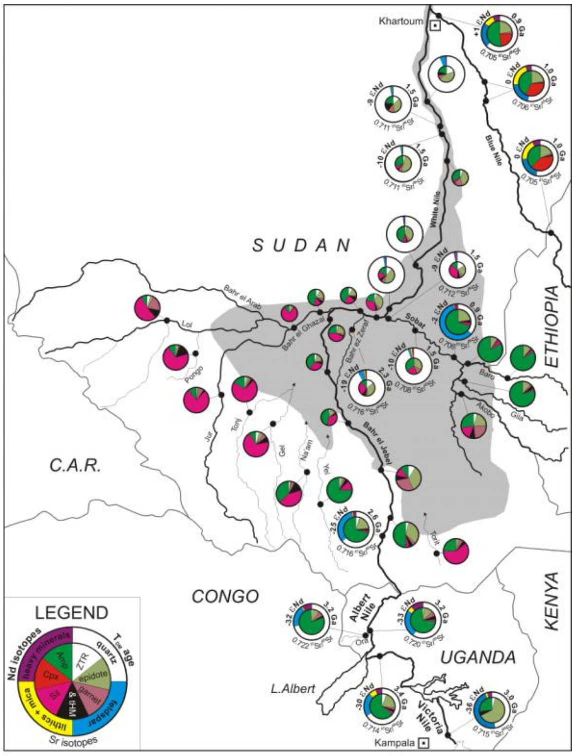

Figure 1. Compositional evolution of White Nile detritus across South Sudan, a scarcely accessible region that suffered decades of civil war. Mineralogical data (Shukri, 1950) integrated by new petrographic, heavy-mineral and geochemical analyses (Padoan et al., 2011) show how sediments derived from Archean gneisses exposed through northern Uganda and from Panafrican basements drained by Ethiopian tributaries of River Sobat become progressively enriched in quartz at the expense of unstable components across the Sudd and Machar Marshes (grey shaded area). Petrographic, mineralogical, and isotopic signatures are gradually homogenized along both the Bahr el Jebel/Bahr ez Zeraf and the Sobat and remain finally unchanged down to Khartoum, which suggests massive sediment dumping in the marshes. This explains why White Nile sediment contribution to the main Nile downstream Khartoum is virtually negligible (Garzanti et al., 2006).

NOTES

Sediment Provenance Studies in the Murzuq Basin of Southern Libya

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The Murzuq Basin of southern Libya is an important petroleum province with proven major petroleum reservoirs in Cambrian, Ordovician and Devonian sandstones. The Paleozoic sedimentary succession of the Murzuq Basin contains substantial thicknesses of clastic, often poorly dated marine and non-marine sediments (the exception is the Carboniferous Mrar Formation). In the absence of biostratigraphic data, the correlation of formations relies solely on lithostratigraphic characteristics. In marine units, macrofaunas are sparse and age dating relies on palynomorphs and other microfossils. Although biostratigraphic studies are possible on fossil material recovered from boreholes, extreme surface weathering ensures that such studies are impossible on material from outcrop. The lack of biostratigraphic data means that other tools have to be sought to test the correlation of units within and between basins.

Here, we present the results of an integrated heavy mineral and mineral chemical study of Precambrian–Mesozoic clastic sediments from the eastern margin of the Murzuq Basin. In addition, first detrital zircon U–Pb ages from Paleozoic and Mesozoic quartz-rich sandstones are discussed. The purpose of this study was to constrain the provenance of sediment and to further assess the value of heavy minerals as a stratigraphic tool.

Conventional heavy mineral analysis was carried out on 64 samples, tourmaline geochemical analysis on 25 samples, garnet geochemical analysis on 4 samples, rutile geochemical analysis on 21 samples, and clinopyroxene geochemical analysis on 2 samples. The study indicates that heavy mineral analysis is a valuable tool for understanding the provenance of Paleozoic and Mesozoic clastic sediments in Libya, despite the intense weathering that surface samples have undergone. Based on heavy mineral ratios and mineral chemical data, there appear to be three key events when the provenance signature changed within the Paleozoic–Mesozoic sedimentary succession at the eastern Murzuq Basin: at the base of the Tanezzuft Formation (early Silurian), at the base of the Tadrart Formation (Devonian), and at the base of the Mrar Formation (Carboniferous), subdividing the succession into four intervals (Hasawnah–Mamuniyat, Tanezzuft–Akakus, Tadrart–Awaynat Wanin, and Mrar–Nubian). Comparing data of the present study with results from the previous work in the Kufra Basin of SE Libya, it is evident that heavy mineral data provide useful evidence for differences in provenance both regionally and stratigraphically in basins of southern Libya.

NOTES

The Evolution of the Niger River: Implications for Sediment Supply to the Equatorial African Margin during the Cretaceous and Cenozoic

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The Niger River is the largest river system in West Africa. Today it drains an area of 1,112,700 km^2, with an annual suspended sediment load of 32 Mt. As such its evolution through time is critically important for understanding sediment supply across NW Africa and especially along the Equatorial African margin. Existing hypotheses include that the Niger once drained through the Volta or that the upper Niger once drained southwest through Sierra Leone. In order to reconstruct the history of the Niger we have examined the geological evidence and run a series of drainage and landscape analyses for the whole Equatorial margin hinterland. In this presentation we present an overview of some of the key methods and results.

Drainage and landscape analyses comprise a variety of geomorphologic techniques for reconstructing the possible evolution of a river basin over geologic time. This methodology has the potential to enable the identification and changes in sediment provenance over time as landscape and river network evolve. These hypotheses are then tested against geological observations.

The methodology includes processing of a high resolution DEM (SRTM3) from which drainage basins and a fully attributed stream network at specified resolutions are generated. Derivatives of the stream network and the DEM are then calculated. These include: river longitudinal profiles; Horton plots; and a set of morphometric parameters. Longitudinal profiles are used to identify knickpoints which can be associated with local uplift and consequent erosion. In addition derivatives of the DEM are used to look at the overall geomorphology of the landscape, especially to detect palaeosurfaces and the effect of differential erosion. These methods include low and high pass filters, hypsometric curves and topographic cross-sections.

The analysis of the Niger River drainage basin, which comprises a very large part of West Africa, shows that it did not always supply sediment to the Niger Delta via the Bida Basin in Nigeria. We find no unequivocal evidence of a SW flowing palaeoNiger during the Cretaceous, nor any evidence of a palaeo-connection with the Volta River. We have concluded that the present day course of the Niger River formed due to relatively recent (Neogene) adjustments within the basin. In our work, we were able to trace back the evolution of the Niger River at least as far back as the Mesozoic.

NOTES

Detrital Zircon ICP-MS Laser Ablation - Supported Provenance Analysis on Alpine Sandstones

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Recent developments in the in-situ laser ablation technology (e.g. Košler et al. 2002; von Quadt et al., 2008) have opened a new chapter in provenance analysis. Because of their robustness and ubiquity in sandstones, the investigation of detrital zircons significantly can contribute to the identification of the sandstone source terranes (Figure 1). In majority, zircons are formed in magmatic rocks. Cathodoluminescence imaging helps in the detection of inherited cores and metamorphic rims. The strong capability of zircons for recycling also ensures that old geodynamic events are still visible through their geochronological and geochemical record.

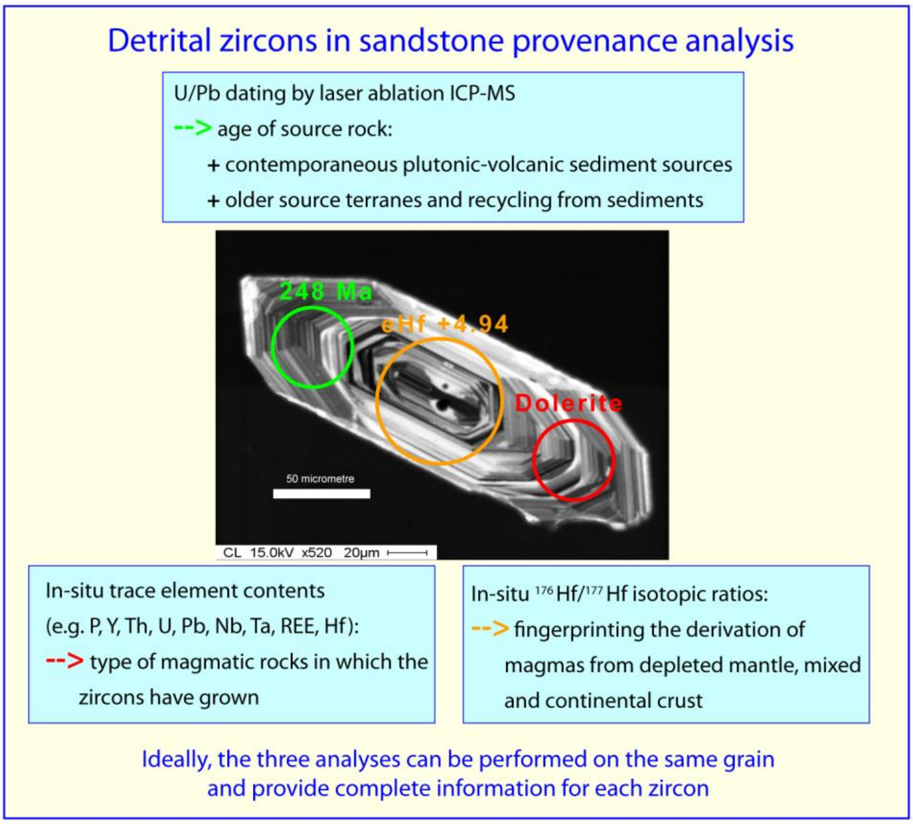

Figure 1: Cathodoluminescence image and provenance information gained from an Early Triassic detrital zircon from a Jurassic sandstone of the Mongol-Okhotsk Belt in Mongolia.

