High Fidelity: the Quest for Precision in Stratigraphy and Its Applications

16 - 17 May 2012

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Wednesday 16 May

Bursting the Limits of Time?- Stratigraphy in the Oil Patch

Bruce Levell, *Chief Scientist Geology, Shell Global Solutions bv, KesslerPark 1, Rijswijk, 2280AB, The Netherlands*

In the Oil and Gas industry Stratigraphy has always been both a powerful integrating science and importantly a powerful tool for deciding between multiple working hypotheses. On the one hand it is useful in creating high value new play concepts from sparse information and optimising field development for better resource recovery. On the other hand stratigraphic tools have a proven track record of helping avoid serious mistakes, from incorrect subsurface models to unsafe drilling operations. Despite this it is currently under-appreciated and probably under-utilised.

NOW is a critical time in the history of the discipline as applied in the oil and gas industry. Bio-stratigraphers are becoming a scarce resource. At the same time new insights into Earth Systems and the need for precision dating in understanding the multiple time scales, down to Kyrs, at which the earth system responds to changes in inputs are refreshing the science of stratigraphy as a whole.

The concurrent increase in "demand" and reduction of "supply" means that quality stratigraphy has the opportunity to be, once again, a competitive differentiator in exploration and reservoir management in the oil patch. The spectacular increases in the resolution and interpretability of geophysical data will never be sufficient alone to address these questions, but are the new stratigraphic tools and techniques appropriate to re-juvenate the discipline in the oil patch?

Applications of the science with increasing prominence include: operational safety, for example through understanding pressure regimes while drilling, reducing footprint (both land and water through accurate completion in particular zones. There is also a persistent need to solve ever-more detailed geological problems- such as finding subtle traps, drilling more complex wells, making more expensive development decisions on less data, understanding field production history when preparing the reservoir engineering for EOR and IOR projects, and assuring the long term integrity of natural and artificial underground storage (eg aquifers and carbon dioxide).

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Integrated Bio-, Chemo- and Sequence Stratigraphy of the Oligo-Miocene Asmari and Pabdeh Formations, SW Iran

Frans van Buchem, *Maersk Oil, Copenhagen, Denmark*

An integrated stratigraphic approach has been applied to construct a regional sequence stratigraphic model for the mixed carbonate-siliciclastic-evaporite system of Oligo-Miocene age (Asmari and Pabdeh Formations) located in the Dezful Embayment of SW Iran. The model is based on both new detailed sedimentological observations in outcrop, core and well logs, as well as an improved high-resolution chronostratigraphic framework constrained by Sr isotope stratigraphy and biostratigraphy. The resulting better understanding of the stratigraphic architecture distinguishes four, geographically separated types of Asmari reservoirs.

The time framework for this complex sedimentary system has been significantly improved by calibrating the age ranges of (presumed) index fossils to an absolute Sr isotope timescale. In addition, systematically applied Sr isotope stratigraphy to a number of outcrop sections and cored wells allowed to detect and estimate the duration of breaks in the sedimentary record as well as variations in sedimentation rate along platform to basin transects.

As a result, three Oligocene sequences (of Rupelian, early Chattian and late Chattian age) and three Miocene sequences (of early Aquitanian, late Aquitanian and early Burdigalian age) have been distinguished basin-wide, representing a period of 15.4 Ma. The stratigraphic architecture of these sequences is primarily controlled by high amplitude glacio-eustatic sea-level fluctuations, except for the Burdigalian, when tectonic control became important with a regional tilt down towards the NE. The improved regional time framework gave a better insight in factors controlling sedimentation, and allowed to construct a high-resolution sequence stratigraphic model that is predictive with respect to the heterogeneous distribution of carbonates, sandstones and anhydrites in this basin. The practical application of this work is a classification of the Asmari reservoirs in four lithologically, geometrically and diagenetically different reservoir types, and a model that predicts how and when these types change laterally from one to another.

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Synchroneity and Diachroneity of Marine Microfossil Bioevents: From a High-Latitude Zonation in the Nordic Seas to the Low-Latitude Standard Zonations of Planktonic Foraminifers and Calcareous Nannofossils

Erik Anthonissen, *Chevron, USA*

At the global scale, the "standard zonations" for calcareous nannofossils and planktonic foraminifera are arguably the most utilized biostratigraphic frameworks in the petroleum industry. But just how reliable are the numerical ages assigned to these zones and can they be thought as being truly global? As the industry aims towards increasingly challenging exploration targets, are there ways of increasing the resolution of the current biozonations?

Recent advances towards an orbitally-tuned global marine composite for the stable isotope records of oxygen and carbon may hold the key. Astronomicaly-tuned isotope records from the Atlantic and Pacific have allowed for 400 kyr eccentricity cycle age-calibration of the Mi, Oi and CM isotope maxima for the Oligocene to Recent interval. This allows identification of additional age-significant climatically-controlled fossil assemblages through calibration to the isotope events. Used within a framework of the standard zonations, this integrated bio-geochemical stratigraphy has the potential to offer improved biostratigraphic resolution in areas where standard markers are in low abundance.

At the regional scale, an exercise in the calibration and refinement of the Neogene biostratigraphy of the Nordic Seas highlights the climatic control on pelagic microfossil distributions. The lack of primary and secondary GSSP correlative markers in Neogene deposits of the North Sea, Nordic seas and northern North Atlantic creates a challenge for the biostratigrapher. This study highlights the closest biostratigraphic approximations in this region to the standard chronostratigraphic boundaries of the Geologic Time Scale. Via correlations to key Ocean Drilling studies and unambiguous magnetostratigraphies in the region, the age of shallower deposits of the North Sea has been better constrained. The closest biostratigraphic approximations to these chronostratigraphic boundaries in the region are presented, together with a framework of calibrated events according to sub-basin. The best approximating boundary events at any given location in this region depends upon both the prevailing paleoclimatic and paleoceanographic settings, with the addition of paleobathymetry controlling the benthic foraminiferal markers.

An improved, age-calibrated biozonation is presented for the Neogene of the northeastern Atlantic Ocean. This study highlights a best-practices approach for industrial biostratigraphers working in high-latitude regions and across intervals representing times of pronounced provincialism. Here the use of integrated biozones, involving two or more microfossil groups, is necessary for arriving at robust biostratigraphic interpretations.

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The Use of Biostratigraphically Calibrated, Stable Carbon Isotopes in High Resolution Correlation

Andrew Scott Gale, *University of Portsmouth*

William Smith's chief legacy to stratigraphy was the discovery of the immense value of fossils as correlative tools, and two hundred years of research have progressively developed, refined, and revised biostratigraphical schemes. Fossils will always be used to underpin correlation, because species ranges are the only truly unique events in the geological record. All others, with the exception of the few geochemically diagnositic meteorite impacts, are either "on-off" (magnetic chrons) or amplitude variations in a continuously varying parameter (e.g. stable isotopes, elemental compositions).

However, biostratigraphy ideally requires testing by an independent correlative tool, because all fossils are facies dependant to some extent, and thus of limited geographical range; first and last occurrences are therefore diachronous. This even applies to species which have an "evolutionary" origin rather than just appearing by migration, because of the nature of allopatric speciation. Magnetostratigraphy provides a broad-brush test, which is not strictly independent, because fossils are widely used to identify chrons. For really high resolution correlation, secular variation in d13C, guided by biostratigraphy, provides the highest resolution means of correlation yet available, with precision in the order of a precession cycle. The value of stable carbon isotopes in correlation is demonstrated by examples from the Cretaceous. Firstly, the OAE2 (Cenomanian – Turonian) provides an example of global correlation in the order of precession (20 kyr). Secondly, the Maastrichtian Stage can be effectively subdivided and correlated with carbon isotope stratigraphy, where biostratigraphy has provided inadequate on account of diachroneity. Finally, carbon isotope stratigraphy is used to test the synchroneity of sea level events, using an example from the Middle Cenomanian.

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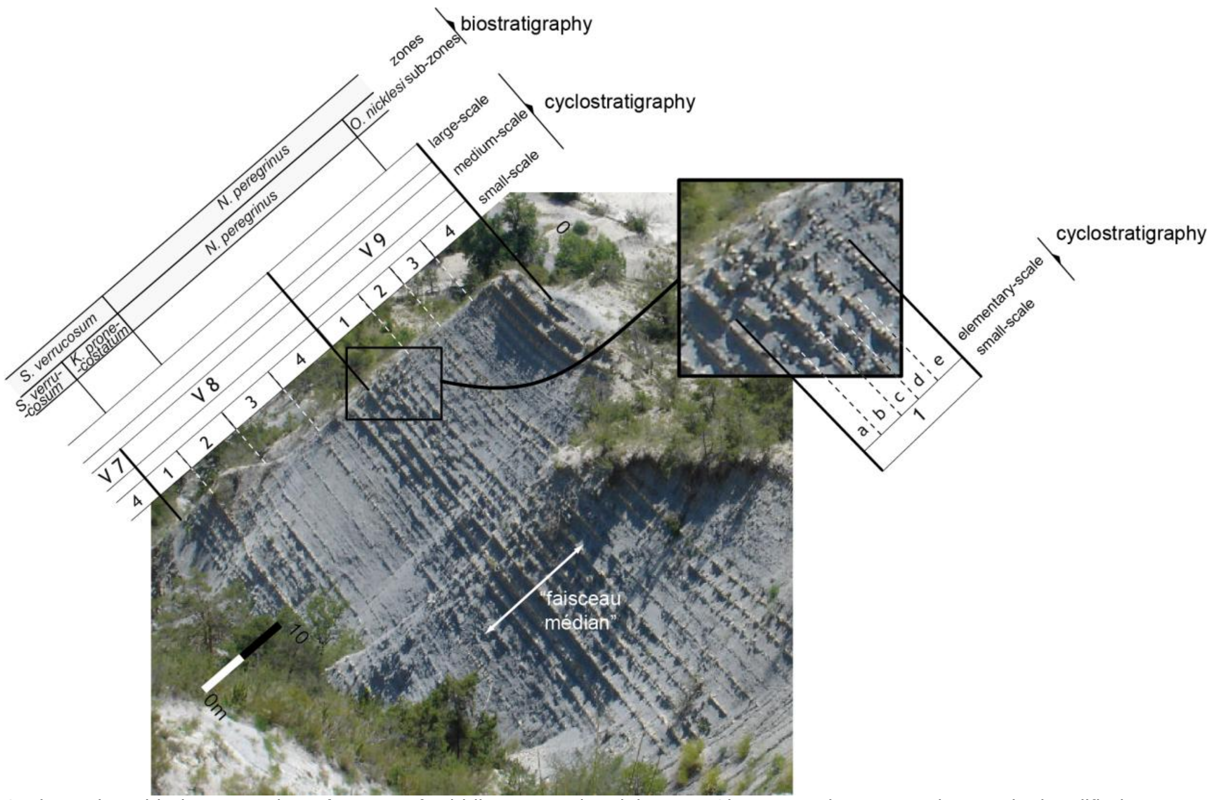
A High-Resolution Multi-Stratigraphic Approach to Global Stratigraphy, Biostratigraphy and Paleoclimatology: The Mid-Valanginian Crisis

Benjamin Gréselle, *Neftex Petroleum Consultants Ltd., 97 Milton Park, Abingdon, OX14 4RY, United Kingdom*

The purpose of many sedimentary and sequence stratigraphic studies is to constrain the causes of, and links between, sea-level, sedimentary, climatic and biotic events, in order to improve both our understanding of processes and causality and prediction away from data points. This objective is, however, often hindered by the lack of definitive time calibration that allows the events under consideration to be placed into a chronological succession.

