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Lausanne, 15th – 16th November 2013

Plenary: Cycles and Events in the Earth System

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Cycles and Events in the Earth System

PLENARY SESSION, Friday November 15th 2013

Palais de Rumine, place de la Riponne.

13:30 - 14:00	<ul style="list-style-type: none"> • Welcome address by the Minister of Education, Youth and Culture of the Canton of Vaud • Welcome address by the Rector of the University of Lausanne 	Anne-Catherine Lyon Dominique Arlettaz
	<i>Chairperson: Benita Putlitz</i>	
14:00 - 14:35	<ul style="list-style-type: none"> • Fluids and Crustal Processes through Orogenic Cycles 	Bruce Yardley University of Leeds
	<i>Chairperson: Eric Verrecchia</i>	
14:35 - 15:10	<ul style="list-style-type: none"> • Banded Iron Formation and the Rise of Oxygen 	Kurt Konhauser University of Alberta
	<i>Chairperson: Karl Föllmi</i>	
15:10 - 15:45	<ul style="list-style-type: none"> • The impact of oceanic anoxic events on marine biota, ocean chemistry and Earth processes 	Angela Coe The Open University
15:45 - 16:30	Coffee break	
	<i>Chairperson: Stuart Lane</i>	
16:30 - 17:05	<ul style="list-style-type: none"> • Accounting for extreme events in Earth Surface Processes: the critical challenges 	Oliver Korup University of Potsdam
	<i>Chairperson: François Bussy</i>	
17:05 - 17:40	<ul style="list-style-type: none"> • Carbonation of mantle peridotite: Natural systems, global carbon cycle, engineered capture & storage 	Peter Kelemen Columbia University
	<i>Chairperson: Pierre Dèzes</i>	
17:40 - 18:30	<ul style="list-style-type: none"> • Communications Platform Geosciences • Presentation SGM 2014 in Fribourg • Paul Niggli Medal • Swiss Geological Society Award • CHGEOL Award 	Bruno Schädler Bernard Grobéty Klaus Holliger Neil Mancktelow Mikael Hänni
18:30 - ???	<ul style="list-style-type: none"> • Swiss Geoscience Party (food, drinks and rejoicing) for registered participants 	

Large picture: View from the Tierbergli on the Steisee, the Sustenpass and the Titlis (BE)

Small picture: Warning sign along the Wyssa aqueduct (bisse/Suone) above Mund (VS) (Pictures: Pierre Dèzes, SCNAT)

0. Plenary Session

- 1 Yardley, B.: Fluids and Crustal Processes through Orogenic Cycles
- 2 Konhauser K.: Banded Iron Formation and the Rise of Oxygen
- 3 Coe A.: The impact of oceanic anoxic events on marine biota, ocean chemistry and Earth processes
- 4 Korup O.: Accounting for extreme events in Earth Surface Processes: the critical challenges
- 5 Kelemen P.: Carbonation of mantle peridotite: Natural systems, global carbon cycle, engineered capture & storage

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Fluids and Crustal Processes through Orogenic Cycles

Yardley, Bruce

School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

There are some features of orogenic belts that have been repeated through time around the world, and almost certainly reflect fundamental properties of materials rather than coincidental repetition of plate movement patterns. One of the most basic observations in metamorphic terranes is that sedimentary sequences undergo pervasive ductile deformation while they are being buried and heated, beginning at very low temperatures, but when they subsequently cool through the same temperature range any deformation is more limited, and is strongly focussed. This universal cycle reflects the changing role of water through the orogenic cycle: during prograde metamorphism it is continuously released and allows extensive deformation by pressure solution at temperatures well below the notional brittle-ductile transition, whereas incipient retrograde reactions rapidly consume remaining pore water once cooling sets in, precluding deformation by mechanisms that require the presence of a water phase. Only where major structures such as shear zones allow water to penetrate deep crystalline crust does it show intense ductile deformation. The evidence of many years of accumulated geological observation is that rocks undergoing burial and heating are very weak, whereas those returning to the surface are strong and act as massive blocks, but this is simply the inevitable consequence of mineral equilibria dictating the fugacity of water in rock pores.