A broad range of the U-Pb zircon age compositions is established for Triassic rifting-related sandstones in different Alpine paleogeographic domains. The Helvetic Mels Fm shows a major M. Cambrian – Devonian population peaking in the Silurian and depicting the pre-Variscan history of the basement. A Permian population (reworked Verrucano?) dominates the Lower Austroalpine Fuorn Fm. The South Alpine Val Sabbia Fm depicts a contemporaneous Middle Triassic mafic magmatic source, which according to Hf-isotope ratios is originating from crustal melts (Beltrán et al. 2011).

Jurassic rifting-related deposits (the Middle Penninic Falknis Breccia, the Austroalpine Saluver Fm and the Helvetic Inferno Series/Scopi Zone) display a major Variscan – late Variscan age composition, and an intensive reworking of Early Paleozoic and

Proterozoic material, in particular in the Gotthard Mesozoic para-autochthonous sedimentary cover (Inferno Series).

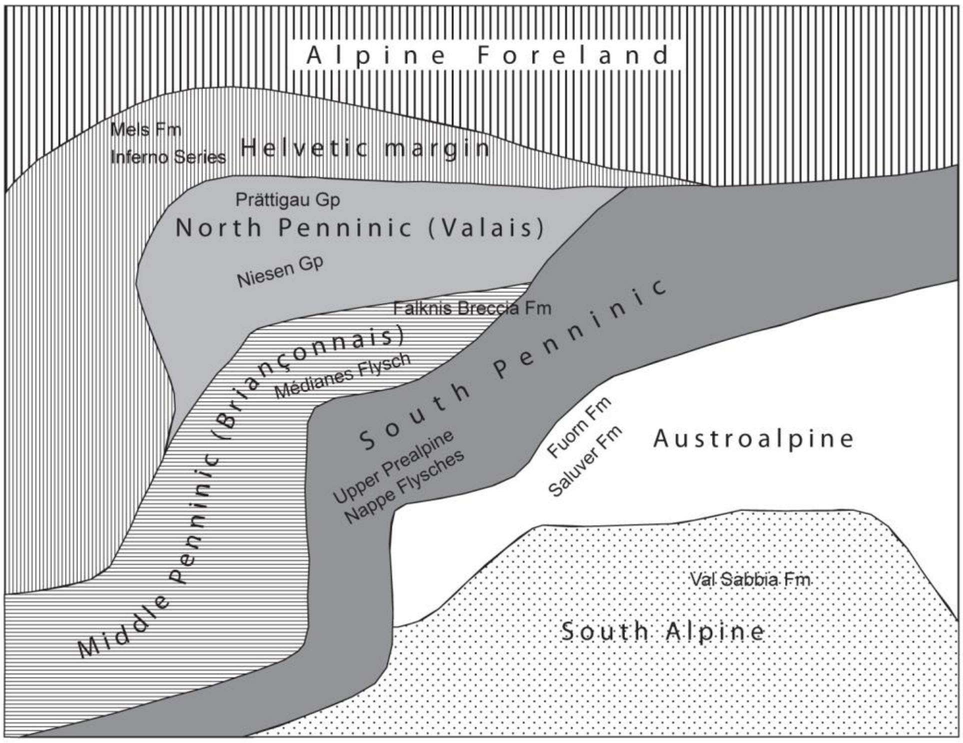

Figure 2: Palaeogeographic location of the investigated sandstone formations in the Alpine Tethys.

The lower part of the North Penninic Prättigau Group (Early Cretaceous – Paleocene) shows a wide but constant U-Pb age compositions of Late Palaeozoic (Variscan) – late Neoproterozoic zircons. The topping Eocene Ruchberg Fm (flysch) is distinctive by a wider and older range of Early Mesozoic – Palaeoproterozoic zircons, revealing the activation of new sediment sources in comparison with the older Bündnerschiefer formations. In the North Penninic Niesen Group, there is not a significant distinction between the Jurassic sedimentary basement (Leyderry conglomerate) and the overlying latest Cretaceous Niesen Flysch, except for the presence of rare Mesozoic zircons in the upper unit.

Prealpine flysch formations (Médianes, Reidigen, Mocausa/Rodomont) show variable populations of Variscan and Pan-African detrital zircons similar to the Schlieren Flysch (Buetler et al. 2011).

NOTES

Provenance of Carboniferous Sedimentary Sequences, Northeastern Siberia

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The study area is located on the northeastern margin of the Siberian Craton (fig. 1a), where the Early Carboniferous was marked by an extensive marine transgression. Carbonate sedimentation was widely distributed during this time with accumulation of a 200-metre thick complex of Tournaisian limestones. Visean deposits are found only in the northeastern part of the study area, where they unconformably overlie Tournaisian limestones. Lower Visean Krestiakh and Atyrdakh formations are composed of sandy turbidites (up to 200 m thick) and cherts (up to 50 m thick) respectively (fig 1b).

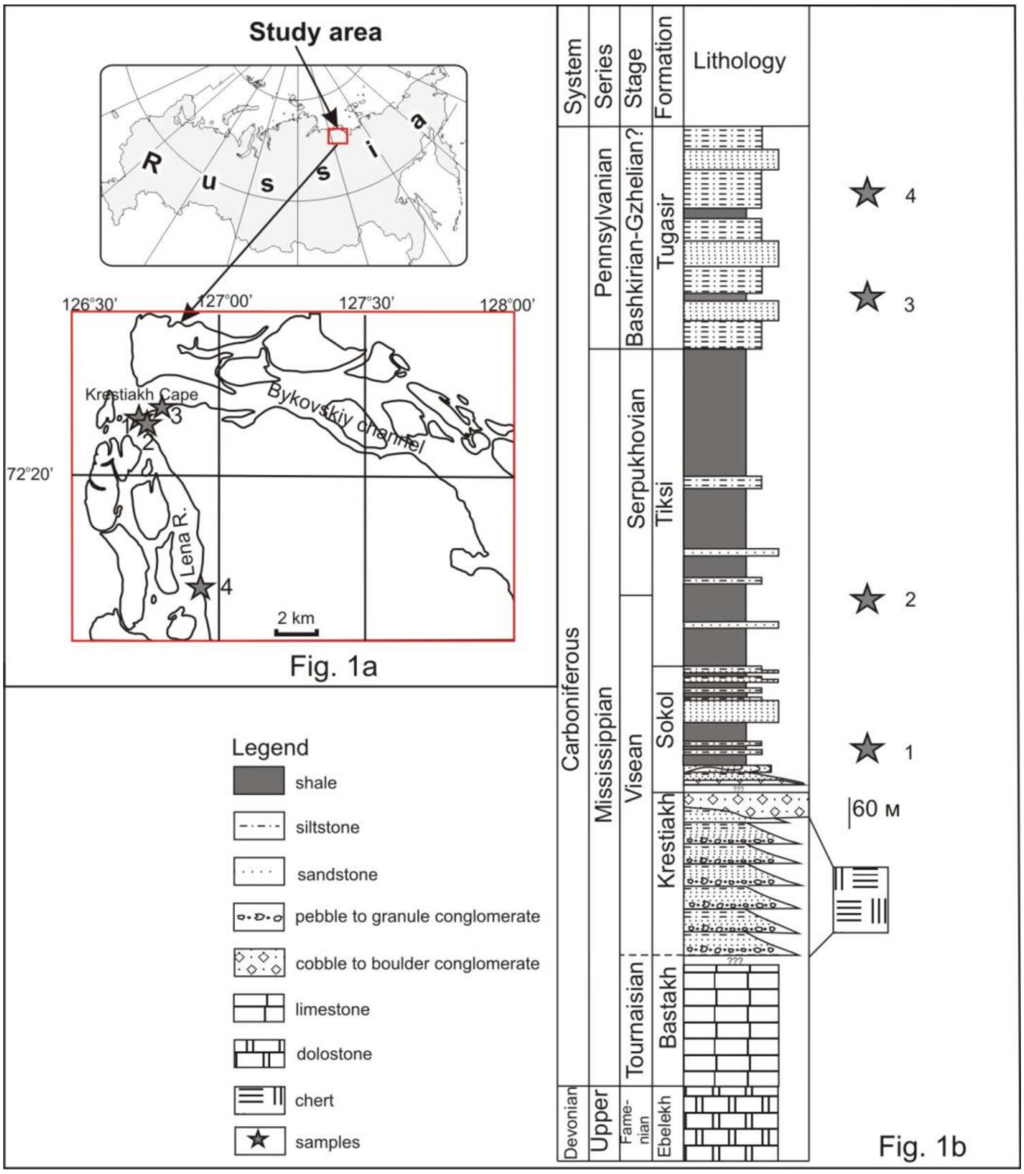

Fig.1. Location of study area and levels of samples: 1a – Study area and location of studied sections and U-Pb dating samples; 1b – Simplified stratigraphic column of study area

The Upper Visean Sokol Formation comprises up to 150m of siltstones with interbedded sandstones. The Serpukhovian is characterized by up to 1 km of shales and siltstones with occasional thin sandstone beds. The Late Carboniferous deposits are up to 300m thick and predominantly comprise siltstones and sandstones.