The mid-Valanginian global carbonate crisis, during the Early Cretaceous, has been investigated in the Vocontian Basin and surrounding platforms (SE France). This interval is characterised by the dramatic global demise of most carbonate platforms as well as a significant drop in pelagic carbonate production. Furthermore, these crises are coeval with a worldwide $\delta^{13}C$ positive excursion. Although some authors have proposed the crises were triggered by strong volcanic activity and subsequent global warming, precise dating is still debated and the mechanisms for this mid-Valanginian event are neither clearly understood or properly time constrained.



Cyclostratigraphic interpretation of a part of middle Late Valanginian, La Charce section, Vocontian Basin (modified from Gréselle & Pittet, 2010).

A multidisciplinary approach combines faciologic, sequence stratigraphic, biostratigraphic and cyclostratigraphic data to establish a solid time framework that encompass a time interval of 9.4 Myrs (i.e. ranging from the Middle Berriasian to the earliest Hauterivian). This work emphasizes the construction and testing of this cyclostratigraphic model. It is based on the recognition of 4 orders of hierarchically-organised depositional sequences. They present a typical 1/4/20 pattern (1 mediumscale sequence/4 small-scale sequences/20 elementary sequences) that suggests an orbital control on the formation of these sequences (i.e. Milankovitch cyclicities). Durations of 400, 100 and 20 kyrs, which correspond respectively to long- and short-term eccentricity and to precession cycles, are proposed for each of these sequence types. A duration of 4.7 Myrs is proposed for the entire Valanginian stage, based on the recognition of 11.75 medium-term sequences in the complete hypostratotype section within the Vocontian Basin.

The high-resolution time framework constructed for the Valanginian allows a precision below 20 kyrs for (1) the calibration of regional sea-level changes; (2) the estimation of the time contained in subaerial exposure surfaces on the platform; (3) the determination of ammonite zone duration (from 0.55 to 1.5 Myrs long); and (4) the discussion of the physical and time links between major events. High-resolution sequence- and cyclostratigraphic correlations from the inner domain of the Jura Platform to the Vocontian Basin showed, for instance, that less than 10% of the Valanginian time corresponds to deposition in the stratotype section of Valangin (Swiss Jura). Consequently, this suggests that subaerial exposure accounts for at least 90% of the time.

A new paleoenvironmental scenario is proposed. This integrates important variations in basinal sedimentary fluxes, high-amplitude asymmetrical sea-level oscillations, the carbonate platform crisis, the $\delta^{13}C$ positive excursion and interpreted nutrient influx changes. This integrated model proposes that an intensification of continental weathering is responsible for increased clay and nutrient influx in the basin, as well as the demise of the surrounding carbonate platforms. The implied climate humidification and the following cooling by at least 4°C are most probably related to the latitudinal migration of climatic belts. In turn, this climatic modification is linked to the development of high-latitudinal ice caps during the Late Valanginian.

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Integrated Approach to Stratigraphic Understanding of the Shallow Offshore HA Field, Niger Delta, Nigeria

Giwa, Gideon[1], Adejinmi, Kehinde[2], Isowamwen, Evans[2]

[1]*Shell International Exploration and Production, The Hague, Netherlands*
[2] *Shell Petroleum Development Company, Warri, Nigeria*

Integrated stratigraphic analysis of data from the SPDC operated HA field, offshore Nigeria was undertaken with a view to generating higher order stratigraphic framework in order to impact reservoir modelling.

Third order sequence stratigraphic interpretation was accomplished from an integrated analysis of seismic, well logs and biostratigraphic data. The late Miocene Me-2 sequence was penetrated. Fourth and fifth order stratigraphic subdivision was attempted using the principles of cyclostratigraphy. Cyclostratigraphy was used to identify rhythmic and cyclic depositional patterns in sedimentary successions, which are thought to relate to variations in climate cycles (so called Milankovitch cycles) caused by variations in the Earth's orbit.

Spectral analysis of facies dependent datasets such as Gamma Ray logs offers the best avenue for applying cyclostratigraphic techniques. Using Cyclolog software, spectral analysis curves were generated. When constrained by pre-existing third-order surfaces, this application enabled the delineation of fourteen "higher order" parasequences over a 600 Ky. period.

100ft of cores were described from well HA-06. When integrated, this aided the identification of the lowstand fluvial channels and Transgressive Shoreface deposits. BHI logs from wells HA-06 were also integrated.

The resulting stratigraphic framework is a prograding lowstand system tracts of distributary channels and mouth bars truncated by trangressive marine shale, which was then overlain by a succession of transgressive shoreface deposits. This laid the foundation for robust reservoir static models enabling improved volume estimation and well planning.

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Why Is High-Resolution Biochemostratigraphy in the Early Palaeozoic Imperative and How Can It Be Achieved?

Thijs R. A. Vandenbroucke[1] and Bradley D. Cramer[2]

[1] *UMR8217 du CNRS: Géosystèmes, Université Lille 1, Bâtiment SN5, Avenue Paul Langevin 59655, Villeneuve d'Ascq cedex, France.*
[2] *Kansas Geological Survey - Department of Geology, University of Kansas, 1930 Constant Avenue, Lawrence, Kansas 66047, USA.*

The paucity of abyssal sediments, deep-ocean cores and astrochronology, which allow Cenozoic and Mesozoic timescales to carry error bars of a few thousand years, causes most of the Palaeozoic timescale to carry error bars of up to a few Myr. Chronostratigraphic control better than ±1 Myr has long been considered "high-resolution", and working out short-term (<<1 Myr) cause and effect relationships within the ocean-atmosphere-climate system has been virtually impossible in the Early Palaeozoic. This was not thought of as a fundamental problem by most workers, as almost the entire Ordovician-Silurian period has been considered to be an interval of relative climatic stability, only interrupted by a very short-lived end-Ordovician (Hirnantian) glaciation. Apart from this event, the Ordovician-Silurian was presumed to be a period during which high sea levels and a greenhouse climate combined to produce a ~70 Myr-long episode of little interest.

Over the past decade however, this view gave way to other interpretations: in the newly established paradigm, the Hirnantian glaciation (~444 Ma) is a discrete event of a few 100.000 years during a much longer Early Palaeozoic Ice Age (EPI). The exact timing of the onset of cooling in the EPI, ultimately culminating in the Hirnantian glacial maximum, is still is a matter of debate, but several glacial events have been identified in the Katian (~454 Ma), and even as early as the Floian (~470 Ma). Likewise, the Silurian Period (443.7-416.0 Ma) represents one of the climatically most dynamic episodes in our planet's history. The large positive carbonate carbon isotope ($\delta^{13}C_{carb}$) excursions preserved in Silurian and Ordovician strata represent major perturbations of the global carbon cycle and consequently an extremely unstable ocean-atmosphere-climate system.

Causal mechanisms for these events, and a wide variety of climatic/oceanographic models have been developed. However, considerable debate remains regarding their validity and the relationships between sea level, glaciation, organic carbon burial, oceanic anoxia, and faunal turnover. The major difficulty facing Silurian (and for that matter all Palaeozoic) global climate studies is imprecise global chronostratigraphic correlation. As a result, Ordovician and Silurian workers are beginning to see the need to return to basic stratigraphic research and the establishment of a high-resolution chronostratigraphy has become imperative to understand the Palaeozoic global climate system in detail. Before we can determine the cause-and-effect relationships within the Earth System we must first know the precise order of events. This is one of the key objectives of the IGCP 591 project. This project aims to demonstrate globally the temporal resolution now achievable for the deep time portion of the stratigraphic record, as shown by regional case studies. This talk will showcase some of our achievements so far, based on an integrated bio-and chemostratigraphic approach.

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The Late Ordovician to Middle Silurian: A Record of Pronounced Sea Level Change

David Ray, *Neftex Petroleum Consultants Ltd, UK*

The Late Ordovician to Middle Silurian records some of the most pronounced sea level changes of the Palaeozoic. These oceanic events appear coupled with the development of Gondowanan ice-sheets and have been major drivers of oceanic, atmospheric and biotic change. Based upon an evaluation of key published sections from 20 countries, 12 global sequence stratigraphic cycles (4 Ordovician and 8 Silurian) and their associated systems tracts and surfaces have been identified.

In establishing our record of sea level change we have only used sections that are biostratigraphically well constrained (typically by chitinozoans, conodonts or graptolites), show an unambiguous sedimentological expression of relative sea level change and are associated with tectonically stable regions. Furthermore, attention has been given to sections exhibiting carbon/oxygen isotope excursions, extinction events, glaciogenic sediments or palaeo-water-depth indicators. At present 165 reference sections and points have been recorded, allowing the synchronicity between oceanic, atmospheric and biotic change to be assessed.

The Late Ordovician began with a broad sea level high in the Sandbian and was followed by two pronounced sea level cycles during the middle to late Katian, possibly indicating the establishment of minor Gondwanan ice-sheets. The Hirnantian is associated with the development of a major Gondwanan ice-sheet, extinction event, isotope excursions and a pronounced lowstand. Following the Hirnantian glaciation, the Rhuddanian (Silurian) is broadly characterised by sea level rise. A minor sea level lowstand is identified in the mid-Rhuddanian, associated with an extinction event and an isotope excursion. During the Aeronian, Gondwanan ice-sheets were re-established resulting in several pronounced sea level cycles, many of which are associated with glaciogenic sediments, extinction and isotope excursions. Deglaciation and sea level rise characterise the Telychian, when Silurian sea levels reached their peak. A further episode of pronounced sea level fall, extinction and isotope excursions took place around the Telychian-Sheinwoodian boundary and was followed by an equally pronounced sea level rise and deglaciation event. A further extinction and isotope excursion, took place in the Homerian, although associated sea level perturbations are of smaller magnitude than earlier events. Based on these data, globally correlatable oceanic, atmospheric and biotic events can be demonstrated.