A second change between the burial and uplift stages of orogeny concerns rates of reactions. During burial and heating, rates of endothermic devolatilisation reactions are limited by heat supply, and so overall regional reactions proceed very slowly. During cooling and uplift, 2 types of reactions are possible, but both are subject to quite different constraints to prograde reactions. Retrograde reactions that reverse changes that took place during heating are limited by infiltration of volatiles; hydration reactions proceed very rapidly if water is present but the preservation of abundant high grade rocks demonstrates that this is very rarely the case. Rapid uplift and erosion leads to rapid decrease in pressure and under some metamorphic conditions, devolatilisation reactions can result. When this occurs, temperature becomes buffered by the mineral assemblage according to the prevailing pressure, and temperature drops as heat is consumed by endothermic reactions. These reactions can proceed more rapidly than those driven by heat input (Figure 1) and may be responsible for some orogenic gold deposits.

The direction of temperature change dictates whether crystalline rocks contain water, and thereby whether they are weak or and strong. These rheological differences in turn affect large scale crustal behaviour. While many aspects of orogenic belts do reflect the plate tectonic setting in which they originated, there are geochemical and petrological consequences of heating and cooling, burial and uplift, which also have a profound influence on their geological behaviour irrespective of external tectonic forces.

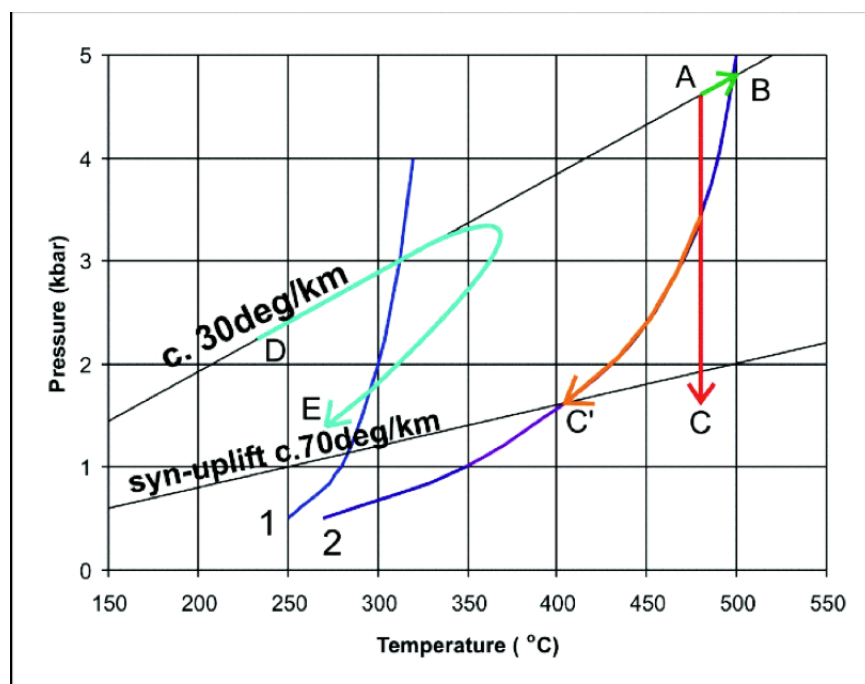


Figure 1: P-T diagram indicating possible P-T changes for a rock A sitting on an average crustal thermal gradient over a 4 Ma period. A-B denotes continued regional burial and heating. Path A-C is for rapid uplift without reaction, while A-C' shows the effect of uplift coupled to dehydration driven by the drop in pressure. For reference, path D-E shows heating followed by cooling with hydration reactions.