We determined U-Pb ages for detrital zircons from 4 samples of Carboniferous sandstones from the northeastern Siberian Craton (fig.1b). All samples have similar age populations, although there are some variations in abundance of each population. Zircons of Palaeoproterozic-Archean, Neoproterozoic and Devonian-Early Carboniferous ages are most widespread, whilst Cambro-Ordovician ages constitute an insignificant portion. The analyzed samples are dominated by Proterozoic-Archean zircons. These zircon populations could have been derived from weathering of nearby basement rocks of the Siberian Craton and/or reworking of Meso-Neoproterozoic clastics, widely distributed in the northern Siberian Craton. The abundance of Neoproterozoic zircons in the studied samples suggests additional provenance areas, as the basement of the Siberian Craton does not contain Meso-Neoproterozoic magmatic rocks. Similarly, the Siberian Craton provenance must be rejected as a possible source area for Palaeozoic zircons in the studied samples, as Palaeozoic magmatic rocks are also absent. The only known potential provenance areas with magmatic rocks comparable in age with the Palaeozoic zircon populations are the Altay-Sayan and/or Taimyr Fold-Thrust belts. The broad spectrum of age ranges within individual samples indicates that clastic detritus was derived from multiple sources, including crystalline basement of the Siberian Craton and reworking of overlying Meso-Neoproterozoic clastic sedimentary cover, along with the Taimyr and/or Altay-Sayan fold belts.

Acknowledgments.
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NOTES

Trace Element Geochemistry as a Provenance Indicator of Ahwaz Sandstone Member of Asmari Formation, Zagros, Iran

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The Zagros fold–thrust belt lies on the northeastern margin of the Arabian plate (Figure 1). The geological evidence suggests that the Zagros region was part of a passive continental margin, which subsequently underwent rifting during the Permo-Triassic and collision during the Late Tertiary (Berberian and King, 1981; Beydoun *et al.*, 1992). The Asmari Formation (one of the best-known carbonate reservoirs in the world) was deposited in the Oligocene- Miocene shallow marine environment of the Zagros foreland basin (Alavi, 2004). Lithologically, the Asmari Formation consists of limestones, dolomitic limestones, and argillaceous limestones (Motiei, 1993). In the south of Dezful embayment, its lithology changes into a mixed siliciclastic-carbonate deposit consisting of carbonate beds with several intervals of sandstone, sandy limestone and shale. This facies provides the Ahwaz Sandstone Member in some oil fields such as Ahwaz, Marun and Mansuri (Motiei, 1993).

The Ahwaz Sandstones are shoreface deposits. Alsharhan and Nairn (1997) considered the Ahwaz Sandstone to correlate with Ghar Formation in Kuwait (Figure 2) whose clastic input is believed to have been derived from the pre-rift uplift of the Red Sea to the west (Alsharhan and Nairn, 1997). Former studies based on petrographic and major element geochemistry analyses showed that the Ahwaz Sandstones have petrographic (texture, framework mineralogy, quartz types and inclusions in quartz) and geochemical characteristics that suggest quartzose recycled sedimentary rocks as the main source rocks, in addition to high-grade metamorphic and plutonic igneous rocks as minor parent rocks.

Also, Aljubouri et al, (2010) suggested that the Ghar Formation sandstones plotted in the continental block and partly in the recycled orogen fields of Dickinson (1985) consistent with derivation from the Arabian Shield (Buday, 1980; Drysdall *et al*., 1984).

In this study we analyzed geochemistry (trace elements) (table1) of thirteen sandstone samples of Ahwaz sandstone member in Ahwaz oil field.
Immobile trace elements such as Y, Sc, Th, Zr, Hf, Co and U are believed to be useful indicators of geological processes, provenance and tectonic setting (Bhatia and Crook, 1986; McLennan et al., 1993). In our study, the La/Sc, Th/Sc, Th/Co and Th/Cr values in sandstones are more similar to values for sediments derived from felsic source rocks, suggesting that these sandstones were probably derived from a felsic terane.

Th/U in sedimentary rocks is of interest, as weathering and recycling typically result in loss of U, leading to elevation in the Th/U ratio. In sedimentary rocks, Th/U valuees higher than 4 may indicate intense weathering in source areas or sediment recycling. The Th/U ratio in most upper crustal rocks is typically between 3.5 and 4(McLennan et al., 1993). This ratio in sandstone samples of Ahwaz sandstone member range from 5.7 to 9.3, with an average of 7.28, indicating the derivation of these sediments from recycling of the crust.

Bhatia and Crook(1986) believed Th-Sc-Zr/10 and Th-Co-Zr/10 to be the most useful trace element tectonic discrimination plots. Data from the Ahwaz sandstones fall within passive continental margin fields (Figure 3), confirming the conclusion from the major element analysis (Jafarzadeh and Hosseini-Barzi, 2008). Conclusively, the obtained geochemical data and former petrographical and geochemical data are consistent with a long distance transport over the Arabian shield, which supplied these sands to their depositional basin along the passive marginal coast of the Oligocene-Miocene Zagros foreland basin.

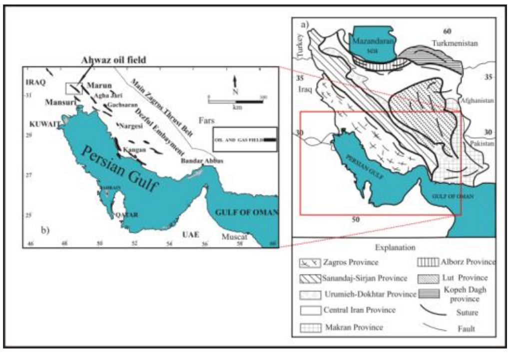

Figure 1. a: General map of Iran showing all the eight geologic provinces. The study area is located in the Zagros province (modifi ed after Vaziri-Moghaddam *et al.*, 2006); b: location of Ahwaz oil fi eld in the Dezful Embayment of Zagros basin (modifi ed after Insalaco *et al.*, 2006);

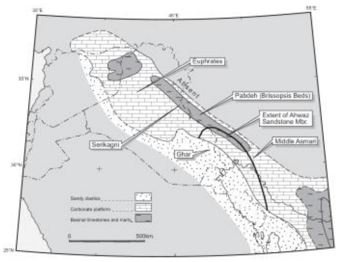

Figure2: Early Miocene (Aquitanian) palaeogeography of the studied area (modified after Goff et al., 1995).

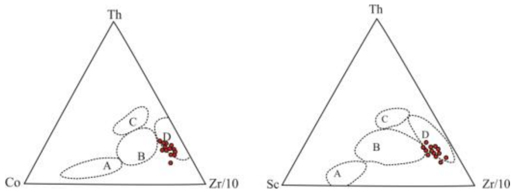

Figure 3: Ternary diagrams of Bhatia and Crook (1986). The sandstones mainly plot within the passive continental margin field.

Sample no.	2693	8929	8951	2731	9073	9510	2644	9424	8930	2861	2701	9081	2612	Mean
Ba	190	100	218	322	211	186	235	328	268	211	177	237	233	224.3
Zr	425	398	411	582	386	432	343	370	387	401	308	421	335	399.9
Co	3	5	4	9	3	4	5.2	6.8	4.6	5.1	4	5	7	5.1
Cr	21	91	49	51	34	30	57	87	61	35	63	85	15	52.2
La	25.3	30.1	26.7	25.2	21.5	31.5	26.7	27.8	22.5	25.6	27.9	28.5	23.4	26.4
Y	13	12	13	20	12	15	13	15	14	18	15	14	13	14.4
Th	11.3	12.2	10.6	10.3	10.9	11.9	13.2	11.9	10.5	10.2	11.8	11.1	12.7	11.4
Sr	310	95	132	185	325	132	254	356	98	125	167	303	98	198.5
U	1.5	1.3	1.7	1.5	1.2	1.9	1.5	1.5	1.5	2.1	1.3	1.9	2.2	1.6
Sc	8	11	10	9	8	8	10	9	8	11	9	7	9	9.0
Ni	31	25	45	41	32	40	35	37	39	55	29	37	34	36.9
Pb	31	15	8	9	26	34	9	18	12	12	15	38	18	18.8
V	24	35	31	43	35	23	27	28	20	29	27	22	27	28.5
Zn	29	38	43	45	33	41	32	29	28	41	37	41	43	36.9
Hf	4.9	7.1	10.1	4.5	9.1	6.5	8.3	10.4	8.6	8.6	9.5	9.8	7.8	8.1
Th/Sc	1.4	1.1	1.1	1.1	1.4	1.5	1.3	1.3	1.3	0.9	1.3	1.6	1.4	1.3
La/Sc	3.2	2.7	2.7	2.8	2.7	3.9	2.7	3.1	2.8	2.3	3.1	4.1	2.6	3.0
Th/Co	3.8	2.4	2.7	1.1	3.6	3.0	2.5	1.8	2.3	2.0	3.0	2.2	1.8	2.5
Th/Cr	0.5	0.1	0.2	0.2	0.3	0.4	0.2	0.1	0.2	0.3	0.2	0.1	0.8	0.3

Table 1: Trace elements values (ppm) of the selected sandstone samples of the Ahwaz sandstone member, Asmari Formation, Zagros, Iran.