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New Developments in High-Precision U-Pb Geochronology and Their Application to Late Paleozoic Ice Age Stratigraphy, Astrochronology and Paleoclimatology

Mark D. Schmitz and Vladimir I. Davydov, *Department of Geosciences and Isotope Geology Laboratory, Boise State University, 1910 University Drive, Boise, Idaho, 83725-1535, U.S.A.*

We will review recent developments in the application of high-precision U-Pb zircon geochronology, with a particular focus on improvements in precision and accuracy. Chemical abrasion of zircons, use of internationally calibrated EARTHTIME mixed U-Pb isotope dilution tracers, and improved mass spectrometry guided by detailed error analysis result in an age resolution of <0.05%, or *ca* 100 ka, for Late Paleozoic volcanics. This precision allows the resolution of time in the Milankovitch band throughout the Phanerozoic; we present two examples of the utility of this enhanced resolution.

High-precision ID-TIMS U-Pb zircon ages for 12 interstratified tuffs and tonsteins are first used to radiometrically calibrate the detailed lithostratigraphic, cyclostratigraphic, and biostratigraphic framework of the Carboniferous Donets Basin of eastern Europe. The calibration of rock accumulation rates using multiple precise radiometric dates in Moscovian strata results in an age model that can be applied to the fourth order and higher frequency sequences defined by Donets basin cyclicity. This calibration quantitatively affirms the long-standing hypothesis that individual high-frequency Carboniferous cyclothems and bundles of cyclothems into fourth-order sequences are the eustatic response to orbital eccentricity (100 and 400 ka) forcing. Additional ages for Mississippian strata provide among the first robust radiometric calibration points within this subperiod, and result in variable lowering of the base ages of its constituent stages compared to recent global time scale compilations.

In a second example, a quantitative biostratigraphic and radiometric calibration is presented for the Pennsylvanian through Early Permian global time scale, based upon a constrained optimization (CONOP9) composite of over 5000 bioevents in 35 stratigraphic sections, and over 40 high-precision (CA-TIMS) U-Pb zircon ages for interstratified ash beds in the marine to paralic successions of the Silesian Basin (eastern Europe), Donets Basin (Ukraine), and southern Urals (Russia).

Significant shifts in the duration of several stages are demonstrated, ranging from one to six million years, compared with prior estimates. The unprecedented density of radiometric calibration points for the Pennsylvanian–Permian transition provides a high-resolution (~0.1-Ma) global chronostratigraphic standard for testing and improving biostratigraphic correlations across Euramerica. We integrate radiometric ages, biostratigraphic correlation, and digital correlation of major cyclothems to the long-period (404-ka) eccentricity cycle to elucidate the tempo, magnitude, and forcing of eustatic changes and cyclothemic deposition associated with the waxing and waning of Gondwanan ice sheets, and establish a pan-Euramerican chronostratigraphic framework for most of Late Paleozoic Ice Age.

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Cyclostratigraphic Calibration of the Frasnian (Late Devonian) Time Scale (Western Alberta, Canada)

De Vleeschouwer David[1], Whalen Michael T.[2], Day James E.[3], and Claeys Philippe[1]

[1] *Earth System Sciences and Department of Geology, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium, dadevlee@vub.ac.be*
[2] *Department of Geology and Geophysics, University of Alaska Fairbanks, P.O. Box 755780, Fairbanks, AK 99775, USA*
[3] *Department of Geography - Geology, Illinois State University, Campus Box 4400, Normal, IL 61790-4400, USA*

Currently, few U-Pb isotopic dates constrain the Devonian geological time scale. For this reason, absolute age estimates of Devonian stage boundaries display wide error bars, up to ± 3.8 Myr (Kaufmann, 2006). The uncertainty on the absolute age of stage boundaries and on the duration of different stages hampers a detailed understanding of rates of sedimentation processes, environmental changes and key-events in the evolution of life on Earth (e.g. the Late Devonian extinction, the land plant invasion, the fish-tetrapod transition, etc.). One possible way to reduce uncertainties in the Devonian geological time-scale is the recognition of astronomical cycles in its stratigraphy. This study reports frequency analyses of high-resolution (10-20 kyr) magnetic susceptibility (MS) data of the Frasnian (Late Devonian), derived from carbonate-platform and surrounding slope and basin deposits in western Alberta, Canada. Previous studies demonstrated the generally consistent pattern of MS change across the Alberta basin and demonstrated the utility of MS stratigraphy as a refined regional correlation tool, compared to biostratigraphy. In the present study, it is shown that astronomical forcing significantly influences the MS stratigraphy of the Frasnian in western Alberta. Cyclicity in the studied sections is ascribed to different Milanković astronomical parameters. The astronomical interpretation of observed periodicities is supported by the presence of several amplitude modulations consistent with astronomical theory, and by average sedimentation rate patterns that agree with the existing lithostratigraphy. Sixteen 405-kyr long eccentricity cycles are recognized in the Frasnian MS stratigraphy. By using these cycles as a geochronometer, a Frasnian astronomical time-scale is constructed. This time-scale indicates a 6.5 ± 0.4 Myr duration for the Frasnian. Calibrating this duration to the Kaufmann's (2006) Devonian chronology, the absolute age of the Givetian/Frasnian boundary is recalculated to 383.6 ± 3.0 Ma and the age of the Frasnian/Famennian boundary to 376.7 ± 3.0 Ma. These new absolute ages take into account the astronomically derived duration of the Frasnian, and yield a narrowing of the error margins of the absolute ages by several hundred thousand years. Therefore, this study demonstrates that the recognition of astronomical cycles can significantly refine the Paleozoic geological time-scale.

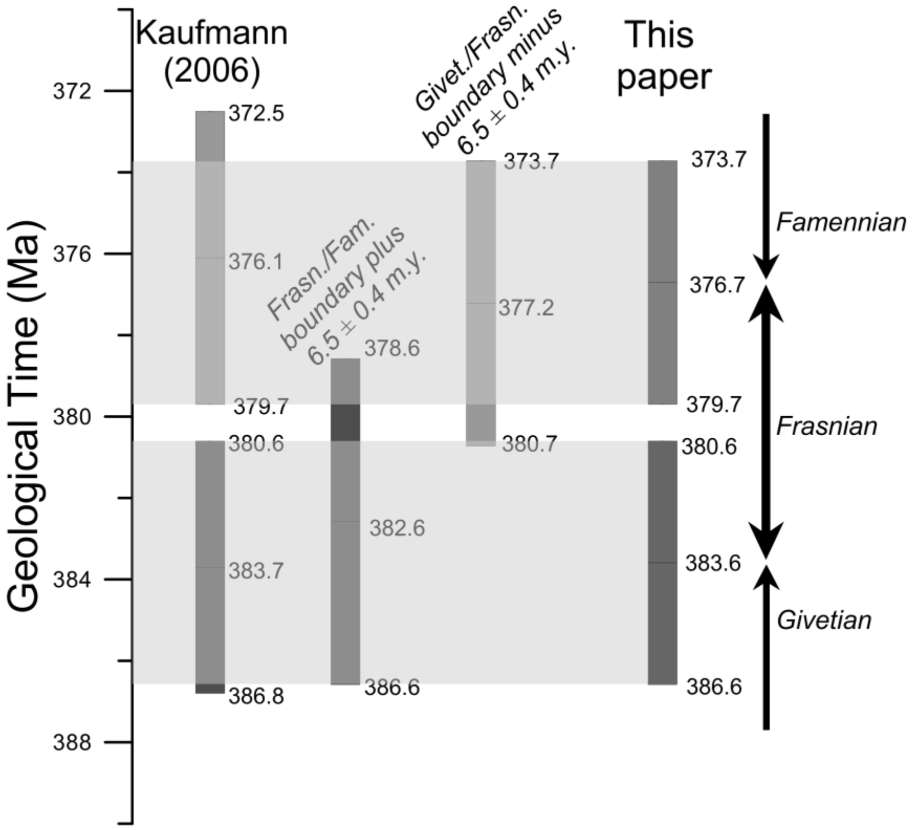

Figure: Recalibration of the Frasnian time scale. By respectively adding and subtracting 6.5 ± 0.4 Myr to/from the absolute age of the Givetian-Frasnian boundary and Frasnian-Famennian boundary (after Kaufmann, 2006), additional age estimates for those boundaries are calculated. By a simple overlay between Kaufmann's (2006) ages (left) and the additional ages (middle), refined absolute age estimates are obtained (right): 383.6 ± 3.0 Ma for the Givetian-Frasnian boundary and 376.7 ± 3.0 Ma for the Frasnian-Famennian boundary.

References:

Kaufmann, B., 2006, Calibrating the Devonian Time Scale - a synthesis of U-Pb ID-TIMS ages and relative, time-linear conodont stratigraphy: Earth-Science Reviews, v. 76, no. 3-4, p. 175-190.

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Astronomical Tuning and Carbon Isotope Stratigraphy of the Maastrichtian in Sopelana and Zumaia (Basque Country, N-Spain)

Sietske J. Batenburg[1,2], Andrew S. Gale[2], Frederik J. Hilgen[3], Silja Hüsing[4], Jacques Laskar[5], Xabier Orue-Etxebarria[6], Mario Sprovieri[1,7], Silke Voigt[8]

[1] *Istituto per l'Ambiente Marino Costiero (IAMC-CNR), Napoli, Italy*
[2] *Department of Earth and Environmental Sciences, University of Portsmouth, Portsmouth, United Kingdom*
[3] *Department of Earth Sciences, Utrecht University, Utrecht, the Netherlands*
[4] *Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, Utrecht, the Netherlands*
[5] *ASD, IMCCE-CNRS UMR8028, Observatoire de Paris, Paris, France*
[6] *Departamento de Estratigrafía y Paleontología, Universidad del País Vasco (UPV/EHU), Bilbao, Spain*
[7] *Istituto per l'Ambiente Marino Costiero (IAMC-CNR), Capo Granitola, Italy*
[8] *Institute of Geosciences, Goethe-University Frankfurt am Main, Frankfurt, Germany*

