Exploding stars, colliding comets, DNA based life on Earth – they all connect in the search for extra-terrestrial life.

Image - Courtesy NASA/JPL-Caltech
Earth Chemistry

Introduction

The chemistry and isotope chemistry of natural materials is highly indicative of provenance and process throughout geological history. Our studies range in time from the earliest solar system through to processes that are actively taking place today, and in scope from planetary systems to individual molecules. Active areas of research centre on planetary studies, metamorphic and igneous geochemistry and geochronology, geochemistry of life processes, and chronology of all processes encompassed.

Most of our analytical work involves detailed analysis on the microscale, or concentrating trace elements from larger samples for high precision analysis. Isotopic systems can reveal both the nature of the processes involved (stable isotopes) as well as the timing of events (radiogenic isotopes), while chemical and molecular abundances can reflect protolith contributions and processes affecting various systems including biologic systems. As revealed in this year’s research contributions, analytical work can be applied to topics in tectonics, ore genesis, metamorphic petrology, paleoclimate, paleoecology and regolith dating.

Highlights

Following on from the establishment of the SHRIMP and Chemistry laboratory facilities in JS, the J3 laboratory where SHRIMP II was formerly located, was renovated as a Thermal Ionization Mass Spectrometry laboratory. The Thermo-Finnigan Matt 261 mass spectrometer has been installed and is now operational. The award of a LIEF grant to fund a new Triton mass spectrometer will provide the latest technology for high-precision isotopic analysis of Earth and Planetary materials. Earth Chemistry personnel participated in the Geochemistry, Mineralogy, and Petrology review and enjoyed the opportunity of presenting their research agendas to the committee. Members of Earth Chemistry participated at numerous conferences, in particular Goldschmidt 2009 in Davos, Switzerland, Australian Space Science Conference in Sydney, and the American Geophysical Union Conference in San Francisco, USA.

Personnel

Dr Vickie Bennett was promoted to Associate Professor.

Dr Daniela Rubatto was awarded the Dorothy Hill Prize of the Australian Academy of Science for 2009.

PhD studies were completed by Ryan Ickert.

Postgraduate studies were commenced by Ms Jane Thorne and Ms Barbara Fraser (supervised by Professor Trevor Ireland), Ms Katherine Boston (supervised by Dr Daniela Rubatto), Ms Jia-Urnn Lee (supervised by Dr Marnie Forster), and Mr Aditya Chopra (supervised by Dr Charley Lineweaver).

Dr Tsuyoshi Lizuka, a long-term visitor from the University of Tokyo, was awarded an ARC post-doctoral fellowship to continue his studies in early Earth and planetary systems.
SHRIMP 'keyhole' geochronology: evidence for an extension of the Svecofennian orogenic province into north-eastern Poland

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The basement rocks of Poland are buried beneath an extensive cover of much younger sedimentary rocks. The thickness of the cover ranges from about 500 m in the east to over 5 km in the west. The broad geological structure of the basement has previously been mapped using magnetic and gravity surveys, supplemented by deep seismic investigations. The only samples of the basement rocks that can be studied directly, however, are drill cores recovered from a limited number of boreholes, mostly drilled to investigate deep geophysical anomalies. As part of a joint research project between RSES and PGI, we are piecing together the geological evolution of the Polish basement using the limited view provided by these irregularly-spaced 'keyholes' into the buried terrane.

Our work initially focused on studies of rocks collected from holes drilled in areas that showed the most pronounced geophysical anomalies, especially magnetic or gravity highs. For example, the rocks beneath Lomza, about 150 km NE of Warsaw, were shown to be part of a late Paleoproterozoic mafic igneous suite; the 'Archean' crystalline basement of the Mazowsze granitoid massif in far NE Poland was shown to be actually of late Paleoproterozoic age; and a belt of rocks from the Warmia area about 50 km SE of Gdańsk, once considered to be high grade metasediments, was shown to be of igneous origin and coeval (possibly cogenetic) with the Mesoproterozoic Mazury Complex to the east.