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Banded Iron Formation and the Rise of Oxygen

Kurt Konhauser

Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, T6G 2E3

Iron formations (IF) are iron rich (~20-40% Fe) and siliceous (~40-50% SiO₂) sedimentary deposits that precipitated throughout much of the Precambrian. Their trace element composition is now being used as a proxy for ancient seawater chemistry, with the view of better understanding the evolution of O₂-producing cyanobacteria and subsequent aerobic metabolisms. Two related examples are provided here. First, it has been shown that the Ni content in IF has changed dramatically over time, and that a drop in Ni availability in the oceans around 2.7 billion years ago would have had profound consequences for microorganisms that depended on it, that being methane-producing bacteria called methanogens¹. These bacteria have a unique Ni requirement for their methane-producing enzymes, and crucially, these bacteria have been implicated in controlling oxygen levels on the ancient Earth as the methane they produced was reactive with oxygen and kept atmospheric oxygen levels low. It is possible that a Ni famine eventually led to a cascade of events that began with reduced methane production, the expansion of cyanobacteria into shallow-water settings previously occupied by methanogens, and ultimately increased oxygenic photosynthesis that tipped the atmospheric balance in favour of oxygen, the so-called Great Oxidation Event (GOE) at around 2.5 Gyr. Second, a recent compilation of Cr enrichment in IF shows a profound enrichment coincident with the GOE². Given the insolubility of Cr minerals, its mobilization and incorporation into IF indicates enhanced chemical weathering at that time, most likely associated with the evolution of aerobic continental pyrite oxidation. If we accept that IF can serve as useful proxies for the composition of ancient seawater, the question then becomes what do other trace elements in IF tell us about the ancient biosphere? In this regard, we have also been examining the temporal changes in U, Co and Zn concentrations in IF as a means of corroborating the oxidation trends observed via Ni and Cr. Perspectives for the future also include evaluating marine trace element evolution from other lithologies, such as black shales, cherts and/or carbonates, in an effort to better understand the paleo-nutrient landscape that, as today, should have varied along an ocean transect.

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The impact of oceanic anoxic events on marine biota, ocean chemistry and Earth processes

Angela L. Coe

Department of Environment, Earth and Ecosystems, Centre for Earth, Planetary, Space and Astronomical Research, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

There have been at least four short periods in Earth history when significant amounts of marine organic matter were deposited and preserved globally. These periods have been termed oceanic anoxic events (OAEs) and almost all of them occurred during the greenhouse conditions of the Cretaceous. All of the OAEs are associated with severe environmental change including large perturbations to the carbon cycle, rapid global warming, major changes in ocean chemistry, an increase in the hydrological cycle and mass extinction. In addition, several putative oceanic anoxic events have been suggested including some in the Palaeozoic and a well-studied Cenozoic event, the Paleocene-Eocene thermal maximum (PETM), which occurred 56 million years ago.

The past decade has seen many advances in our understanding of these dramatic OAEs and seawater anoxia. These advances have been partially driven by advances in scientific techniques including the development of new isotopic tracers and refinement of the geological timescale using astronomical cycles. However, the other major driver has been the search for analogues of present day environmental change and the need to understand changes in the Earth system over millennial and decadal timescales.

One of the major impacts of global warming at present day is deoxygenation of the oceans. Areas with lower oxygen levels in the oceans have increased exponentially over the past 50 years and now cover 7% of ocean area and affect over 400 marine ecosystems. Putting this into context, the continental shelves cover 10% of the ocean area. The long-term biotic effects of deoxygenation of the oceans are likely to include changes in the marine food web, extinctions, smaller body size and reduced biodiversity. Similar to past events, the chemical and physical effects are likely to include a different chemical balance of many elements in seawater and changes in ocean circulation.

This talk will present some recent advances in our understanding of OAEs including:

- How both the micro- and macro-biota changed in response to the extreme conditions.
- The Mo-isotope proxy that can be used to determine the areal extent of deoxygenation.
- Proxies for the negative feedbacks that allowed the Earth to eventually recover from these extreme conditions.
- How astronomical cycles have been used to understand the duration and pacing of these events and their possible role in driving the events.