Astronomical tuning has led to significant refinement of the Geological Time Scale for the Cenozoic, however the Late Cretaceous time scale still has potential errors of ~0.5 Myr. The Basque sections of Sopelana and Zumaia (N-Spain) provide a high-resolution sedimentary archive encompassing the Maastrichtian up to the Cretaceous/Paleogene boundary. Rhythmic limestone-marl alternations, deposited in a hemipelagic setting, reflect the influence of the periodicities of eccentricity modulated precession. Starting from a K/Pg boundary age of 66.0 Ma, consecutive 405-kyr minima are tuned to the new astronomical solution La2011. This orbital tuning, together with the expression of individual precessional cycles, allows for unprecedented refinement of the Geologic Time Scale for the Maastrichtian with errors <100 kyr. The cyclostratigraphic interpretation is thoroughly tested by time series analysis of magnetic susceptibility and colour reflectance data. A cyclostratigraphic framework and orbital tuning of the Zumaia section has recently been obtained. This is extended further back in time by correlation to the Sopelana section by recognition of orbital patterns and marker beds. The total amount of time represented by the two sections is 5 Myr. The lower boundary falls within chron C32N1n, almost reaching the Campanian/Maastrichtian boundary. Magnetostratigraphic and biostratigraphic data allow for application of the cyclostratigraphic framework worldwide, and comparison to previously published Maastrichtian time scales. Additionally, we present an orbitally tuned bulk carbon isotope curve. The high resolution and large amplitude of shifts in $\delta^{13}C$ on the 405-kyr and 1.2-Myr scales enables correlation to deep marine oceanic sites, several sections from the Boreal chalk sea and Italy and, importantly, the Campanian/Maastrichtian boundary GSSP at Tercis, France. This will provide a globally applicable cyclostratigraphic framework for the entire Maastrichtian. We will discuss the implications for the orbital pacing theory of the late Cretaceous climate system. Furthermore we will elaborate on the enigmatic presence of a strong 1.2 Myr cyclicity in lithological and proxy record data and its possible relation to carbon cycle dynamics and/or orbital forcing.

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Encoding and Decoding Periodic Signals in the Stratigraphic Record: Implications for Cyclostratigraphy

Simon Vaughan[1], Robin J. Bailey[2], and **David G. Smith[3]**

1. Department of Physics and Astronomy, University of Leicester, UK.
2. Southwell, Nottinghamshire, UK.
3. Truro, Cornwall, UK.

Cyclostratigraphy seeks to identify the influence of orbitally-forced climate change in the stratigraphic record. Under the cyclostratigraphic model, climate change is driven primarily by the quasi-periodic variations in the solar energy received at Earth's surface, and has a detectable influence on sediment deposition. For the last 50 Ma, the quasi-periods of insolation variation (typically in the 20-400 ka range) can now be calculated for any latitude, with remarkable precision. For earlier periods of Earth history (> 50 Ma) they are assumed to have been qualitatively similar, though the details of the insolation fluctuations may never be known.

Orbital control of sedimentation is best established for Neogene successions, particularly those sampled by deep ocean drilling. Even for Neogene cases, the fluctuations in climatic proxy data do not faithfully track the insolation record and are identified with it only by careful wiggle-matching in an independently determined time framework. The search for a relationship between strata and insolation becomes still more difficult in older sections, where time frameworks lack precision, and where a much wider range of facies is investigated.

Objections, especially those invoking non-linearity and threshold effects, can be advanced against most of the links in the causal chain that supposedly connects insolation to the lithological cycles; in this paper we focus on two issues. Our first concern is the nature of the stratigraphic record and the fidelity with which it may be capable of *encoding* a generally weak signal that is external to Earth's surface systems. Secondly, we question the statistical criteria used to separate this deterministic signal from the typical red noise in stratigraphic data series – the *decoding* that must be done for positive identification of stratigraphic cyclicity.

The encoding problem in its simplest form supposes (1) that climate at the site of deposition or elsewhere is linearly related to insolation; and (2) that the quasi-periodic climatic signal is linearly captured by some proxy in the stratigraphic record and can be detected (without significant loss of information) by physical or geophysical sampling.

The use of spectral methods to search for periodicity in a one-dimensional outcrop profile or borehole data-series must assume, *a priori*, sufficient long term continuity and steadiness in the rate of accumulation to ensure the encoding of the insolation signal. Against this is the evidence that no stratigraphic succession shows the homogeneity consistent with truly continuous accumulation at an unvarying rate. Variation in accumulation rate is clearly implied by any degree of lithological variation; continuity is ruled out by the presence of bedding surfaces and by obvious discrepancies between long-term (net) accumulation rate and the much faster 'instantaneous' rates needed to explain most depositional facies. The truth that there is 'more gap than record' is further supported by considering modern sedimentary environments, in which constant remobilisation of previously deposited sediment shows the predominance of erosional processes.

Despite these reservations, the view persists that the record can be regarded as a combination of 'signal' (the deterministic, quasi-periodic influence of insolation), and 'noise' (a stochastic background added both by the sedimentation system and by the substantial random component of climatic variation); the implication is that the two can be analytically discriminated. We argue that the record is better regarded as the cumulative outcome of rare ‘events’ of accumulation, separated by hiatuses over a wide range of time scales; ‘background sedimentation’ is a misleading concept. The scale-invariant relationships between accumulation events impart the typically fractal-like character to sedimentary layering. The hiatuses in accumulation can also be shown to have a very wide distribution in their range of durations. The mode of accumulation of the typical stratigraphic record is incompatible with the steady, continuous encoding of a periodic ‘signal’.

The counter-argument to those who ‘harp on about the incompleteness of the stratigraphic record’ is that the existence of cycles has been mathematically proven by spectral analysis in many datasets. The second part of our paper considers the spectral methods that have become routine in cyclostratigraphic analysis and the errors of interpretation that they can cause.

Spectral analysis starts with the null hypothesis that the data series in question is random. If this is the case, the variance, or power, across its frequency spectrum will be statistically indistinguishable from that of ‘red noise’. If there is cyclicity at some spatial frequency in the data series there will be a corresponding peak in spectral power. The aim of the analysis is then to show that this peak has a small (usually < 0.05) probability of being a chance attribute of the data. This being the case, the peak is interpreted as representing as a cycle at that frequency.

In cyclostratigraphic studies based on spectral analysis there are two common sources of error leading to an incorrect identification of cyclicity.

1) Since rates of accumulation, including net rates, are generally indeterminate, there is no means of deciding which of the peaks in the power spectrum of a data series have time frequencies corresponding to orbital (Milankovitch) quasi-periods. Thus, all peaks must be tested against a null hypothesis that they belong to a random, red noise spectrum. Multiple, simultaneous applications of the test increases the probability that peaks arising by chance will exceed the confidence threshold. Avoiding this source of false positives requires proportionate adjustment of the confidence parameter. Analysis of synthetic random datasets confirms that, without this correction, false positive cycle identifications arise at a predictable rate.

2) In order to conduct the null hypothesis test there must be a statistical model of the expected noise in the data. Since stratigraphic data series typically show red noise characteristics, it has become conventional to adopt one of the simplest representations of red noise: first-order autoregression (AR(1)). We show that, in a number of cyclostratigraphic studies, false positive cycle identifications have arisen simply because this noise model imperfectly represents the actual data.

These sources of mistaken cycle recognition feature in many of the spectrally-based cyclostratigraphic studies conducted to date. It follows that the cycles and the high-resolution chronostratigraphic calibrations they suggest are suspect. We give some recommendations for analytical procedures that will limit false positive cycle identification.

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Improving the Geologic Time Scale

Felix M. Gradstein[1], James Ogg [2], Gabi Ogg [2], Mark Schmitz [3] et al.

[1] *Oslo University, Norway;*
[2] *Purdue University, West Lafayette, IN, USA;*
[3] *Boise University, ID, USA.*

Arthur Holmes, the Father of the Geologic Time Scale once wrote: "*To place all the scattered pages of earth history in their proper chronological order is by no means an easy task*". Ordering these scattered and torn pages, and understanding the physical, chemical and biological processes that acted on them since Earth appeared and solidified requires a detailed and accurate time scale.'

Calibration to linear time of the succession of events recorded in the rocks on Earth has three components: (1) the standard stratigraphic divisions and their correlation in the global rock record, (2) the means of measuring linear time or elapsed durations from the rock record, and (3) the methods of effectively joining the two scales, the stratigraphic one and the linear one.

Under the auspices of the International Commission on Stratigraphy (ICS), over 65% of international stratigraphic divisions and their correlative events are now standardized, especially using the GSSP (Global Stratigraphic Section and Point) concept.

The radiometric (U-Pb and $^{40}Ar/^{39}Ar$) and orbital tuning methods are becoming better calibrated, and external error analysis improved. Existing $^{40}Ar/^{39}Ar$ ages become 0.64% older, and U/Pb ages stratigraphically more realistic, although often scaling uncertainty remains between the sedimentary levels of an age date and that of a stage boundary. Resolution of age dating exceeds that of biochronology, but not of orbital tuning.

Since 1981, six successive Phanerozoic GTSs have been published, each new one achieving higher resolution, better error analysis, and more users worldwide. The next GTS will become available mid 2012, with over 65 specialists taking part in a full color Elsevier publication of 32 book chapters, as follows:

Introduction, *F.M. GRADSTEIN*
Chronostratigraphy, linking time and rock *F.M. GRADSTEIN and J.G. OGG*
Biochronology, *F.M. GRADSTEIN*
Cyclostratigraphy and astrochronology, *L.A. HINNOV and F.J. HILGEN*
The geomagnetic polarity time scale, *J.G. OGG*
Radiogenic isotopes geochronology, *M. SCHMITZ and M. VILLENEUVE*
Strontium isotope stratigraphy, *J.M. MCARTHUR, R. J. HOWARTH and G. SHIELDS*
Osmium isotope stratigraphy, *B. PEUCKER-EHRENBRINK and G. RAVIZZA*
Sulfur isotope stratigraphy, *A. PAYTAN*
Oxygen isotope stratigraphy, *E. GROSSMAN*
Carbon isotope stratigraphy, *M. SALTZMAN and E. THOMAS*
A brief history of plants on Earth, *S.R. GRADSTEIN and H. KERP*
Sequence chronostratigraphy, *M. SIMMONS*
Statistical procedures *F. P. AGTERBERG, O. HAMMER and F.M. GRADSTEIN*
The Planetary time scale, *K. TANAKA and B .HARTMANN*
The Precambrian: the Archean and Proterozoic Eons, *M.VAN KRANENDONK et al*
The Cryogenian Period, *G.A. SHIELDS, A.C. HILL and B.A. MACGABHANN*
The Ediacaran Period, *G. NARBONNE, S. XIAO and G.A. SHIELDS*
The Cambrian Period, *S. PENG, L. BABCOCK and R. A. COOPER*
The Ordovician Period, *R.A. COOPER and P. M. SADLER*
The Silurian Period, *M.J. MELCHIN, R.A. COOPER and P. M. SADLER*

The Devonian Period, *T. BECKER, F.M. GRADSTEIN* and *O. HAMMER*
The Carboniferous Period, *V. DAVYDOV, D. KORN AND M.SCHMITZ*
The Permian Period, *CH .HENDERSON, V. DAVYDOV* and *B.WARDLAW*
The Triassic Period, *J.G. OGG*
The Jurassic Period, *J.G. OGG* and *L. HINNOV*
The Cretaceous Period, *J.G. OGG* and *L. HINNOV*
The Paleogene Period, *N. VANDENBERGHE, R. SPEIJER* and *F.J. HILGEN*
The Neogene Period, *F.J. HILGEN, L. LOURENS* and *J. VAN DAM*
The Quaternary Period, *B. PILLANS* and *P. GIBBARD*
The Prehistoric Human Time Scale, *J.A. CATT* and *M.A. MASLIN*
The Anthropocene, *J. ZALASIEWICZ*, *P. CRUTZEN* and *W. STEFFEN*
APPENDIX –*M. SCHMITZ*; APPENDIX - *E. ANTHONISSEN* and *J.G. OGG.*

To ensure linear continuity between geologic periods and undertake error analysis, the linear scale using 265 recalibrated radiometric dates was constructed by *F. Gradstein, O. Hammer, J. Ogg and M. Schmitz*, in close consultation with individual chapter authors.