NOTES

Poster Presentation Abstracts

(in Alphabetical order)

Diverse and Complementary Geochronometers Applied to the Study of the Yarlung Tsangpo–Brahmaputra Detrital System: Determining the Sediment Routing History in the Bengal Basin and Testing Erosion-Tectonic Feedback Models in the Easternmost Himalaya

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While geochronology of detrital minerals from sedimentary basins is nowadays routinely applied to constrain source areas and basin evolution, the importance of a multitechnique approach is not always recognized. Radiometric dating methods sensitive to different temperature ranges can be successfully applied to detrital mineral grains from the same sample in order to obtain a robust dataset capable of providing information on the various crystallization and cooling events that affected the source terrains which contributed detritus to the basin of study. Source and sink can then be tied, and palaeodrainage and palaeogeographies then interpreted.

Such an approach is used to investigate the evolution of the Yarlungo Tsangpo-Brahmaputra fluvial drainage during Neogene times with the aim to better constrain the depositional history of the Bengal Basin and to shed light on crustal deformation processes and erosion-tectonic interactions in the eastern Himalaya. Here, the unusual fluvial drainage configuration of the eastern syntaxial region (Namche Barwa, Fig.1) has been interpreted either as distorted drainage resulting from crustal shortening (due to India-Asia convergence) and lateral extrusion of crustal material, or as the result of river capture (of the Yarlung Tsangpo by the Brahmaputra river) tectonically-induced by surface uplift.

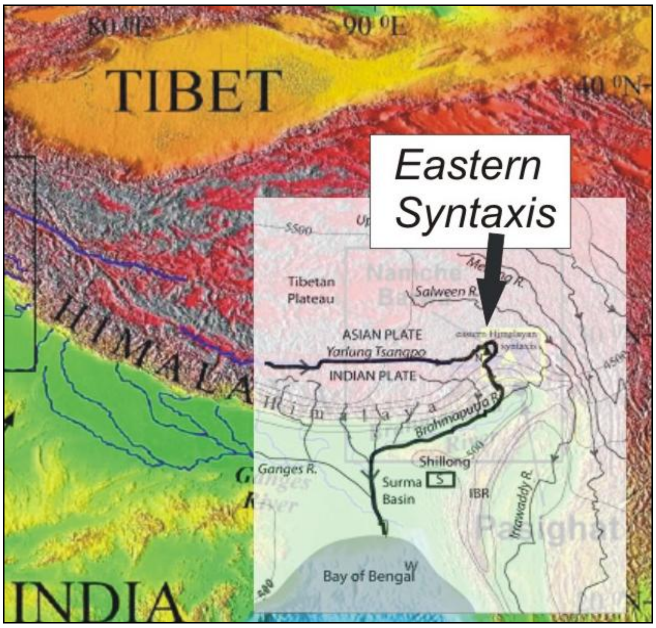

FIG. 1. Major fluvial drainage systems of the Eastern Himalayan-Tibet region (overlay) superimposed on a digital elevation map (adapted from Clark et al., Tectonics, 2004 and Stewart et al., Geology, 2008).
The Yarlung Tsangpo-Brahmaputra River, central to the proposed research, is traced in thicker outline. Black triangle labelled "N" = Namche Barwa of the Eastern Himalayan Syntaxis; rectangle labelled "S" is Surma Basin; Shillong = Shillong Plateau; IBR = Indo-Burman Ranges.

In addition, rapid fluvial incision by the Yarlung Tsangpo in the Namche Barwa area due to the proposed river capture potentially resulted in sufficient erosion by focused weakening of the crust, that deep seated ductile rocks were induced to flow upwards and be rapidly exhumed (erosion-tectonic coupling model). Detritus from the rapidly exhuming region now dominates the Brahmaputra sediment load downstream of the syntaxis, a situation that is thought to have persisted for at least 6 Ma. Hence, assessing the occurrence and timing of the river capture is crucial to better understand the depositional history of the basin and the effect of capture and increased sediment load to the architecture of the delta.

The first arrival of detritus carried by the Yarlung Tsangpo (draining the Jurassic-Paleogene Trans-Himalayan arc of the Asian plate) in the Neogene deposits of the palaeo-Brahmaputra river in Bangladesh (Surma Basin) should constrain the timing of the proposed river capture, prior to which the Brahmaputra would have drained the southern Himalayan slopes composed only of Precambrian-Palaeozoic Indian crust. As to the erosion tectonic coupling hypothesis, this would be verified whether detritus from the rapidly exhuming eastern syntaxis (very young, i.e.<10 Ma, and rapidly exhumed mineral grains) was deposited in the palaeo-Brahmaputra repository shortly after the river capture event.

A further complication to the overall evolution of the Bengal Basin is represented by the not yet constrained timing of the uplift of the Shillong Plateau, the only raised topography in the foreland of the Himalayas, north of the Surma Basin. Indeed, the uplift of the plateau likely produced changes in the sediment routing and depositional sites, while the erosion of its Indian basement and Tertiary Himalayan cover potentially provided a major source of detritus to the palaeo-Brahmaputra deposits in the Surma Basin.

To address the river capture and the erosion-tectonic coupling hypoteses in light of a better understanding of the depositional history of the Bengal Basin, U-Pb LA-MC-ICP-MS dating and microtextural analysis of detrital zircon grains are complemented by zircon fission track dating, $^{40}Ar/^{39}Ar$ dating of detrital white mica and U-Pb dating of detrital rutile in this ongoing study.

The Diagenetic Destruction of Potentially High-Quality Plutoniclastic Reservoirs: The Diligencia and Maniobra Formations, Diligencia Basin, Southern California, USA

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Plutoniclastic deposits are generated in diverse tectonic settings related to erosion of felsic crustal terranes, such as basement uplifts associated with rift basins and transcurrent faults (i.e., Dickinson, 1985). These deposits generally form thick strata of continental alluvial/fluvial or marine origin. Plutoniclastic sands have framework compositions consisting dominantly of monomineralic quartz and feldspars, and negligible aphanitic lithic fragments. This monomineralic composition is due to the coarse crystal size of plutonic sources (Pettijohn et al., 1972). Quartz and feldspar provide consistent framework rigidity, which helps maintain intergranular space during burial diagenesis (Bloch, 1991). In addition, secondary porosity generated by feldspar dissolution during diagenesis may enhance reservoir quality (Schmidt and McDonald, 1979). All these features make plutoniclastic sandstone attractive as potential reservoirs. Good examples of high-quality quartzofeldspathic reservoirs have been widely documented (e.g., Frio Formation in the Texas Gulf Coast; Brent Formation in the North Sea).

The Diligencia Formation of southern California was deposited in the Diligencia basin, which formed as an extensional half-graben during latest Oligocene - Early Miocene crustal extension; this continental half graben was superposed on an Eocene fault-controlled submarine canyon in which the Maniobra Formation was deposited (Spittler and Arthur, 1982; Advocate et al., 1988; Law et al., 2001; Ingersoll, 2009). The combined sedimentary succession, mainly consisting of arkosic sediments (mean of $Q_{31}F_{65}R_{4}$), is 2500 to 3000 m thick.

The original petrophysical character of the sandstone framework would predict a high-quality reservoir with preserved primary porosity or at least important intergranular volume (I.V.). However, inspection of sandstone samples indicates that diagenesis was intense, as several diagenetic processes drastically reduced the reservoir quality. Dominant diagenetic processes were compaction and cementation. Mechanical compaction, expressed as intense deformation of ductile grains and chemical compaction acting as pressure solution reduced the I.V. of sandstones at the bases of the Maniobra and Diligencia formations to low levels (10-20%). In the upper parts of both units, early diagenetic cements partially inhibited compaction, maintaining I.V. values close to 35%.

Several mineral phases constitute cements responsible for primary porosity occlusion. Many of these phases also replaced framework components and early cements. The more important cements are: (1) Quartz and k-feldspar, which appear mainly as grain overgrowths, although quartz mosaics have been observed at the base of the Maniobra Formation; (2) carbonates, such as siderite, dolomite and calcite in diverse textures and with significant occluding character; (3) phyllosilicates, such as kaolinite that developed mainly in Diligencia sandstones as early pore fillings, and locally as illite coats around detrital grains; and (4) other mineral phases, such as Fe-oxides and fluorite, which occur exclusively at the base of the Maniobra Formation, exhibiting aggressive textures against framework grains and older cements.

The chronology of diagenetic processes includes marine early diagenesis (eodiagenesis) for Maniobra sandstones, characterized by K-feldspar, siderite and dolomite cements. A continental early diagenesis is identified in Diligencia sandstones, enhanced by illite, kaolinite and Fe-oxide cements. Mesodiagenetic processes are similar in both formations. In addition, hydrothermal phases (fluorite and quartz mosaics) are identified at the base of the Maniobra Formation.