Over the last two years we have turned our attention to the basement rocks cored away from the geophysical anomalies in areas that are geophysically bland. Such areas are extensive, but the density of coring is relatively low. Drill holes at Jastrzebna and Monki in far NE Poland, for example, intersected a monotonous sequence of metasedimentary rocks possibly representative of the host rocks to the igneous complexes throughout NE Poland.

Superficially the Polish metasediments resemble the Paleoproterozoic metasediments of the Svecofennian Domain exposed to the north in Finland and to the northwest in Sweden. Chemical analyses of the metasediments and SHRIMP U-Pb dating of zircon and monazite have shown that the resemblance is more than superficial—the rocks from Poland are so closely related to those in Finland and Sweden in composition, provenance and metamorphic history that they are probably part of the same orogenic province (Williams et al., 2009; Krzemińska et al., 2009).

The most compelling evidence that the Polish metasediments are part of the Svecofennian Domain comes from the ages of the detrital zircon cores. The age distribution is distinctive; a main, bimodal zircon population with ages in the range 2.05–1.85 Ga, and a secondary population with ages in the range 3.0–2.6 Ga. The same pattern of ages is seen in the detrital zircon cores from Svecofennian metasediments in Finland and Sweden (Fig. 1).

It is highly likely that the Polish basement metasediments were derived from the same source region as the 'classical' Svecofennian metasediments, and were deposited in the same basin or basin system. The ages of the detrital zircon cores do not match the ages of any known igneous rocks currently exposed within the Baltic Shield, but do match the ages of rocks to the east, indicating their possible derivation from source areas in Sarmatia and adjacent regions.

The next step will be to explore further afield to find out how far the Svecofennian basement extends.


Figure 1. Relative probability plots of the $^{207}\text{Pb}/^{206}\text{Pb}$ ages of zircon cores from metasediments from NE Poland, and representative Svecofennian metasediments from Finland and Sweden, showing the close similarities between them.
Experimental study of monazite/melt trace element partitioning

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Monazite is a common accessory mineral (LREE, Th)PO4. In Earth Science monazite is relevant for Th, U-Pb geochronology and as host of REE, Th and U during metamorphism and melting.

Monazite is an ideal mineral for Th, U-Pb dating because of its high closure temperature and low common lead content. However, the interpretation of monazite ages may be hampered by limited knowledge of its behavior during metamorphic and igneous processes. One powerful method for the interpreting the relationship between age data and petrological events is linking accessory mineral ages with garnet growth zones through the equilibrium partitioning of trace elements. Partitioning of trace elements between monazite/garnet and monazite/melt have so far been estimated only in natural samples.

During melting the presence of monazite as a residual phase could produce enrichment in the restite of elements that are strongly incompatible in other circumstances (Rapp et al, 1987). Monazite also plays a critical role in the fractionation of REE relative to one another and could be responsible for granites with unusual REE patterns. Recently monazite has been identified as an important player in the melting of sediments withing subduction zones and magma generation at subarc depths (Hermann and Rubatto, 2009).

Experimental determination of monazite-melt partitioning was performed at conditions revalent for melting within the crust and in subduction zones. The starting composition was granite with about 8% H2O and doped with trace elements. Experiments in piston-cylinder press were performed at 10 kbar over the temperature range from 750 and 800 to 1300°C with steps of 100°C. Additionally, a pressure series form 10 to 50 kbar with steps of 10 kbar was conducted at 1000°C. In order to reach conditions relevant to subduction zone environments, additional temperature series is planned at 30 kbar.

Experiments at temperature >800°C and pressure <30 kbar produced melt with monazite. At lower temperature additional quartz and plagioclase appeared in the experimental charges. At higher pressures, kyanite, coesite, jadeite, apatite, zircon and allanite start to crystallize. Monazite was produced in all experiments but with very small grain size (<5µm), making it impossible to determine the trace element composition of monazite alone. As alternative, LA-ICP-MS analyses of monazite-melt mixes were performed and the monazite composition was calculated using regression analysis.