Relative to GTS2004, 26 of 100 stage or series boundaries have changed age, of which 14 have changed more than 4 myr, and 4 (in the Middle to Upper Triassic) between 6 and 12 myr.

Precambrian is at the dawn of a geologically meaningful stratigraphic scale. Stratigraphy of the Cryogenian and Ediacaran Periods in the latest Precambrian is developing rapidly, with many new chemostratigraphic, biostratigraphic and radiometric correlation levels.

Paleozoic chronostratigraphy and geochronology (541 - 252 Ma) are becoming stable. A majority of stages have ratified boundaries. Integration of a refined 100 and 400 kyr sedimentary cycle scale with a truly high-resolution U/Pb age scale for the Pennsylvanian is a major step towards the global Carboniferous GTS. Visean with 17 myr duration is the longest stage in the Phanerozoic Era.

Several stages in the Mesozoic Era (252 - 66 Ma) still lack formal boundary definition, but have consensus boundary markers. Lack of the latter and of sufficient radiometrics for the Carnian, Norian and Rhaetian Stages in the Triassic, make these 3 long stages less certain. The Triassic-Jurassic boundary is well dated at 201.3 ± 0.2 Ma. Earliest Triassic Induan, with 1.5 myr duration is the shortest Mesozoic stage.

The single ~400 kyr Earth eccentricity component is very stable and extends orbital tuning from the Cenozoic well into the Mesozoic GTS. Jurassic and Cretaceous now have long orbitally tuned segments that confirm the GTS2004 scale built using seafloor spreading. Recalculation of $^{40}Ar/^{39}Ar$ ages at the Cretaceous–Paleogene boundary yields an age estimate of 65.91 ± 0.11 Ma, instead of 65.5 ± 0.3 Ma in GTS2004; the new age rounds off to 66 Ma.

A completely astronomical-tuned GTS (AGTS) for the Cenozoic is within reach, showing unprecedented accuracy, precision and resolution. Burdigalian in the Miocene, and Chattian, Bartonian and Priabonian Stages in the Paleogene still require formal definition. Cenozoic and Cretaceous microfossil biochronology is being actively tied to the orbitally tuned scale.

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Prospects for a High Fidelity Permian Stratigraphy

Charles M. Henderson, *Department of Geoscience, University of Calgary, Calgary, AB. Canada,*

The stratigraphic record has so many complexities that it is difficult to imagine that a truly precise, high-fidelity record will ever be achieved, especially deep into the Paleozoic. The best prospects for a high fidelity Permian stratigraphy will come from the integration of as many stratigraphic techniques and correlation tools as possible; no single technique will suffice to get us there. Complexities include, but are not limited to, the occurrence of unconformities - especially the cryptic variety, distribution of facies, provincialism, and biologic evolution. Correlation tools like stable-isotopic analysis, geochronology using IDTIMS on high-temperature annealed and chemically abraded single zircons, orbital cyclicity tuning, and biostratigraphy are becoming increasingly precise, but apparent conflicting results can occur, indicating that some underlying assumptions may not be as well understood as we would like. Quantitative biostratigraphic techniques like CONOP9 and unitary association are very useful, but it can be argued that there is considerable scope for what might be called traditional (first appearance datum or FAD) biostratigraphy. Two case studies, one near the base of the Permian and one near the top, will be discussed to consider some of the complexities and problems limiting the prospects of a high fidelity Permian stratigraphy.

The stratigraphic record for the latest Carboniferous and earliest Permian is dominated by glacial eustatic driven cyclothems, each with an eccentricity cycle duration of about 404 Kyrs. Schmitz and Davydov (2011) have provided a high resolution record of the Uralian succession in Russia using geochronology and biostratigraphy. As a result, the 3.4 Myr Asselian is zoned by speciation within the conodont genus *Streptognathodus* and the 5.4 Myr Sakmarian and Early Artinskian are zoned by speciation within the conodont genus *Sweetognathus*. Schmitz and Davydov (2011) compared the Uralian record to that of the Council Grove and Chase groups in the North American mid-continent (NAM) basins (Boardman et al., 2009). They expected 22 cyclothems in the 8.8 Myrs of the Asselian and Sakmarian, but only 10 are preserved between the respective conodont datums (*Streptognathodus isolatus* for base-Asselian and *Sweetognathus whitei* for base-Artinskian). They made the very valid assumption that there are more gaps than record and suggested that considerable time was recorded as missing during the formation of various paleosols at the top of many cyclothems. Henderson et al. (2009) suggested, on the basis of correlation with a Bolivian succession marked by both ash beds and abundant conodonts that two distinct lineages of *Sweetognathus* developed at different times. The Uralian *Sweetognathus "whitei"* and the NAM *S. whitei* may be separated by as much as 5 million years. In this case, the 10 cycles may easily represent the first 4 million years of the Permian (Asselian to Early Sakmarian) and paleosol gaps restricted only to within some part of each 404 Kyr cycle. The veracity of this assumption still needs to be tested using a technique like strontium isotopic analysis of conodonts, but it does point out the complexities of interpreting an evolutionary record that may actually repeat itself.

Profound Middle and Upper Permian provincialism makes interregional correlations difficult between Tethyan faunas in South China zoned by *Jinogondolella* and *Clarkina* and Boreal faunas in the Canadian Arctic zoned by *Mesogondolella*. Permian biodiversity declines gradually throughout the Middle and Upper Permian in the Canadian Arctic succession such that there are no calcareous benthic fossils remaining as the Permian-Triassic boundary (PTB) is approached. A final extinction of hyalosponges and demosponges has been traditionally correlated with the Tethyan extinction making the reasonable assumption that the largest extinction in Earth's history was synchronous. Is this true from a high fidelity perspective that will be needed if we are to truly understand the series of events including rapid temperature

increase and ocean acidification associated with CO_2 increase from Siberian trap volcanism? Fortunately, because of early stages of climatic warming,Tethyan species of *Clarkina* were able to migrate into the Sverdrup before the PTB. Algeo et al. (2012) demonstrated that the end-Permian extinction was globally diachronous using a number of geochemical proxies, but primarily stable organic carbon isotopic trends integrated with traditional conodont biostratigraphy. A high-resolution Late Permian record in South China was reported by Shen et al. (2011) in which they integrated numerous precise CA-IDTIMS dates with an analysis of abundant biostratigraphic data using CONOP9. By comparing these two records, Algeo et al. (2012) demonstrated that the Arctic sponge extinction preceded the Tethyan extinction by about 100 Kyrs. Recent attempts to test this interpretation in Western Canada using conodont Sr-isotopes reveal potentially useful secular changes, but values are far more radiogenic than previously reported
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The above cases suggest that a high fidelity record is possible for the Permian around certain key points or events like end of glaciation and extinction, but that we are still a long way from devising tests that will confirm the accuracy of our assumptions and interpretations.

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Recent Development in High-Precision, High-Accuracy, Radio-Isotopic Dating Applied to the Stratigraphic Record

Daniel J. Condon, *NERC Isotope Geosciences Laboratory, British Geological Survey, NG12 5GG, UK*

In the past decade a concerted effort has been made to refine and advance the radio-isotopic dating methods (primarily U-Pb and ^{40}Ar-^{39}Ar) commonly applied to the dating of minerals from volcanic layers that are in turn used to infer the age and amount of time in certain stratigraphic units. The need for increased temporal resolution within a given succession, and the robust integration of disparate records has been a major driver for development of methodologies. Improvements in laboratory protocols and mass spectrometry have resulted in increased precision, however whilst increasing precision is attractive it has revealed some limitations: (1) bias between both laboratories and radio-isotopic decay schemes, thus hindering the integration of data generated in different laboratories, using different decay schemes; and (2) complexity in high-precision dates obtained on single crystals (or fragments) and how the mineral dates relate to the age of a particular stratigraphic level.

Inter- and intra-chronometer bias is being addressed through a series of calibration experiments carried out by the geochronology community under the auspices of the EARTHTIME initiative. Non-simple mineral systematics revealed through higher-precision dating is being addressed through detailed petrographic studies guiding the sampling for radio-isotopic dating, and multi-chronometer studies that exploit the strengths of different systems. In turn, high-precision radio-isotopic dates are being integrated with temporal information derived from studies of cyclicity resulting in high-accuracy, high-resolution age models for certain stratigraphic successions. This presentation will highlight a number of recent studies, from the Neoproterozoic to the Cenozoic, where this integrated high-resolution approach for the quantification of time in the stratigraphic record has been applied.

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The Role of Chemostratigraphy in Developing a Sequence Stratigraphic Scheme for the Middle to Upper Jurassic Successions of the UK Central Graben

Lees, B.M.T[1]; Pearce, T.J[2]; Meadows, N[3]; Martin, J.H[2]

[1]Chemostrat Ltd, Unit 1 Ravenscroft Court, Buttington Cross Enterprise Park, Welshpool, Powys, SY21 8SL, U.K.
[2]Chemostrat Ltd, Unit 1 Ravenscroft Court, Buttington Cross Enterprise Park, Welshpool, Powys, SY21 8SL, U.K.
[3]Redrock International Ltd, 38 Queens Drive, Prenton, Wirral, CH43 0RP, U.K.