The geotectonic scenario in which diagenesis occurred explains these postdepositional processes. During latest Oligocene - Early Miocene crustal extension, the Diligencia basin developed in an area of high heat flow, as expressed in the eruption of interbedded basaltic-andesitic lavas (Spittler and Arthur, 1982; Law et al., 2001; Ingersoll et al., in prep.). High heat flow favors compaction and cementation, accelerating these diagenetic processes during a relative short interval of time. Hydrothermal fluxes produced mineral phases that contributed to the destruction of a potentially good reservoir by intense diagenesis.

U-Pb Dating of Zircons from SW Borneo: Insights into Provenance from Metamorphic Basement Rocks and River Sediments

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New dating of zircons constrains the provenance of meta-sedimentary basement rocks from SW Borneo. Dating provides zircon age fingerprints for rocks from the Schwaner Mountains which have been an important sediment source for many of the hydrocarbon-bearing basins during the Cenozoic.

SW Borneo is the eastern-most part of Sundaland, the Mesozoic continental core of SE Asia formed by the progressive accretion of blocks rifted from Gondwana. The 'Pinoh Group' meta-sedimentary rocks of the Schwaner Mountains are the basement of this part of Sundaland and have been regionally metamorphosed to greenschist facies. Contact metamorphism occurred during the intrusion of acid to intermediate plutonic rocks between 130 and 76Ma.

Metamorphic rocks of SW Borneo include low grade phylites, schists and hornfels. Occasional mafic gneisses and psammites are also seen. Zircons were picked from samples of hornfels and garnet-mica schists. Zircons were taken from a 250-63µm fraction yet are typically less than 100µm in diameter. The yield is low in all samples and around 2-3kg of each was processed in order to acquire sufficient grains for analysis. Cathodoluminescence imagery of zircon grains reveals rounded cores. Metamorphic resorbtion is observed in some grains. Growth patterns include concentric-, convolute-, patchy- and sector- zoning. Complex zircon textures reflect the detrital nature of source-rocks as well as the effect of metamorphic conditions. SHRIMP ages from ongoing work will be discussed.

Rivers draining the Schwaner Mountains were also sampled. Zircons from these samples are typically euhedral or subhedral although some grains are well rounded. Internal textures resemble those typical of metamorphic rocks. Euhedral grains with simple and concentric zones thought to be derived from igneous rocks are also found. LA-ICPMS age data will be discussed and compared to ages obtained from the metamorphic samples.

These data give invaluable information about the nature of the material that is being eroded from the Schwaner Mountains in the present. Furthermore, the zircons dated reflect multiple phases of recycling and provide information on the protoliths of metasedimentary rocks from SW Borneo. These data therefore provide information not only useful to modern sedimentary basin studies, but also shed light on the as-yet unresolved tectonic history and provenance of SW Borneo itself.

Timing of Early Andean Uplift Inferred From a Detailed Provenance Analysis: A Methodical Approach That Can Be Used To Emphasise the Quality of Hydrocarbon Reservoirs in the Levantine Basin

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The tectonic evolution of the western margin of South America is controlled by the continuous subduction of the Nazca plate. The Central Andes, which reach altitudes of 6500 m, are characterised by continental crust up to 70 km thick. Two major pulses of surface uplift are recognised: a first episode during Oligocene to Early Miocene (Isacks, 1988) and a second one during Late Miocene (Lamb and Hoke, 1997). Crustal thickening started in mid-Eocene time and is accepted to be responsible for the Oligocene to Early Miocene uplift. However, the timing of this early uplift phase is not well constrained.

Since the early Paleozoic the Central Andes have been a locus for synorogenic sedimentary basins development. The focus of this study is on Cenozoic continental siliciclastic formations, named the Moquegua Group, deposited between the Western Cordillera and the Coastal Cordillera in southern Peru. Techniques employed include geochemistry analysis of single detrital heavy mineral grains (amphibole and Fe-Ti oxide), U-Pb dating of detrital zircon using LA-SF-ICP-MS as well as zircon fission-track thermochronology. The data are used to develop a sediment provenance model from which the timing of the early episode of Andean uplift can be better constrained.

The combination of field observations, stratigraphic and petrographic descriptions taken from the literature, and our geochemical, geochronological and thermochronological data indicates uplift induced a significant change in provenance at around 35 to 30 Ma. This change in provenance is related to major reorganisation of the drainage sytem due to the formation of relief. This reorganisation directly affects the nature of the deposited sediments in a basin and thus the quality of any potential hydrocarbon reservoirs.

This study demonstrates the value of detailed provenance analysis based on a variety of techniques for reconstruction of regional tectonic history, drainage systems evolution and the link to hydrocarbon reservoir quality.

On the eastern part of the Levantine Basin, offshore Lebanon, a detailed provenance based study is planned which will allow us to better constrain the timing of uplift of the Mount Lebanon and Anti-Lebanon. The provenance model will be used to describe the evolution of the regional drainage systems and thus, estimate the quality of the potential hydrocarbon reservoirs offshore Lebanon.

Determining the Palaeodrainage History of the Nile River: Investigating Rift Tectonics and Land-Ocean-Atmosphere Interactions

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It has been proposed that Nile river hydrology is directly forced by events ranging from solid earth tectonics to, large-scale oceanographic and climatic changes (Hammann et al. 2009); that the river has influenced ocean anoxia and sapropel development (Scrivner et al. 2004) as well as hominid dispersal and ancient civilizations (Osborne et al. 2008); and that its palaeodrainage has the potential to record plume and rift related tectonics (Pik et al. 2008). Therefore, the palaeo-Nile cone sediments have the capacity to provide a unique archive to research these interactions.

We propose to conduct a provenance study of the well-dated Nile cone sediments to document the time of transition from locally sourced detritus to initiation of an extensive Nile drainage catchment. This study will also address temporal variations in palaeodischarge. We will work on BP Egypt's Oligocene-Recent cores from the East and West Nile deltas, integrating results with subsurface seismic and well data to provide information on sediment nature, regional flux and dispersal pattern. Robust provenance interpretations are best derived when a multi-technique approach is used. Therefore, we will use techniques which discriminate between detritus from Red Sea Hills, the Blue Nile / Atbara rivers which drain the Ethiopian Continental Flood Basalts, the White Nile river which drains the ancient African craton, and aeolian dust. These techniques will include determination of bulk rock (mudstone) Rb-Sr and Sm-Nd isotopic characteristics, sandstone petrography and heavy mineral analysis, clay mineralogy and composition studies, chemical composition of minerals such as ilmenite, clinopyroxene and Cr-spinel, and U-Pb detrital zircon and rutile dating.

A better understanding of the Nile's palaeodrainage will help to determine the timing of rift tectonics since the associated uplift is proposed to have resulted in initiation of the Nile drainage. It will also contribute to understanding regional land-ocean-atmosphere interactions which its discharge records. The documentation of spatial and temporal variability in core samples studied will enable a greater understanding of correlative changes in porosity, permeability and sediment dispersal patterns which have implications for well correlation and the distribution of reservoir systems. Furthermore, the study will establish a better insight into controls on the development of sapropels, which are thought in the Mediterranean to be linked to Nile discharge variations and which are key oil source rocks not only in the Nile cone hydrocarbon system but also worldwide.

Pb Isotope Compositions of Detrital K-Feldspar Can Quantify Recycling of Detrital Zircon: Examples from Permian Fluvial Sandstones in Antarctica

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Zircon provides an array of precise and accurate information on the age and crustal evolution history of igneous and metamorphic rocks. Geochronology and geochemistry on detrital zircon is thus a powerful tool for characterising source regions and is routinely applied in sedimentary provenance studies. Nevertheless, zircon can bias interpretations of sources because it is unevenly distributed in different lithologies and its robust nature means it may survive multiple cycles of mountain building, erosion, transportation by rivers or ice, and incorporation into new sedimentary rocks. K-feldspar is susceptible to mechanical and chemical breakdown during a single sedimentary cycle of erosion, transport, deposition and diagenesis. K-feldspar provenance studies are, therefore, beneficial because they may allow the recognition of first-cycle detritus. Zircon records much information on its ultimate source region, hence, it is critical to distinguish first-cycle from poly-cyclic grains, such that this information can be correctly interpreted. This study, which combines U-Pb geochronology of detrital zircons and Pb isotopic analysis of detrital K-feldspars from the same samples, provides a mechanism for achieving this overarching goal.

Upper Permian fluvial sandstones of the Beacon Supergroup, and other correlative rocks from Antarctica, provide a means of testing if recycled zircons can be identified through the integrated approach advocated above. The sandstones were deposited within a fluvial braidplain, part of retro-arc foreland basin, and is inferred from field and petrological evidence to have two primary upland source regions. The first source region lay within West Antarctica and comprises predominantly Ordovician and younger rocks with a Permian volcanic arc which developed along the Palaeopacific margin. The second source region is within cratonic East Antarctica and comprises mostly Cambrian and older rocks. In addition to the age differences, the two source regions have markedly different K-feldspar Pb isotope compositions.