Preliminary results show that monazite solubility decreases of a factor of two at pressures above 20 kbar. However, because high pressure experiments produced different melt composition and higher water content, changes in monazite solubility are likely a combination of pressure and melt composition. Study of monazite composition have shown that only REE, Th, U, Y and As strongly partitioning into monazite, whereas other trace elements (Li, Be, B, Sc, Ti, V, Mn, Sr, Zr, Nb, Ba, Hf, Ta, Pb) have a partitioning coefficients lower than 10. Monazite has the highest preference for LREE, with a decrease in partitioning coefficients for Sm, MREE and HREE. Partitioning for Th is much higher than for U.
We are made of star dust
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One way of answering the question ‘What is life?’ is to look at the ingredients of life on Earth. In terms of chemical elements, oxygen, carbon, hydrogen and nitrogen, make up 96.8 ± 0.1% of the mass of life (based on humans and bacteria). Phosphorus and sulfur together make up 1.0 ± 0.3%. The remaining 2.2 ± 0.2% is dominated by potassium, sodium, calcium, magnesium and chlorine, while 0.03 ± 0.01% is attributed to trace elements such as iron, copper and zinc.

All atoms that are or have been part of living matter on Earth have either been produced during big bang nucleosynthesis or in different processes of the stellar nucleosynthetic pathways that take place in stars. Around ~4.5 billion years ago our Sun was formed out of a collapsing molecular cloud that was polluted by earlier stellar processes and a proto-planetary disk that was made of the remaining dust gave rise to terrestrial planets like the Earth.

While the elemental composition of planets reflects to a large extent the composition of the Sun, relative to the Sun, the Earth is depleted in the most volatile elements hydrogen, helium and the noble gases. These elements were swept away by the solar wind from the region of the solar nebula where rocky planets like Earth formed. However, later input of volatile elements from chondritic material, comets and other objects from the outer solar system led to a surface crust on the Earth which exhibits elemental abundances more like the Sun depleted in volatile elements than the bulk Earth.

Life does not reside in the mantle or the core of the Earth and so its elemental abundances are more reflective of abundances in the crust (specifically the biosphere) than abundances in the bulk Earth.

Since, the abundance of most elements in life forms and their environments on Earth follow cosmic abundances (as represented by the Sun), perhaps extraterrestrial life on Mars or moons of Jupiter and Saturn or perhaps extra-solar planetary systems, will also exhibit elemental abundances similar to those found in life on Earth.


www.tinyurl.com/ACCL08
Figure 2. The positive correlation between elemental abundances (by number of atoms) in life (as represented by humans) and the Sun.
Sugar, spice and everything nice... The search for elemental ingredients of life

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We are finding out if the most primitive organisms on Earth started out with basic ingredients of life and became more complex as they evolved. The findings from the research, could give hints on where and how life got started on Earth.

Over the next few years, we will collect samples of bacteria and archaea (a very ancient form of bacteria). The samples will include including extremophiles, the life forms that thrive in punishingly hot or acidic environments. We then use atomic emission spectrometry, mass spectrometry and elemental analysers to know precisely what these life forms are made of. We will measure the abundances of about half of the 80 most abundant stable elements in nature including major elements such as carbon, hydrogen, oxygen, nitrogen, sulphur and phosphorus and trace elements such as sodium, potassium, calcium, iron and copper.

With this information we will find out if the most ancient life forms are made of fewer elements than the life forms that appeared on Earth more recently. Just as a novice chef starts baking a cake with simple ingredients like flour, eggs and sugar, life may have started with the most abundant (or bio-available) elements. These could be elements like carbon, hydrogen, oxygen, nitrogen, sulphur, phosphorus and ions like calcium or boron to stabilise its structures, and catalytic metals like iron.

Later, life began to accessorise with more elements like bromine and selenium – like an experienced chef who has learnt to use vanilla, cinnamon and the rest of the spice rack. This increase may be in response to changes in the bioavailability of elements in environments such as the oceans – particularly during the great oxidation event ~2.4 billion years ago.