In the Middle to Upper Jurassic of the UK Central Graben, the key to exploration lies in the mapping of the distribution of turbidites, shallow marine and shoreface sandstones, which are proven reservoirs. However, drilling occurs in a HPHT regime and the establishment of a reliable chronostratigraphic framework is hampered by moderate to poor biostratigraphic recovery and inconsistent wireline correlations. To counter these issues an independent sequence stratigraphic model for the Jurassic successions, based on the integration of chemostratigraphic, sedimentological, biostratigraphic and heavy mineral data, has been established.

This paper reports on Phase 1 of an ongoing basin wide study over 100 wells. This multidisciplinary approach has led to the establishment of a detailed chemostratigraphic correlation framework, which in selected type wells can be tied to existing biostratigraphic zonations and associated sequence stratigraphic schemes. The corroboration of the chemostratigraphic scheme in the type wells enables the chemostratigraphic methodology to be applied basin wide with the creation of a new chronostratigraphic framework to constrain paralic, shallow marine and basinal facies within the Jurassic succession. This chemostratigraphic scheme reflects changes in mineralogy, depositional environment, climate and provenance as recognised by changes in the elemental concentrations. A sedimentological model developed as part of this study for the Pentland/Fulmar Formations also suggests the successions may be subdivided into highstand and lowstand systems tracts on the basis of sedimentary facies and evidence for paralic/marine environments. From this model, it is evident that while many of the reservoir sandbodies lie within lowstand systems tracts this is not universally the case and episodes of increased sediment flux resulted in forced regressions such that fluvio-distributary channel sandbodies occur interbedded with shallow marine facies.

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Brute Force Biochronology: Building Parsimonious High-Resolution Palaeozoic Time-Lines by Constrained Optimization

Peter M. Sadler, *Department of Earth Science, University of California, Riverside, California 92521, USA*

First-appearances of a few hundred index taxa from five fossil clades currently serve to divide early Palaeozoic time into zones and subzones. First- and last-appearance events of thousands more trilobite, graptolite, conodont, chitinozoan and acritarch taxa are potential contributors to a much more finely divided time-line. Relatively few of these events are recovered from any one section of contiguous strata and their order tends to vary from section to section. Contradictions between local sequences of range-end events are an inevitable result of the dynamic, provincial and patchy distribution of living organisms that is further complicated by incomplete preservation and sampling. Yet there is a simple underlying relationship: locally recovered taxon ranges tend to under-estimate true regional and global ranges. Local range charts can be brought into agreement by stretching the observed ranges to fit a single global sequence. Although true sequences of first- and last-appearances are probably unknowable, practical and parsimonious approximations exist.

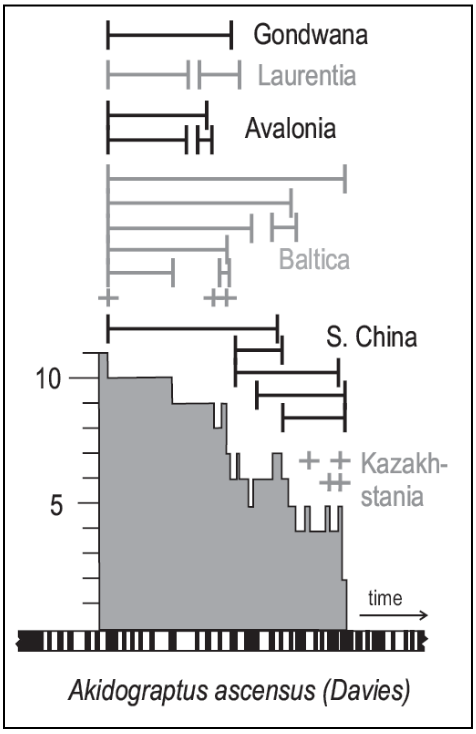
Constrained optimization algorithms can find sequences of large numbers of range-end events that minimize the implied net short-fall of observed local ranges. Local ranges are stretched to the minimum amount necessary to bring all local range charts into agreement with a single time line of events. Rather than building up a composite sequence from the data, adding sections one at a time as in graphic correlation, the algorithms invert the graphic procedure and consider all the information from the outset. A trial-and-error process makes iterative improvements to a largely random initial sequence of events, via a very long series of mutations. Each mutation is evaluated for its fitness by comparison with the data, using a simulated annealing heuristic. The problem is underdetermined and the search yields numerous equally well fit sequences that differ in small details. The variation in position of an event across all equally well fit time-lines provides a natural measure of uncertainty and a limit to the number of uniquely resolvable events.

Currently this approach provides about a ten-fold increase in resolving power relative to biozones, when applied to single clades. Several large Paleozoic data sets have been compiled, sequenced, and subjected to varying degrees of quality control based on the outcomes: the entire graptolite clade (2135 taxa from 544 sections); Cambrian to earliest Devonian conodonts (2589 taxa, 640 sections); latest Silurian to Mississippian conodonts (1441 taxa, 364 sections), chitinozoans (910 taxa, 144 sections); Cambrian-Devonian acritarchs (1629 taxa, 93 sections); and the end Permian of Perigondwana (4111 taxa, 55 sections). Resolving power can presumably be increased by combining clades, but plausible outcomes depend upon sections in which known ranges for more than one clade.

Once the best-fit sequence is found, locally observed ranges are mapped back into the resulting composite range for each taxon. This indicates the support for the range ends, a means to identify outliers that might result from non-uniform taxonomy or data entry errors, and an opportunity to analyze geographic diachronism. The algorithms would make the local range ends of each taxon isochronous, if that were possible; typically it is not (Fig. 1).

Because the optimizing algorithms search among possible solutions by brute-force trial-and-error, it is easy to code other event types for which there is a predictable relationship between observed and true position in sequence. The number of equally parsimonious sequences and computation times can be significantly reduced by including events that are better constrained than taxon range ends. Some marker horizons, like ash-fall tuffs, may be assumed to correlate without any uncertainty. The limits and peaks of carbon isotope excursions and the analytical errors of radioisotopic age determinations may be expressed as conservative uncertainty intervals. Unlike taxon ranges that stretch to fit during optimization, uncertainty intervals shrink to fit the emergent optimal sequence. Dated tuffs facilitate time calibration. They enter the optimization in two sections. In the section from which they are sampled (ideally one with taxon ranges) their position may not be adjusted. In a time-scaled pseudo-section that holds all dated events, their two-sigma uncertainty is entered as an interval that may shrink to better fit all other evidence. Thus, superposition is honoured and the order of dated events with overlapping uncertainty may be resolved.

Plausible outcomes are reached most efficiently by initially sequencing only those taxon ranges known from five or more sections. The resulting composite sequence is entered as if it were an additional section and weighted heavily in a subsequent run that includes all the taxa. The key to good outcomes is to codify as much available time-stratigraphic information as possible, without over-estimating the precision of any of it. Traditional stratigraphic expertise is not abandoned. Rather, the computer algorithms apply stratigraphers' logic to otherwise unmanageably large volumes of information – hundreds of local range charts, thousands of taxa and dozens of other events. It is possible, but rarely necessary, to weight independently every range end event in every section. The method is explicit and reproducible. It places a premium on careful taxonomy, integrated studies of single sections, and publication of detailed range charts. It



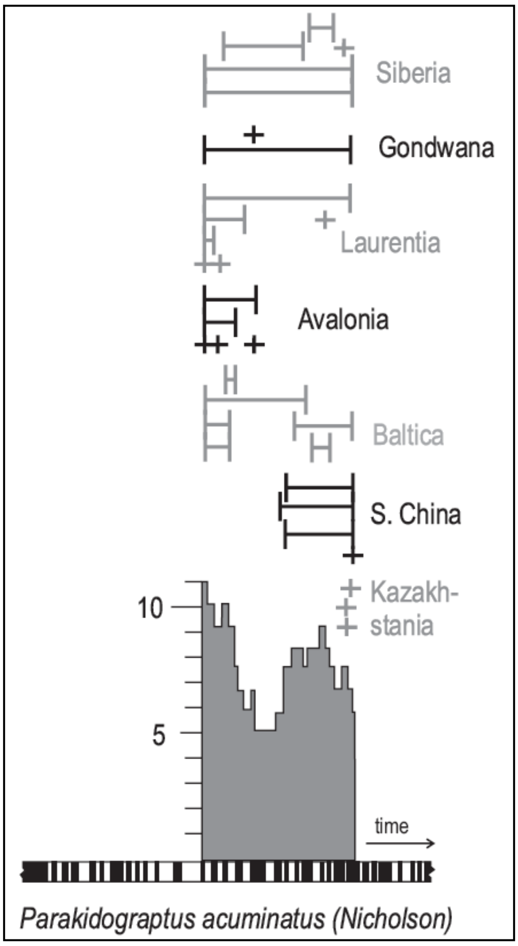


Figure 1: Local support for two composite graptolite ranges. Gray histograms show the number of local ranges (horizontal bars) as a function of position in best-fit composite range. Black bars in the basal time line are scaled positions of other graptolite range end events.

NOTES

Magnetic Susceptibility as a High-Resolution Correlation and Paleoenvironmental Tool in Palaeozoic Records: Merits and Pitfalls.

Anne-Christine da Silva[1], Mark J. Dekkers[2], David De Vleeschouwer[3], Philippe Claeys[3], Frédéric Boulvain[1]

[1] *Pétrologie sédimentaire, B20, Boulevard du rectorat, 15, Liège University, 4000 Liège, Belgium. Email : ac.dasilva@ulg.ac.be*
[2] *Faculty of Earth Sciences, Department of Earth Science, Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, Utrecht, The Netherlands*
[3] *Earth System Sciences and Department of Geology, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium*

Magnetic susceptibility (MS) is a commonly used tool in sedimentary rocks for paleoclimatic research and for high resolution correlations. High resolution correlations between sections are feasible on the basis of the link between MS and detrital input which is argued to have a higher magnetic susceptibility than carbonates. MS is a very interesting for this kind of work because data acquisition is fast and straightforward, providing the high amount of samples needed for such study. However, the original paleoenvironmental signal can be affected by different syn- or post-depositional processes, mostly in the case of Palaeozoic rocks.

In this contribution, we synthesize 10 years of our research on the application and on the origin of the magnetic susceptibility signal in the Devonian record of Belgium. This record is of particular interest, because the biostratigraphy is well known and there is a relatively continuous record over 20 My and through various paleoenvironments (platform, ramp, atoll) with different diagenetic maturity.