Three Permian sandstone samples were selected for detrital K-feldspar analysis. K-feldspars in sandstone from the Theron Mountains in Coats Land, which was deposited closest to the volcanic arc, have Pb isotopic compositions which show that they were uniquely derived from the West Antarctica source region. In contrast, K-feldspars in sandstone from Kirwanweggan in Dronning Maud Land, which was deposited farthest from the volcanic arc, have Pb isotopic compositions consistent with derivation from the East Antarctica source region. The third sandstone sample, from Heimefrontfjella in Dronning Maud Land, has feldspar compositions which suggest derivation from both West and East Antarctic source regions. Zircons from the Kirwanveggan sandstone (Veevers & Saeed, 2007) are all Cambrian or older, and are consistent with the feldspar Pb data and suggest that very little of the zircon in these rocks has been recycled through multiple sedimentary cycles. In contrast, approximately half of the zircons from the Theron Mountains are Cambrian or older and so are not compatible with derivation from West Antarctica, as is indicated from the detrital K-feldspar Pb isotopic compositions. We infer that these older zircons are recycled from (meta)sedimentary rocks within the West Antarctica source region.

A Heavy Mineral-Based Provenance Study of the Permian Takrouna Formation, Antarctica

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The Takrouna Formation represents the Permian continental Gondwana succession that crops out in the northern part of North Victoria Land. This up to 300 m thick siliciclastic sequence is thought to belong to a system of basins that occupied the south-eastern margin of Gondwana, draining towards Tasmania. The nature of the basin is unclear, as well as the relationship to similar, contemporaneous deposits in South Victoria Land (East Antarctica). The preliminary results are presented here approach the further description of the type of basin, combining a detailed heavy mineral analysis and a lithostratigraphic correlation of sections in an outcrop belt with an E-W extension of 125 km and an N-S length of more than 160 km. Several vertical and lateral sections of the Takrouna Formation in six mountain ranges were logged in order to provide a consistent sedimentological model based on facies associations, architectural elements and stacking patterns of the braided stream deposits.

The Takrouna Formation overlies a unit of up to 60 m thick diamictites or unconformably overlies pre-Devonian basement, which consists of three major fault-bounded terranes. A clear proximal-distal trend is visible in the sedimentology, showing mainly coarse-grained facies in the eastern part of the study area and fine-grained deposits in the West. Paleocurrent directions point mainly towards the Northwest. All sections are characterised by fining-upward of grain-sizes from pebbly conglomeratic facies at the base to carbonaceous medium-grained sand- and siltstone-dominated units at the top. A coarse-grained, pebbly sandstone facies that was recognized in all sections allows for a lithostratigraphic correlation of most sections, together with distinct architectural facies elements.

The studies sediments can be classified as dominantly litharenites. The light mineral petrography does not provide distinct patterns of vertical or lateral variation within the sections, due to the intense alteration of the lithic rock fragments. However, the heavy mineral assemblages are very distinct, with a general predominance of tourmaline, zircon and garnet. Three different groups of heavy mineral assemblages can be allocated to the different mountain ranges. The western part of the study area is characterized by very high amounts of tourmaline, derived from both Li-poor granitoid or pegmatite sources as well as from metapelitic and metapsammitic rocks. Garnet is abundant only in the uppermost part of all sections. In contrast, the easternmost section shows a distinct predominance of garnet over the entire vertical succession. The origin of the garnet is still uncertain. They have mostly low Mg and variable Ca and Mn contents, which indicates medium to higher grade metasediments but also possibly granitic origin. Only sections that are located close to the border of the Wilson and the Bowers Terrane, in the center of the study area, contain epidote in their heavy mineral spectrum. All observations indicate a strong influence of local sources during the onset of the fluvial sedimentation that possibly took place in small sub-basins. The increase in abundance of garnet, with a so far uncertain source, as well as the correlation of lithofacies across the Takrouna basin, might indicate a major fluvial trunk system that drained the continental margin of Gondwana. Further mineralogical investigations and zircon age dating will help to detect source areas and refine the model of the Permian basin that covered the eastern margin of Gondwana.

Determining Forties Sandstone Member Provenance: Using Heavy Mineral Analysis and the Implications for Exploration and Production in the UK Central Graben

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The deep-water sandstones of the Central North Sea are known to derive from Northern Scotland and the Shetlands with two discrete source areas; an axial system from the Northwest (Moray Firth and the Shetland Islands) and a lateral system from the west (Grampian Highlands). Previous work on the Lista and Sele Formations has suggested that garnet assemblage analysis can differentiate between these two source areas. This is of particular importance because proximity to the shelf can determine reservoir quality (grain size, porosity, permeability). Previous work suggests that the lateral fan is an important component in the Sele Formation. It is now possible to test this work using heavy mineral analysis in the Forties Sandstone Member Cycles (T65, T70 and T75).

The analysis has been based on the percentage composition of garnets collected within 16 samples in 4 wells. The results have been matched with known standards from different terrains of Scotland's hinterland and basinal turbidite systems.

It can be shown that the majority of samples have a garnet assemblage associated with an axial turbidite system, showing the typical high-Mg, high-Fe+Mn garnet assemblage associated with the Lewisian/South Harris/Moine terrains. A single sample collected from the well 22/30A-5 shows a different provenance signature, typical of a lateral turbidite system sourced from the Grampian Highlands. However, core analysis suggests that the sample is potentially reworked (by salt diapirism) as is possibly associated with older Lista or Maureen Formation material. This study demonstrates that the Forties Sandstone Member is dominated by axially sourced sandstones with laterally sourced components making up a minor proportion of the Central Graben deepwater deposits. Further work is needed to understand the importance of these findings but there is a significant potential impact on our understanding of reservoir quality distribution.

Sm-Nd Study of the Permian to Paleogene Strata, the Northeast Part of Siberian Craton: Provenance Interpretation

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The Northeast part of the Siberian Craton contains a thick Permian – Paleogene clastic succession in which Permian – Jurassic rocks were deposited on the craton's margin, Cretaceous rocks were deposited in the Priverkhoyansk foreland basin, whereas Paleogene rocks fill in rift basins. Here we present results of Sm-Nd study to identify possible provenance of clastic rocks. For provenance analysis we used variations in $e_{Nd}(t)$ values where epsilon Nd value is referred to the time of sedimentation. Data on Th/Sc ratio values are incorporated as well.

Permian sediments have $e_{Nd}(t)$ values varying from -4 to -10 that we interpret to reflect mixed cratonic and juvenile sources. More juvenile source is recorded in Triassic sandstones by increasing $e_{Nd}(t)$ values up to 0. The Th/Sc ratio values from Triassic sediments are typical for mafic rocks pointing to their wide distribution in the provenance. Significant variation of $e_{Nd}(t)$ values in Jurassic sediments point to existence of two source areas with predominance of cratonic and juvenile rocks correspondently. Cretaceous and Paleogene sediments show significant decreasing in $e_{Nd}(t)$ values indicating increasing importance of the cratonic source. Data on Th/Sc ratio values correspond with this conclusion.

According to the Nd isotopic and Th/Sc data, in Permian to Paleogene there were several types of sources for the studied clastic succession such as cratonic and juvenile ones. The cratonic sources were the Siberian craton basement uplifts including, probably, the Anabar and Aldan shields. Mafic rocks with juvenile component are likely related to Norilsk traps and their correlatives located far to the east from their modern distribution.

Provenance Study in the Tertiary Sedimentary Rocks from the Rakhine Accretionary Wedge, Burma (Myanmar)

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Since the discovery of the giant Shwe gas field offshore Myanmar, the Bay of Bengal has become the focus of one of the last unexplored deep water basins in the world. Due to the relative inaccessibility of the Arakan (Rakhine) area (Fig. 1) onshore and its offshore islands, we are faced with a lack of any modern integrated study, and hence of the understanding of the Total Petroleum System. One of the main problems is the origin of the sands, e.g., do they all belong to the Bengal fan and are as such derived from the Himalayas, or can local fans be expected, sourced from the onshore Rakhine area and possibly as far as from the Myanmar Central Basin (MCB).

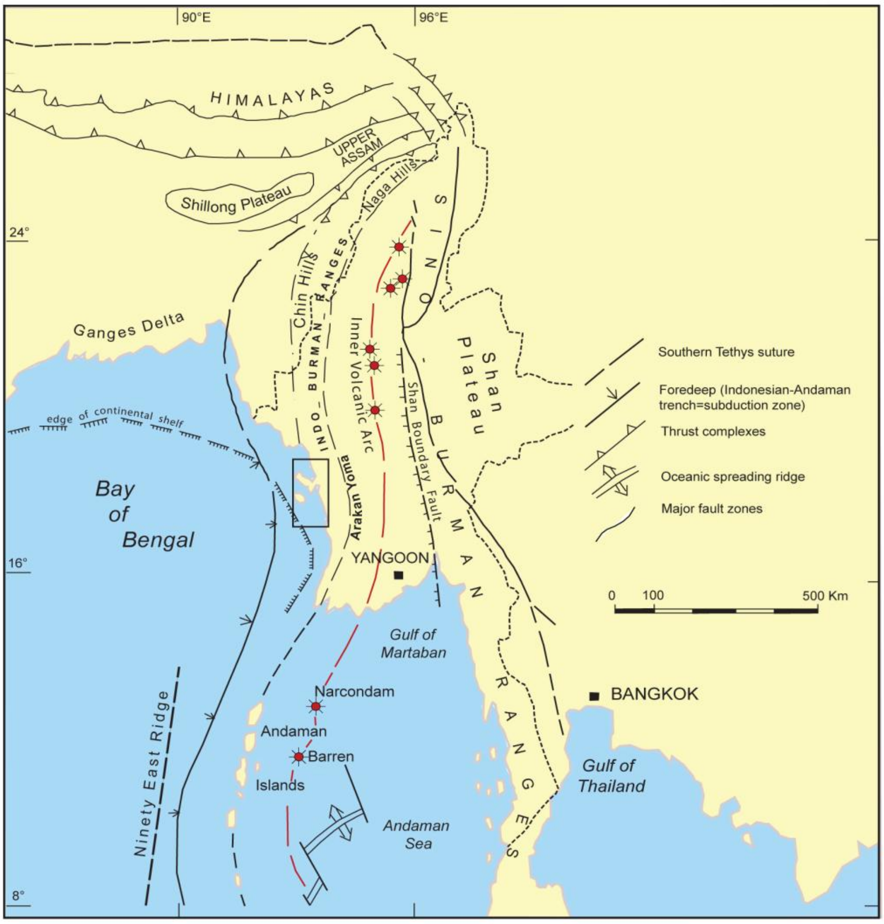

Figure 1: Schematic tectonic map of Myanmar (from Bender, 1983). The box indicates the working area in the Rakhine coastal area.