In particular, the only OAE that occurred during the Jurassic (Toarcian OAE, 183 Ma ago) will be discussed. This event occurred in four stages paced by Milankovitch cycles. It was associated with an area equivalent to approximately all of the continental shelves being deoxygenated periodically, a mass-extinction in marine biota and significant extinctions in the terrestrial realm. A recent study that collected data from 36,000 bivalve specimens shows that just two bivalve species were adapted to the conditions and suggests that the size of the bivalves were linked through primary productivity to changes in ocean chemistry.



The sedimentological expression of the Toarcian Oceanic Anoxic Event in the cliffs near Whitby, Yorkshire, UK

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Accounting for extreme events in Earth Surface Processes: the critical challenges

Oliver Korup

*Institute of Earth and Environmental Sciences, University of Potsdam, D-14476 Golm, Germany,
e-mail: oliver.korup@geo.uni-potsdam.de*

The steadily growing number of field and remote sensing data continues to underscore systematic inverse relationships between the magnitude and frequency of Earth surface processes, based on metrics such as mass-wasting volume, flood discharge, wildfire size, turbidite thickness, or sediment yield. Such frequency-magnitude relationships have turned out to be a useful tool, if not paradigm, for assessing the geomorphic efficacy of a given process, while serving as a quantitative basis for assessing concomitant natural hazards.

In the light of contemporary global warming and environmental change, however, current research interest has shifted towards quantifying potential changes to frequency-magnitude relationships in order to predict future consequences and regime shifts in Earth surface processes. This research focus raises a number of issues that have been partly disregarded in previous work mostly for reasons of mathematical convenience. Here I encapsulate and discuss some of these issues and highlight potential avenues of future research.

The most pertinent issues include (1) statistical means to distinguish reliably different frequency-magnitude relationships with a view towards the question of their particularity vs. universality; (2) the pitfall of confusing frequency with abundance; and (3) adequate choice of model fit, which eventually dictates our capability of meaningfully detecting changes to frequency-magnitude curves brought about by external changes. I outline possible solution pathways to resolving these issues by presenting several current examples from natural hazards research.

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Carbonation of mantle peridotite: Natural systems, global carbon cycle, engineered capture & storage

Peter B. Kelemen*

*Dept. of Earth & Environmental Sciences, Columbia University, Lamont Doherty Earth Observatory, Palisades NY 10964,
peterk@ldeo.columbia.edu*

Starting in 2007, my colleagues and I have been studying natural mineral carbonation systems in exposed mantle peridotite, part of a block of oceanic crust and upper mantle thrust onto the Arabian continental margin in Oman and the United Arab Emirates (the Samail ophiolite). There are two, distinct, well exposed examples. The low temperature system, continuing to the present day, occurs at 25 to 60°C [1-3], forming extensive travertine deposits on the surface, composed mainly of calcite, and complementary carbonate veins formed in the subsurface, at depths up to perhaps 3 km, composed mainly of magnesite and dolomite. Most of our samples from travertines and veins have ¹⁴C ages less than 50 ka, with an average of ~ 20 ka for travertines and 30 ka for veins [1,2,4]. This low temperature process is well understood and modelled as the consequence of surficial weathering of the peridotite, forming Mg-HCO₃-rich ground water, followed by subsurface reaction with extensive precipitation of Mg-carbonates + serpentine, and then by return of carbon-depleted water to the surface in alkaline spring waters (pH 11-12, Ca-OH-rich) which react with atmospheric CO₂ to form travertines [e.g., 5,6]. The rarity of veins older than 50 ka suggests that vein formation and erosion take place at the same rate. Abundance and ages of travertines and veins suggests uptake of 104 to 105 tons of CO₂ per year via peridotite carbonation in the ophiolite [1,2].