The first step was to compare MS with facies and to try to correlate the different sections. On the Frasnian platform sections, there is a clear link between MS and facies, with MS increasing towards shallower facies. This increase of MS towards shallower facies seems logical since these facies were deposited closer to the detrital inputs sources. When considering ramp (Eifelian-Givetian) and atoll sections (Frasnian), the MS relationship with facies is opposite and MS increases towards the deepest facies. This was interpreted as related to the water agitation and carbonate production rate being lower in the deeper environments and allowing concentration of detrital particles. Although, correlations were possible between the different Frasnian atoll sections, but not with the carbonate platform sections, since the MS signals are opposite in both settings. So the depositional setting can be a key parameter influencing the way the original magnetic susceptibility signal is recorded and should be interpreted.

In order to identify some of the external parameters influencing the magnetic susceptibility signal; a MS curve from the Eiflian-Givetian ramp was selected for time-series analysis. This spectral analysis highlights persistent high-frequency meter scale cycles which are interpreted as reflecting changes in flux of magnetic minerals, most likely controlled by monsoon rainfall-intensity. By combining chrono- and biostratigraphic information with theoretical knowledge of sedimentation rates in different depositional environments, these cycles are interpreted as astronomically driven (precession-dominated). So this shows that, in some cases, the magnetic susceptibility signal can be affected by astronomical forcing, through detrital inputs
.
To get a better understanding about the nature and origin of the magnetic susceptibility signal, it is crucial to identify the magnetic minerals which are carrying this MS signal. Geochemistry and magnetic analyses (hysteresis and acquisition curves of the Isothermal Remanent Magnetic Saturation IRM) were performed on three sections (two Frasnian platform sections and one Eifelian Givetian platform section). Magnetic parameters show that the MS signal is mostly influenced by fine-small grained

magnetites which were formed during a Variscan remagnetization event. This remagnetization occured during the Carboniferous and is thought to be related to the transformation of smectite to illite (releasing the iron for the magnetite formation). In two sections (the Eifelian Givetian platform section and one of the Frasnian platform), there is a strong link between the MS signal and TiO_2, Al_2O_3 and Zr which are detrital proxies. This shows that despite the remagnetization, the MS signal is still related to detrital input, indicating that the newly formed magnetite probably remained associated with the original clay minerals, leading to a globally increased signal still reflecting the primary trends. In one section (Frasnian platform), there is no strong link between MS signal and detrital proxies, indicating that in this case the MS signal was affected by the remagnetization event (possibly in relation with fluid circulation).

In conclusion, MS appears as a convolved signal, influenced on one hand by primary parameters such as detrital inputs and orbital cyclicities. These paleoenvironmental trends can also be affected by depositional parameters such as water agitation and carbonate production. Furthermore, the diagenesis can also have a strong impact on the final signal. This clearly highlights the need to use magnetic susceptibility in conjunction with other techniques (comparison with other paleoenvironmental proxies or magnetic or geochemical analysis).

NOTES

Towards an Astronomically Tuned Early Paleogene Time Scale

Frederik J. Hilgen[1], **Sietske J. Batenburg[2,3]**, Lucas J. Lourens[1], and Klaudia F. Kuiper[1,4]

[1] *Department of Earth Sciences, Utrecht University, Utrecht, the Netherlands*
[2] *Istituto per l'Ambiente Marino Costiero (IAMC-CNR), Napoli, Italy*
[3] *Department of Earth and Environmental Sciences, University of Portsmouth, Portsmouth, United Kingdom*
[4] *Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands*

Demonstrating very long period astronomical forcing of periods of exceptional warmth - hyperthermals – in the early Cenozoic Greenhouse world critically depends on the astronomical tuning of climate proxy records and the accuracy of astronomical solutions. During the last years, significant progress has been made in constructing an astronomical time scale for the Paleocene and Early Eocene and in establishing a much improved numerical solution for the Solar System, with La2011 being potentially accurate over the last 54 million years for full eccentricity. However, cyclostratigraphic interpretations differ in the number of 405-kyr cycles, while different tuning options to 405-kyr eccentricity have in addition been presented in literature. In this debate, the intercalibration of different numerical dating techniques (Ar/Ar, U/Pb and astronomical dating) and in particular the astronomically calibrated age of 28.201 +- 0.046 Ma (2s) for the Fish Canyon sanidine Ar/Ar dating standard plays a decisive role. For instance, a discrepancy of ~0.5 Myr was found around 50 Ma between radio-isotopic and astronomical age models used for the construction of the standard Paleogene time scale in GTS2012. Also, there is ongoing debate and uncertainty in establishing the age of the K/Pg boundary. Here we will give an overview of the current impasse and come up with a possible solution for the problems encountered in establishing the astronomical time scale for the early Paleogene.

NOTES

The Neogene Astronomical Tuned (Polarity) Timescale between 5 and 14 Ma Revisited

Christian Zeeden; Dr. Frederik Hilgen, Prof. Dr. Lucas Lourens, Dr. Silja Hüsing, *Department of Earth Sciences, Utrecht University.*

The Monte dei Corvi section (near Ancona, Italy) comprises an orbitally forced cyclic pattern and a good magnetostratigraphy, which allows the direct orbital tuning of magnetic reversal ages. However, it became obvious that the orbital solution using recent day values for tidal dissipation and/or dynamical ellipticity does not give a good fit with the geologic cyclic pattern.

Using high resolution colour data, we apply cross spectral analysis between an orbital target curve and the colour data as proxy for the observed pattern. We translate leads/lags to the tidal dissipation parameter of the Earth in the orbital solution and thus optimise the fit of geological pattern with the orbital solution.

This approach results in most accurate ages for precession- and obliquity-pattern in the tuned record. Because the polarity timescale is based on the tuned timescale, our results have direct implications on the polarity timescale.

The research leading to these results has received funding from the [European Community's] Seventh Framework Programme ([FP7/2007-2013] under grant agreement n° [215458].

NOTES

Dynamics of a Stepped Carbon-Isotope Excursion: Ultra High-Resolution Study of Early Toarcian (Early Jurassic) Environmental Change

Hermoso, M.[1], Minoletti, F.[2,3], Rickaby, R.E.M. [1], **Hesselbo, S.P.[1]**, Baudin, F. [2,3] and Jenkyns, H.C. [1]

[1] *University of Oxford, Department of Earth Sciences, South Parks Road, Oxford OX1 3AN, United Kingdom*
[2] *UPMC Univ Paris 06, UMR 7193 ISTeP, 4 place Jussieu, 75005 Paris, France*
[3] *CNRS, UMR 7193 ISTeP, 4 place Jussieu, 75005 Paris, France*

In the Toarcian (Early Jurassic; ~183 Myr ago), the ocean–atmosphere system was subject to one of the largest perturbations of the carbon cycle in the last 250 Myr, known as the Toarcian Oceanic Anoxic Event (TOAE). This event was accompanied by a −6 per mil negative carbon-isotope excursion (CIE) caused by massive injection of isotopically light carbon into the ocean–atmosphere system, possibly from destabilisation of gas hydrates. This study reveals the pacing and sequence of events leading up to the CIE and to widespread deposition of organic-rich sediments. The very high-resolution isotopic record from exceptionally well preserved carbonate and organic matter from the Paris Basin enables recognition of increased carbon dioxide levels ~130 kyr in advance of the major negative CIE. An accelerated increase in the pCO2 is registered ~25 kyr before the onset of this negative excursion and was so rapid and so intense that it led to a water column undersaturated with respect to calcium carbonate in the Paris Basin. Undersaturation is expressed as a dramatic drop in the accumulation of the biogenic calcite produced by the surface-dwelling calcifiers. These environmental perturbations, representing precursor phases of CO2 injection, predate the first step towards relatively light carbon-isotope values in carbonate and organic matter, and are tentatively attributed to Karoo–Ferrar magmatism. This negative shift was registered slightly earlier in terrestrial carbon than marine carbonate. Subsequent global warming is credited with liberating isotopically light carbon, and ultimately fostered anoxia in the Paris Basin: the response of these cumulative inputs of carbon to the Earth system. Isotopic and sedimentological evidence indicates continuously elevated phytoplanktonic productivity throughout the first step of the negative CIE, suggesting that the biological pump accelerated the drawdown of excess carbon leading to temporary recovery of carbonate sedimentation, ~45 kyr after the first step of the CIE. This re-establishment of the saturation state of the water column was only fleeting before the further stepwise release of isotopically light carbon.

NOTES

Comparison and Palynological Correlation of Pennsylvanian to Cisuralian Glacigene Rocks in Oman, Yemen and Pakistan

Michael H. Stephenson[1], Irfan U. Jan[2] and Sa'ad Zeki A. Kader Al-Mashaikie[3]

[1]*British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG, United Kingdom*
[2]*National Centre of Excellence in Geology, University of Peshawar, Pakistan;*
[3]*Geological Survey and Mineral Resources Board, Sana'a, Yemen*

Understanding of the biostratigraphy of isolated basins that preserve Pennsylvanian to Cisuralian non-marine, glacigene sediments has improved recently, but a pan-Gondwanan biostratigraphical scheme remains elusive. This means that the key events of glaciation across the continent, for example the timing of the onset of glaciation or deglaciation, cannot easily be compared.

Gondwana non-marine Pennsylvanian to Cisuralian glacigene sediments are difficult to correlate because they lack key zonal fossils, for example, foraminifera, corals, and most importantly conodonts. Correlation thus relies mainly on palynology; however palynological correlation across Gondwana is difficult also - mainly because of palynomorph (plant) provinciality.

One way to sidestep the effects of provinciality is to correlate precisely between nearby basins or regions and then use cosmopolitan palynomorph taxa to link high-resolution, regional-based schemes.

The objectives of the present study were to (1) test the applicability of a newly-published high-resolution Oman biozonation across nearby basins in Yemen and Pakistan; (2) correlate using the biozonation if applicable; and (3) thereby understand the age-distribution of glacigene rocks in the three areas. A secondary objective was to look for linking taxa.

Palynological assemblages from sections in Yemen and Pakistan are similar enough to allow the application of biozones based on the glacigene sediments of interior Oman. Thirty four samples from the upper 84 m of a 125 m thick section of the Tobra Formation at Zaluch Nala, western Salt Range, Pakistan yielded palynomorph taxa indicating the late Pennsylvanian Oman 2165B Biozone. Eleven samples from the Yemen Kuhlan Formation, and 22 samples from the underlying Akbarah Formation from approximately 300m of a section near Kuhlan in northwest Yemen, suggest a 2165A Biozone age (also late Pennsylvanian). This correlation indicates the widespread nature of glacial sediments of a narrow biostratigraphic late Pennsylvanian age range (the Oman P5 unit) in basins across part of the north Gondwana margin. New data from three samples from the Tobra Formation at the Choa Road section in the eastern Salt Range, Pakistan indicate the earliest Permian 2141B Biozone, indicating a possible correlation between the 'Tobra shale' and the Rahab Shale Member of Oman, which is considered to mark the final deglaciation sequence in Oman.