Aditya Chopra, Charles H. Lineweaver, Jochen J. Brocks and Trevor R. Ireland,

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Figure 2. A possible sequence of increasing diversity of elements used by life.
Testing the significance of hafnium isotopes in rutile across a crust-mantle transition

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The study of metamorphic rocks that have been brought to the Earth’s surface gives us an insight into processes that are occurring today in parts of the Earth we cannot observe – such as deep in the Earth’s crust, under mountain belts, and in subduction zones. Metamorphic histories are often complex, with multiple phases of deformation and/or heating. A powerful tool for unravelling the story of metamorphism is the study of isotope systems, such as hafnium (Hf).

Hf isotopes can be accurately measured in-situ for the metamorphic mineral rutile using our laser ablation multi-collector inductively coupled mass spectrometer (LA-MC-ICPMS). Hf isotope information is combined with U-Pb ages obtained by SHRIMP, and trace element information measured by LA-ICPMS. The formation temperature of rutile is calculated according to the Zr-in-rutile thermometer of Watson et al. (2006). Each of these techniques can be applied in sequence to a single rutile grain, providing linked age, temperature, chemical and isotopic information.

We aim to assess the significance of Hf isotopes in rutile, and how their behaviour in response to pressure, temperature and fluids compares to that of Hf isotopes in zircon. A study of the Ivrea-Verbano Zone in northern Italy will provide a “natural laboratory” to investigate these questions.

The Ivrea-Verbano Zone (IVZ) preserves a spectacular section through the lower crust and mantle that exposes interlayered metapelites (metamorphosed sedimentary rocks) and metabasites (metamorphosed basic igneous rocks) which have undergone metamorphism at high temperatures and pressures. The higher grade end of the section underwent significant partial melting, forming rutile in metapelites. Partially-digested slivers of metapelitic material are found within the underlying Mafic Complex. In the field, a wide range of degrees of mixing between the mafic igneous and metapelitic end-members can be observed.

Rutile-bearing samples collected from the IVZ record varying degrees of mixing between metapelite and gabbro; a range of pressures and temperatures; and variable amounts of overprinting by a later, lower-temperature metamorphic event. The presence of metamorphic zircon rims in some samples allows comparison of the behaviour of Hf isotopes in the two
minerals – but their absence in other samples emphasises the relevance of a thorough understanding of Hf isotopes in rutile.

Preliminary data indicate that the Hf isotope signature of rutile may be very robust, even in an area that has seen high temperatures, mixing of different lithologies to varying degrees, and significant fluid influx.

Genesis of granites: U-Pb geochronology and O-Hf isotopic analyses
Carboniferous-Permian granites across the boundary between the Lachlan and New England fold belts
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Since significant fractionation of $^{18}$O from $^{16}$O occurs at low temperature, the $\delta^{18}$O value of granite (7-12 ‰ in general) could be used to determine whether the source material of magma experienced low-temperature geologic processes at surface. However, the bulk $\delta^{18}$O value could be easily affected by subsequent geologic events, and magma differentiation (even in a closed system) as the proportion of quartz and feldspar which tend to concentrate $^{18}$O in more felsic magma is changed, whereas the $\delta^{18}$O value of zircon retains constant (Valley, 2003). That is, igneous zircons potentially preserve the oxygen isotopic compositions equilibrated with the magma from the time of their crystallization. Therefore, the $\delta^{18}$O of zircon can be used to trace relative contribution of new, mantle-derived crust ($\delta^{18}$Ozircon value of 5.5 ‰) and crust that has chemically evolved and been reworked ($\delta^{18}$O_zrc value of 12 to 14 ‰; Valley, 2003). In addition, development of in-situ analyses technique using SHRIMP II (Ickert et al., 2008) enables us to identify the timing of each stage of $\delta^{18}$O.