There was also a high temperature, peridotite carbonation system, in the hanging wall of the subduction zone that carried the Samail ophiolite over carbon-bearing metasediments during emplacement on the Arabian margin. Peridotites were completely replaced by listvenite (magnesite + quartz) and related lithologies, in bands up to 200 m thick formed within 0.5 km of the thrust, via reaction with CO₂-rich aqueous fluids at ~ 100°C and 5 to 10 km depth. An Rb/Sr isochron yields 97 ± 27 Ma, consistent with the time of thrusting. Our data reveal unexpectedly large carbon fluxes at low temperature into the “leading edge of the mantle wedge” [7], where mineral decarbonation reactions are not predicted from metamorphic calculations [8]. Instead, carbon transport is via pore waters expelled from compacting sediments with ~ 250 ppm carbon, sufficient to explain the observed fluxes over the 10 to 20 Ma of emplacement.

Kinetic data on olivine carbonation indicate that reaction with CO₂-rich fluids (e.g. CO₂ saturated water at ~ 100 bars), at pH ~ 6-7 and ~ 185°C, is ~ 106 times faster in the near surface conditions prevailing in the Samail ophiolite [reviews in 2,9; our new data in 10]. Thus, one proposed method of engineered, geological carbon storage is to inject CO₂-rich fluid into subsurface peridotite at ~ 150-200°C, rapidly forming solid carbonate for permanent storage. Alternatively, we can emulate the active, natural system in the Samail ophiolite, which produces carbon-free fluids, by creating enhanced pathways for circulation of, e.g., seawater, through subsurface peridotite, and return carbon-depleted waters to the surface where they will draw down atmospheric CO₂ [1,2]. The latter method, for distributed carbon capture from natural waters, might cost ~ \$100/ton of CO₂ [2]. This may be a supplement or alternative to direct air capture, should it be necessary to reduce global, atmospheric CO₂.

Natural mineral carbonation involves positive feedbacks between volume change – due to addition of CO₂ + H₂O to the solid – together with decreased solid density. Stress due to volume change causes fractures, which maintain or enhance permeability and reactive surface area. In the case of the Cretaceous listvenites, this led to 100% carbonation, in which every Ca and Mg atom is in carbonate minerals. Elsewhere, carbonation and hydration involves negative feedbacks, destroying permeability and armouring surfaces. Thus, it is essential to understand the conditions favouring reaction driven cracking. Stress during peridotite carbonation and hydration is on the order of 100-300 MPa, based on independent but consistent estimates from (a) thermodynamic data and (b) fracture density plus mineral physics data [11]. Improved understanding of reaction driven cracking could be applied to geothermal power generation and extraction of tight oil and gas resources, as well as carbon storage [2].

Unexpectedly high fluxes of carbon from footwall sediment into the leading edge of the mantle wedge in the Samail ophiolite motivates review of the role of peridotite carbonation in the global carbon cycle. Peridotites sampled near the mid-ocean ridges have an average of ~ 0.5 wt% CO₂, [2,12]. Combining this with seismic estimates of the extent of peridotite alteration in the oceanic mantle at the outer rise [13], just prior to subduction, yields an estimated flux of ~ 10¹⁰ kg C/yr [14], comparable to the estimated flux in subducting oceanic crust. Carbonate solubility in aqueous fluids increases dramatically with increasing pressure at low temperature, yielding carbon concentrations of 1 wt% or more in aqueous fluids in subducting sediment and oceanic crust [15] and fluxes of ~ 10¹⁰ kg carbon/yr into the cold nose of the mantle wedge at < 75 km depth [14]. At greater depth, subducting, buoyant marbles and calc-silicates with layer thicknesses greater than a few hundred meters could rise as diapirs into the mantle wedge beneath volcanic arcs, where they would react with high temperature peridotite [16], potentially producing carbon-rich fluids or melts, and increasing the carbon content of the upper mantle. These factors have not been incorporated in previous estimates of carbon transfer in subduction systems, and potentially represent globally important sources and sinks in the global carbon cycle.

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