The Rakhine hill ranges and the Rakhine coastal area (Indo-Burman Ranges, IBR, Fig. 1) are a result of the collision between the Indo-Australian plate and SE Asian plate. The IBR is a N-S oriented arc, which forms the tectonic barrier between the Assam shelf in the west and the MCB in the east. It represents an active accretionary wedge linked to the eastward subduction of the Bengal basin oceanic crust. The IBR comprises sedimentary, metasedimentary, intrusive and volcanic rocks forming the backbone of an accretionary prism including slivers of dismembered ophiolites obducted over the east-dipping subduction zone.

The present research is aimed at tracing back the provenance of the Eocene to Miocene turbiditic sediments included into the accretionary wedge along the Bay of Bengal, western Myanmar (Fig.1). The investigations will allow understanding the relationship between large-scale tectonic processes during deposition of the sediments along the eastern margin of the Bengal fan.

Heavy mineral assemblages indicate the derivation of the clastic material from (1) granitoids, associated volcanics and/or recycled rock series (ultrastable zircon, tourmaline, rutile, ZTR-association), (2) medium-grade metamorphic rocks (garnet, epidote group, chloritoid), and (3) ophiolitic rocks (chromian spinel). This excludes the origin of the detritus from the Himalayan range and Bengal fan respectively, because these sediments are typically bearing high-grade metamorphic heavy mineral grains (kyanite, sillimanite, staurolite) (Uddin et al., 2007). In modal counts (e.g. Dickinson, 1985), the variably feldspar-bearing litharenites show a provenance from transitional to dissected arc sources and recycled orogenic terranes. Volcanic-hypabyssal lithoclasts strongly dominate over sedimentary and metamorphic lithic grains. These petrographic results clearly indicate the sources of the detrital material in the IBR and associated volcanic arcs.

Laser ablation ICP-MS detrital zircon U-Pb age results from 3 Eocene, 3 Oligocene and 2 Miocene sandstones show coherent patterns. The Late Cretaceous peaks ranging 95-85 Ma (≈ Cenomanian - Coniacian) dominate the age distributions. The Palaeogene is represented by peaks ranging from approx. 60-30 Ma (Palaeocene - Early Oligocene). The sources of these zircons are in majority the volcanic arcs within the IBR (Cretaceous) and Inner Volcanic Arc, MCB (Tertiary). Minor reworking of Early Mesozoic, Palaeozoic and pre-Cambrian zircons is observed. One particular Eocene sandstone (10TTN03) is characterized by a very broad Palaeozoic and pre-Cambrian zircon distribution. By considering other provenance indicators (heavy minerals) a derivation of the clastic material from the Shan Plateau can be inferred.

Allen et al. (2008) carried out a provenance analysis on similar Tertiary sediments to the north and south of our working area and on modern river sands. They inferred a main source in the Burman arcs for the Palaeogene deposits but a dominant supply from the Himalaya (Bengal Fan) in Neogene formations. Our data set from the Rakhine area, including also the Neogene deposits, confirms the derivation from the Cretaceous and Palaeogene arcs and metamorphic/ophiolitic basement in the Indo-Burman Ranges and Inner Volcanic Arc.

Tracing Sand-Types across the Sverdrup Basin, Canadian Arctic

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Within the Late Paleozoic-Cretaceous Sverdrup Basin and the overlying Paleogene strata there are thick, laterally extensive, commonly quartz-rich, sandstone-dominated formations. These sandstones yield provenance data which may, on a circum-Arctic scale, cause us to question current plate and palaeogeographic reconstructions, and locally, help to trace and predict the occurrence and quality of hydrocarbon reservoirs. The study involved 4 field seasons along the northern and southeastern margins of the Sverdrup Basin on Ellesmere and Axel Heiberg islands. Our approach involves collection of field data by multidisciplinary teams and a comprehensive analytical programme. An age framework is provided by integrated biostratigraphy (macropalaeontology, palynology and micropaleontology). Sediment provenance and transportation information is provided by field observations, petrography, heavy mineral analysis, mineral geochemistry, detrital zircon dating, and palynology (reworked fossils). Uplift and burial histories are provided by vitrinite reflectance and apatite fission track analysis.

We will use an example from the southeastern Sverdrup Basin (Slidre Fiord, Ellesmere Island) to illustrate the changes in sediment provenance observed, and then begin to trace these changes to other parts of the basin. At Slidre Fiord we identify at least 4 sand-types and can place time constraints upon the provenance changes:

- Triassic (Norian and older) and mid Jurassic sandstones have common provenance signatures; they are sublitharenites and subarkoses with abundant apatite and Permo-Triassic detrital zircons
- At the Triassic-Jurassic boundary there is a pulse of mature sandstone, lacking in apatite and Permo-Triassic detrital zircons
- During the mid Jurassic the metamorphic grade of the sediment source area increased, suggesting either an unroofing history, different or possibly deeper source
- Early Cretaceous mature sandstones have a different signature to the underlying units, containing abundant Proterozoic-Archean detrital zircons
- Late Cretaceous-Paleogene sandstones contain kyanite (high-pressure metamorphism) and volcanic debris

Based on published paleogeographic reconstructions it is predicted that sediments on the north and south side of the Sverdrup Basin may have different provenance signatures. However, when data were collected from opposing sides, surprisingly, similar sediment provenance trends are noted, and many of the sand-types identified in the southern part of the basin are also recognised in the northern part.

- Sandstones of Triassic, Norian and older, and mid Jurassic age are characterised by abundant apatite and Permo-Triassic detrital zircons,
- Late Triassic-Early Jurassic a pulse of mature sandstone with few apatite grains and lacking Permo-Triassic detrital zircons.

Work is now underway to provide the same sand-type framework in other parts of the Sverdrup Basin, and to determine the sedimentary source regions.

An increase in sandstone compositional maturity at around the Triassic/Jurassic boundary has also been reported from the Barents Shelf. Prior to early Cenozoic breakup, and formation of the Eurasian Basin and the Norwegian-Greenland Sea, the

Sverdrup Basin and the Barents Shelf were much closer together. Therefore sedimentary succession in the two areas may share a common provenance history. CASP is undertaking a comprehensive provenance analysis programme of Permian to Paleogene age sandstones from the Barents Shelf. This will allow us to determine whether the sandstones from the Sverdrup Basin and the Barents Shelf have a common provenance, prior to breakup.

The data from this on-going study provide a framework on which we can base models of sediment provenance and transport, therefore constraining palaeogeographic reconstructions.

Provenance of Neogene Sandstones, Sabah, Northern Borneo

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The Early Miocene Sabah Orogeny uplifted, deformed and exposed pre-Neogene rocks in northern Borneo. Post-TCU (Top Crocker Unconformity) Neogene sedimentary rocks of the Kudat, Tanjong, Sandakan, and Bongaya Formations were deposited in fluvio-deltaic to shallow marine environments in Sabah.

The majority of Neogene sandstones are compositionally and texturally mature, have a quartzose recycled orogenic source, and ultrastable heavy mineral assemblages dominated by zircon, tourmaline and rutile. An exception is the oldest member of the Kudat Formation, which is compositionally and texturally immature, has a mixed and dissected arc provenance, with heavy mineral assemblages dominated by euhedral and subhedral zircons and garnets.

Petrographic data, garnet analyses and U-Pb geochronological studies of the sandstones indicate multiple sediment sources. LA-ICPMS U-Pb ages from detrital zircons reveal a spread of ages from Proterozoic to Early Miocene, with the majority being Mesozoic. The most significant clusters of ages are Cretaceous, Jurassic and Permo-Triassic.

The Rajang and Crocker Groups were the principal sources throughout the Neogene for the Tanjong and Sandakan Formations in eastern Sabah, to the offshore basins in western Sabah, and contributed to the Kudat Formation of northern Sabah. Sediments were derived from recycled pre-Neogene sedimentary rocks which were ultimately derived from the Schwaner Mountains on Borneo and the Malay-Thai Tin Belt Granites, with some input from northern Borneo ophiolitic basement, and Cenozoic volcanic rocks.

In contrast, during the Early Miocene, granites and metamorphic rocks of the Palawan Microcontinental Block contributed significant amounts of sediment to the oldest member of the Kudat Formation. The Jurassic zircon population indicate a South China source. A new garnet compositional database compiled from the literature to help identify the provenance of detrital garnets supports the derivation of garnets from Palawan.