Based on the $^{176}$Lu-$^{176}$Hf isotopic system having slightly more incompatible daughter than parent, crust which derived from partial melts of mantle contains lower Lu/Hf ratio than residual mantle, and then $^{176}$Hf/$^{177}$Hf ratio in crust increases slower than in mantle where $^{177}$Hf accumulates faster. The $^{176}$Hf/$^{177}$Hf ratios of crust (lower) and mantle (higher) which diverge are generally represented as negative and positive $\varepsilon$Hf values, respectively. The notation of $\varepsilon$Hf expresses the difference between the initial $^{176}$Hf/$^{177}$Hf ratio of rocks and the CHUR (CHondritic Uniform Reservoir) which probably coincide with a bulk earth. Therefore Hf isotopic study of granite could be used to determine crustal and/or mantle sources of magma based on their distinct $\varepsilon$Hf values, and crustal residency and continental growth based on the Hf model age for the formation of the granite or its precursor from the CHUR. Considerable amount of HfO₂ (mostly <3 wt.%) and hardly involved parent Lu in zircon (significantly low Lu/Hf) enables this mineral to well preserve the initial Hf isotopic composition. In-situ Hf analyses of each growth domain for magmatic zircons have been carried out using LA-MC-ICP-MS (Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry). The results could be combined with SHRIMP based U-Pb ages and O isotopic composition on the same analyzed grains to determine nature of the source magma and crustal residence ages which might not correspond to the emplacement ages (Hawkesworth and Kemp, 2006; Kemp et al., 2007).

To provide a fresh approach in granite genesis, a new micro-analytical technique - in-situ combined isotopic analyses of U-Pb, O and Hf for zircons from granites which reserve the information about the nature of protolith, it is possible to determine most reliable emplacement ages of each plutonic body, relative contribution of recycled and/or pre-existing crustal material and juvenile/mantle derived component to magma which give rise to the granites, and crustal residency of source rocks where each zircon domain grew. Particularly, my project focuses on the granites across the boundary between the Lachlan (Carboniferous) and New England (Permian) fold belts in the southeastern Australia. So far, the preliminary results of U-Pb and O isotopic data of zircons reveal that: (1) ages (340-325 Ma) and $\delta^{18}$O (6.5-7.8 ‰) show slight negative correlation and inherited zircons imply possible crustal assimilation consistent with O isotopic inter-granite heterogeneity in the Lachlan Fold Belt; (2) there is no inherited zircons in the late Permian I-type granites in the New England Fold Belt (same range in $\delta^{18}$O with the Lachlan Carboniferous granites); and (3) even S-type granites (early Permian and > 11 ‰ in $\delta^{18}$O) contain only late Paleozoic inherited zircons probably from the volcanogenic sediments of the same fold belt.


The Succession of Oxygen Producers in Early Oceans

A study of the world's oldest molecular fossils

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The dead biomass of organisms in the oceans is almost completely remineralised back to CO₂, water and nutrients. Only a small fraction of dead organic carbon becomes permanently buried in sediments. However, this small fraction determines the redox state of the surface of our planet: for every mole of CO₂ buried as organic C, one mole of O₂ is released into the atmosphere. A major factor contributing to carbon burial and, thus, atmospheric oxygen levels, is the type of organic matter produced by the dominant photosynthetic organisms in the world oceans and on land. For instance, the emergence of land plants led to the formation of enormous coal deposits and increasing atmospheric O₂ levels in the Carboniferous.

In the Proterozoic, the time between 2,500 and 542 million years (Ma) ago, land plants had not yet evolved, and atmospheric oxygen was controlled by single-celled primary producers such as cyanobacteria and various groups of algae. Shifting regimes of these organisms in the oceans must have had dramatic effects on the atmosphere and carbon cycle, possibly triggering the late Proterozoic Snowball Earth events and an increase of oxygen that may have permitted the evolution of animals some 600 Ma ago. The most dramatic regime change in the oceans was probably the shift from cyanobacteria to algae. Most cyanobacteria produce high proportions of digestible carbohydrates, whereas algae often contain resistant cell wall material with a high chance of burial [1].