NOTES

Poster Presentation Abstracts
(in Alphabetical order)

Integrated high resolution chronology of Upper Cretaceous- Lower Paleogene continental successions in the Western Interior Basin, Saskatchewan, Canada

Anne U. Fischer[1], Diana Sahy[2], Klaudia F. Kuiper[1, 3], Jan R. Wijbrans[1], Frits J.Hilgen[3] and Daniel J. Condon[2]

[1] *Faculty of Earth and Life Sciences, Vrije Universiteit, 1085 De Boelelaan, Amsterdam, 1081 HV,*
Netherlands
[2] *NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham, NG12 5GG, United Kingdom*
[3] *Stratigraphy/Paleontology, Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands,*

One of the aims of GTSnext – a Marie Curie Initial Training Network – is to refine the Upper Cretaceous-Lower Paleogene geological time scale. For the marine realm high resolution geochronological records based on integration of magnetostratigraphic data and astronomical tuning of the IODP records and the landbased Zumaia section in Spain became recently available (e.g. Batenburg et al., submitted, Hilgen et al., 2010).

Here we studied two continental sections in Saskatchewan, Canada, which are part of the Western Interior Basin in mid-continental North America. Both sections spanning the Cretaceous-Paleogene boundary (K/Pg) and include the Late Cretaceous Frenchman and the Early Paleocene Ravenscrag formations. The formations consist of clastic continental fluvial and fluvial floodplain deposits appearing as alternations of coal/coaly shale beds with marl and sands. The transition of the Frenchman to Ravenscrag formation is marked by the first occurrence of coal seams. The basal part of the Ravenscrag Formation yields a coal seam, which is known as *Ferris coal* (equivalent to the Nevis coal seam of Alberta and the lower Z coal of Montana) and represents the Cretaceous-Paleogene boundary, indicated by a light pink impact layer and iridium anomaly just above the base of the *Ferris coal* (Sweet et al., 1999, Lerbekmo, 1999). Volcanic ash layers occur within the coal seams and were sampled and dated using 40Ar/39Ar and U-Pb geochronology.

For comparative purposes a lateral continuous volcanic ash just below the top of the K/Pg coal seam was sampled in multiple locations. Further, we attempted to confirm and improve the existing magnetostratigraphic data of Lerbekmo et al. (1985, 1987, 1996). Combined with the new 40Ar/39Ar (sanidine) & U-Pb (zircon) high resolution geochronological ages we will correlate these continental sections to the marine record. Furthermore, we explored the potential of astronomical forcing in a fluvial sedimentary succession, using colour and magnetic susceptibility measurements.

The research within the GTSnext project leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° [215458].

Defining the tempo of paleocommunity collapse and recovery during the Silurian with integrated geochronology and bio-chemostratigraphy

Bradley D. Cramer[1], **Daniel J. Condon[2]**, Ulf Söderlund[3], Carly Marshall[4], Graham J. Worton[5], Alan T. Thomas[4], Mikael Calner[3], David C. Ray[6,7], Vincent Perrier[8], Ian Boomer[4], P. Jonathan Patchett[9] & Lennart Jeppsson[3]

[1]*Kansas Geological Survey – University of Kansas, Lawrence, Kansas 66047, USA*
[2]*NERC Isotope Geosciences Laboratory, BGS, NG12 5GG, UK*
[3]*Department of Earth and Ecosystem Sciences, Lund University, Lund SE-223-62, Sweden*
[4]*School of Geography, Earth and Environmental Sciences, University of Birmingham, B15 2TT, UK*
[5]*Dudley Museum and Art Gallery, St. James' Road, Dudley, West Midlands DY1 1HZ, UK*
[6]*School of Earth and Environmental Sciences, University of Portsmouth, Portsmouth PO1 3QL, UK*
[7]*Neftex Petroleum Consultants Ltd., Abingdon OX14 4RY, UK*
[8]*Department of Geology, Institute of Ecology and Earth Sciences, University of Tartu, Tartu 50411, Estonia*
[9]*Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA*

For the first time in the lower Paleozoic, we have integrated high-precision U-Pb (Zircon) age dating using CA ID-TIMS with high-resolution biostratigraphy of conodonts and graptolites, together with high-resolution $\delta^{13}C_{carb}$ chemostratigraphy (as bio-chemostratigraphy) to produce an exceptionally detailed record of one of the largest global change events during the lower Paleozoic. The 'Big Crisis' or *Grosse Krise* (as it was originally defined by Jaeger) impacted a broad swath of the oceanic community, and the detailed resolution produced in the current study allows the accurate determination of both the relative duration of the biotic and chemical events, and in addition, the investigation of interactions between and among the various members of the marine biosphere. Paleocommunity collapse took place within the span of only a few hundred kyr, and the ecospace and resources made available by the collapse were being utilized within only a few kyr to a few tens of kyr (at most). The entire event, from the onset of biotic turnover to the return to 'background' oceanic chemistry, was on the order of 1 Myr, demonstrating that the tempo of global change events during the lower Paleozoic was not dissimilar from the rest of the Phanerozoic Era. Global change operates within the 'Milankovitch-Band' (10-400kyr), and if we are to fully evaluate any global change event in Earth history we must be able to resolve the stratigraphic record to this level of resolution.

Geologic Time Scale 2012: overview

Felix Gradstein[1], **James Ogg[2]**, Mark Schmitz[3] and Gabi Ogg[2]

[2]Geological Museum, University of Oslo, P.O. Box 1172 Blindern, N-0318 Oslo, Norway;
[1]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana, 47907 USA,
[3]Department of Geosciences, Boise State University, 1910 University Drive, Boise, Idaho 83725-1535, USA

Earth's surface history is a complex interplay of climate, evolution and other processes framed within a geologic timescale with numerical ages. The *Geologic TimeScale 2012* program involved over 60 geoscientists, including officers of most subcommissions of the International Commission on Stratigraphy, working to integrate paleontology, radio-isotopic dating, cycle stratigraphy, geochemical trends, and other stratigraphic information. This synthesis includes detailed summaries of each geologic period with full-page graphics (map, section, photos) of each GSSP (international stage boundary) with age scales derived from a re-evaluation of radio-isotopic ages (including new monitor standards for Ar-Ar) coupled with astronomical cycle tuning. Additional components are a synopsis of our state of knowledge and formal geologic subdivisions of lunar and Martian stratigraphy, a massive synthesis in preparation for revising the Precambrian subdivisions, extensive sets of geochemical curves, and a summary of stages of humanoid evolution. Even though some periods are still lacking international agreement on all stage definitions and reliable high-precision age models, this compilation will be the reference standard for the remainder of this decade.

High precision radio isotopic age constraints on the Late Eocene – Early Oligocene geomagnetic polarity time scale

Sahy Diana[1], Fischer, Anne[2], Condon, Daniel J.[1], Terry, Dennis O. Jr[3], Hiess, Joe[1], Abels, Hemmo[4], Huesing, Silja K.[4], and Kuiper, Klaudia[2]

[1] *NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham, NG12 5GG, United Kingdom*
[2] *Faculty of Earth and Life Sciences, Vrije Universiteit, 1085 De Boelelaan, Amsterdam, 1081 HV, Netherlands*
[3] *Earth and Environmental Science, Temple University, Philadelphia, PA 19122, (4) Department of Earth Sciences, Utrecht University, Budapestlaan 17, Utrecht, 3584 CD, Netherlands*

Several versions of the geomagnetic polarity time scale (GPTS) have been published in the last few decades. Most of these rely on the calibration of marine magnetic anomaly profiles using radio-isotopically dated tie points from land based sections (Ogg and Smith, 2004), but astronomically tuned magnetic reversal records from pelagic sediments are also increasingly becoming available for the Eocene and Oligocene (Pälike et al., 2006). Correlation of local magnetic reversal patterns to the GPTS is often used to obtain numerical ages for deposits that cannot be dated directly using radio isotopic methods, but the uncertainties associated with ages obtained in this way are difficult to quantify and can potentially be quite large. Here we present a revised high precision and high resolution chronostratigraphic framework and magnetostratigraphic record from the terrestrial White River Group of North America with the aim of independently assessing the accuracy and precision of recent versions of the GPTS.

The White River Group consists of reworked volcaniclastic material and locally derived clastic sediments deposited in fluvial and eolian environments interspaced with primary air-fall tuffs. We have collected tuff samples and oriented magnetostratigraphic samples from two overlapping White River sections, at Flagstaff Rim (Wyoming) and Toadstool Geologic Park (Nebraska). Together, these two sections yield a somewhat continuous record which spans ~ 5 Myr and includes the Eocene-Oligocene transition.

The geochronology of our White River record is based on ^{238}U-^{206}Pb ID-TIMS zircon dates obtained from 16 primary air-fall tuffs. These U-Pb dates are consistently younger than previously published ^{40}Ar/^{39}Ar data (Swisher and Prothero, 1990; renormalized to an age of 28.201 for sanidine from the Fish Canyon Tuff) by as much as 0.8 Myr. This interpretation is supported by new preliminary ^{40}Ar/^{39}Ar sanidine dates obtained from 4 of our tuff samples that are in close agreement with the U-Pb dates. The U-Pb age model indicates nearly constant accumulation rates during the Eocene, followed by a sharp increase during the Eocene-Oligocene transition.

700 orientated cores were collected from Toadstool Park and Flagstaff Rim at an average resolution of 50 cm, equivalent to a temporal resolution of 10-30 kyr based on sedimentation rates calculate using the U-Pb data. 350 of these samples have so far been analyzed using a combination of thermal and alternating field demagnetisation techniques. The Oligocene part of our magnetostratigraphic record is in good agreement with previously published data (Prothero and Swisher, 1992), but two new normal polarity zones were identified in the Late Eocene Flagstaff Rim section. Our record correlates to magnetochrons C16n.2n – C12n of the GPTS. Numerical ages for each reversal were calculated using linear interpolation between the ages of the nearest tuffs. Uncertainties associated with these ages are on the order of ± 0.06-0.08 Myr (including systematic uncertainties for the U-Pb age model and uncertainties in the stratigraphic position of the reversals relative to the dated tuffs). Most of our dates fall within ~0.2 Myr of the reversal ages published in the 2004 edition of the Geological Time Scale (Ogg and Smith, 2004) and the astronomically tuned GPTS of Pälike et al (2006). This high-precision, highly resolved data set will hopefully lead to an

improvement in the integration of marine and terrestrial records of the Eocene-Oligocene transition, and additionally it provides a set of well constrained tie points that could potentially be used to improve the calibration of future versions of the GPTS.

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