Sedimentary Provenances of Passive Continental Margins in North-East Russia and Their Implications for Arctic Paleoreconstruction

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Typification of passive margins is carried out on the base of sequence of data (Bond et al., 1995) among which the sedimentological data are the most significant. Passive margins are often characterized by similar facial complexes and single-type stable mineral composition of terrigenous rocks. At the same time many passive margins have individual patterns, related to synchronous and subsequent tectonic events. We considered two passive margins in modern structure referred to conjugate fold belts, Anyui-Chukotka and Verkhoyan-Kolyma. Passive margins development in Permian-Triassic time is the basement for paleoreconstructions in Arctic. In present day structure heavily deformed sedimentary complexes of the two passive margins are brought closely together as a result of collisional processes (Zonenshain et al., 1990; Parfenov et al., 1993; Sokolov, 2003).

Clastic material was carried by large rivers, possessing large reservoir on neighbouring continent. Progradation of delta system in deeper regions is observed. For Chukotka Triassic basin an existence of one large delta system is suggested, for Permian-Triassic Verkhoyansk basin, two systems.

Mineral composition of sandstones from Permian-Triassic deposits is referred to lithitic arenites and sublitharenites according to Pettijohn (1981). Chukotka sandstones are different, containing from 15 to 40% of matrix, they are referred to lithitic greywackes. Assemblages of heavy minerals are represented by stable minerals. On the basis of diagram of source areas according to Dickinson (1980) the source area for Triassic sandstones of Chukotka basin were mainly complexes of orogenic area, but for Lower-Middle Triassic ones, in addition magmatic rocks are observed. Clastic material of Verkhoyansk paleobasin sandstones was carried from recycled orogens.

Geochemistry of sandstones and mudstones imply different evolutionary patterns of the Permo-Triassic rocks. In addition to looking at sediment distribution, specific mineral (like mica and feldspar) composition was used as petrogenic tracers for sources areas. Compositions of detrital zircon assemblages indicate dominant spikes of different ages: Verkhoyansk region is dominated by Proterozoic assemblages, and Chukotka, by Phanerozoic ones.

Thus, sedimentological data indicate difference of sedimentary provinces and different evolution of sedimentation for two passive margins. This presentation discusses how the above geological data are applied to a number of existing geodynamic models.

Topographic and climatic controls on sediment dispersal in the NW European Triassic: insights from the Pb isotopic composition of detrital K-feldspar.

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The NW European Triassic succession, comprising the Early – Middle Triassic Sherwood Sandstone Group (SSG) and the Middle – Late Triassic Mercia Mudstone Group, represents the deposits of large-scale endorheic drainage systems infilling a series of wide, extensional rift basins. Facies encompass ephemeral fluvial, alluvial and lacustrine and sub-ordinate aeolian and sand-flat environments. These accumulated in the arid to semi-arid interior of the Pangaean Supercontinent. Sandstones are arkosic, texturally mature, yet mineralogically immature and are proven reservoirs for hydrocarbons over a broad region. The nature and distribution of these sandstones is thought to be controlled by the complex interplay of climate and tectonics (Ruffell & Shelton 1999). Dispersal of clastic material from upland massifs into the basins was driven by topography but also influenced by seasonal variations in precipitation. Palaeomagnetic data suggest this area of NW Europe lay between 15 and 25° N in a zone of SW-directed subtropical trade winds giving rise to general arid conditions with an annual summer monsoon (Kutzbach & Gallimore 1989; Szulc 1999; Preto *et al.* 2010). The resulting cyclic variability in sedimentation has been recognised in the European Triassic (Meadows & Beach 1993; Bourquin *et al.* 2009) and this evidence suggests that large-scale fluvial systems were more active during phases of increased precipitation (McKie & Williams 2009). Onshore and offshore UK, the Variscan Uplands of west and central Europe are thought to have exerted a strong control on drainage evolution, resulting in large-scale, south-to-north flowing rivers (i.e. the 'Budleighensis' river system; Wills 1970; Audley-Charles 1970; Warrington & Ivimey-Cooke 1992) which fed a series of sedimentary basins and terminated in dryland environments. Sediment dispersal into basins on the Atlantic margin is less well understood. Here, Triassic successions occur in the subsurface and are only occasionally penetrated by hydrocarbon exploration wells.

In this study, the Pb isotopic composition of detrital K-feldspar sand grains has been analysed for a broad range of Triassic sandstones. This is an appropriate tool for investigating the provenance of the Triassic successions as K-feldspar is a likely first-cycle component and is an abundant framework grain in these sedimentary rocks. Furthermore, the composition of potential sourcelands is well constrained in the region. Target sandstones include 1) those associated with the 'Budleighensis' drainage system; and 2) those infilling several Atlantic Margin basins, from the Slyne Basin northward to the Faroe-Shetland Basin.

Pb isotopic data from K-feldspars in Middle Triassic (Anisian) sandstones in the Wessex Basin, onshore southwest UK, and the East Irish Sea Basin (EISB), some 350 km to the north, show that the same grain populations are present. This indicates that the drainage system (the 'Budleighensis" River) feeding these basins originated from the same source/s, most probably the remnant Variscan Uplands to the south (Figure 1). Fluvial and aeolian sandstones display the same grain populations, suggesting that if water- and wind-driven sands were originally derived from different sources, this has been obscured through reworking - possibly during wet to dry periodic fluctuations - prior to final deposition. Furthermore, significant recycling of feldspar from arkosic sandstones in earlier sedimentary basins into the EISB can be ruled out. The provenance data agree with previous deposition models for this system, indicating transport distances in excess of 400 km and regional drainage that linked separate

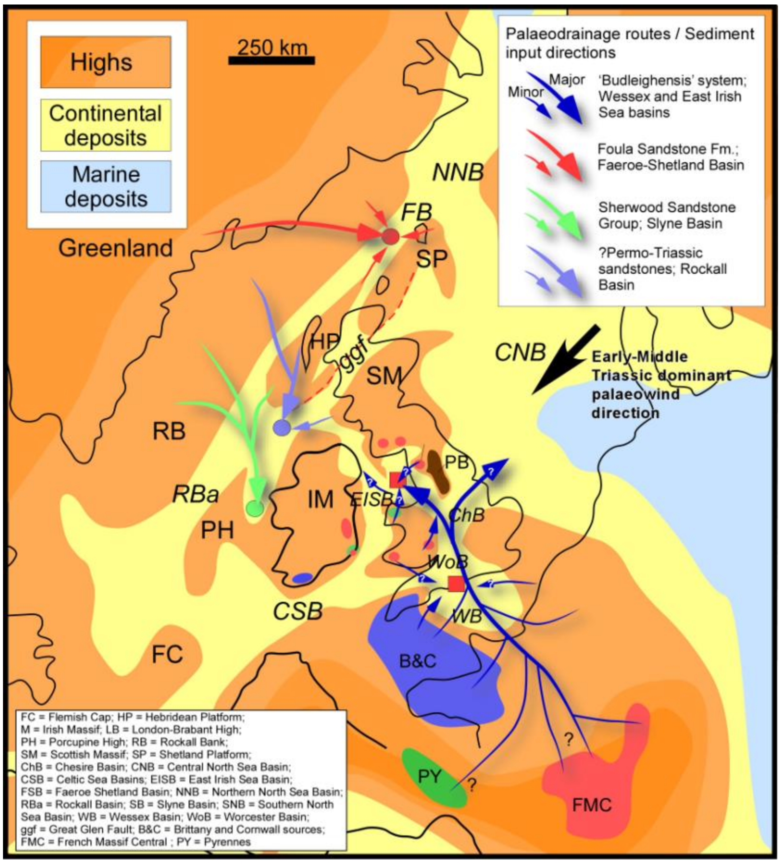

Figure 1: Schematic palaeogeographic reconstruction of the Middle Triassic (after Scotese 2002; Eide 2002; McKie & Williams 2009; Bourquin *et al* .2011; McKie & Shannon 2011) showing the distribution of massifs and sedimentary basins, with potential K-feldspar sources highlighted. Also highlighted are potential drainage directions and sedimentary input points for the 'Budleighensis' system, and for the Triassic basins more marginal to NW

basins. This contrasts sharply with K-feldspar provenance data from Atlantic Margin basins where sandstones show a different provenance, dominantly supplied from Archaean and Proterozoic rocks from the north and west (Tyrrell *et al.* 2007; 2009; 2010). Key sources include the Archaean – Palaeoproterozoic rocks of eastern Greenland and the Rockall Bank (Figure 1). There is no input from the Variscan Uplands in these marginal basins.

These observations agree with the current understanding of Triassic palaeogeography and climate models, where a combination of topography and flooding associated with an annual monsoon is thought to have been responsible for the transport of sediment from the uplands. This combination of processes can also account for the overall textural maturity and mineralogical sub-maturity of the sandstones. In overall terms, the Triassic K-feldspar provenance data collected to date from all basins in the region indicate the presence of two drainage domains (the 'Budleighensis' and the Atlantic Margin basins), separated by a NE-SW oriented drainage divide (Figure 1). Importantly, both drainage domains appear to have been isolated and independent from each other at least in the Early – Middle Triassic. The drainage divide comprised the Irish-Scottish massifs and, although these areas were of sufficient topography to act as a barrier to evolving drainage, they themselves were not a significant source for K-feldspar.

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