To determine when Earth's early oceans were dominated by cyanobacteria, and when and why these organisms were displaced by successive groups of algae, we studied molecular fossils (biomarkers) extracted from sedimentary rocks 2,800 to 500 million years in age. Biomarkers are the hydrocarbon fossils of biological molecules such as lipids. For instance, algae produce a wide variety of steroids, and the fossils of these steroids, the steranes, can be preserved as hydrocarbon skeletons in sedimentary rocks for hundreds of millions of years old.

In contrast to previous studies, and to our great surprise, we found that biomarkers of eukaryotic algae are rarely detected in rocks older than 635 Ma [2, 3], the time before the first animals appear in the geological record. Also, when present in ancient rocks, the steranes were very distinct from later periods in Earth's history. The record of sedimentary sequences with demonstrably indigenous biomarkers is still exceedingly patchy. However, it appears that complex algae may have displaced cyanobacteria as the rulers of the carbon cycle roughly at the time when increasing oxygen levels permitted first animals to evolve.

A new project that was generously funded by the Australian Research Council for 2010 to 2014 will now have a very close look at the exciting history of these biomarkers in the Precambrian, and how the
evolution of early organisms controlled the carbon cycle and influenced the tumultuous climate of the Neoproterozoic (1000 – 542 ma ago).

For more information, go to the home page of the Brocks group. 

Figure 3. The famous Ellery Creek outcrop covers the time period from about 800 to 500 million years ago. On the right is the mid-Neoproterozoic Heavitree Quartzite, and the ridge in the distance is a Cambrian sandstone. The almost vertical-standing layers in between encompass glacial deposits of the Snowball Earth events, a rise in atmospheric oxygen and the first appearance of animals followed by their explosive radiation at the Precambrian/Cambrian boundary.
Molecular characterization of a Neoproterozoic hypersaline ecosystem

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Numerous microorganisms survive and flourish in environments that are often considered "extreme" from an anthropogenic viewpoint. Such environments include hydrothermal vents, hydrocarbon seeps, and acid hot springs. Hypersaline environments are another type of setting where microorganisms live under salinity regimes exceeding those of seawater. In order to understand the evolution of ecosystems from such settings, Neoproterozoic halite-bearing evaporites were investigated for their lipid biomarker content. While previous work identified potential halophiles in the Cambrian and Precambrian, we aim to present a more detailed investigation of a microbial ecosystem under "extreme" conditions.

Thus far, we extracted biomarkers from evaporitic sediments composed of dolomite, anhydrite and/or halite. The samples are derived from evaporitic sediments of the Neoproterozoic Bitter Springs Formation, Amadeus Basin, central Australia. Due to the broad shallow nature of the Amadeus Basin and a tenuous connection with the ocean, the water was characterized by elevated salinity levels during that time. As a result, very thick (100 m to >2000 m) evaporite units were deposited.

The Neoproterozoic evaporites are often composed of numerous microbial mat-like formations that exhibit roll-up structures and tearing. Full scans (gas chromatography - mass spectroscopy, GCMS) of the saturate fraction revealed high ratios of mono- and dimethyl alkanes relative to \( n \)-alkanes. Such patterns are typical of Precambrian and Cambrian samples and observed in a number of facies settings. An outstanding characteristic are several pseudohomologous series of both regular (to C\(_{25}\)) and irregular (to C\(_{40}\)) acyclic isoprenoids. These isoprenoids are present in high concentrations and have never before been reported in the Precambrian. The presence and relative concentrations of these compounds vary with regards to the sedimentology of the host rock. Hopanes and steranes are often present in low concentrations or are absent.

Based on these results, we present an ancient and extreme, saline environment dominated by prokaryotes – with potentially the oldest evidence of haloarchaea in the geologic record. The presence of exceptionally well preserved biomarkers in anhydrite, despite the fact that sulfate and biomarkers are thermodynamically not stable together, raises the prospect of finding biomarkers in sulfate deposits on Mars.
Rate of growth of the preserved North American continental crust

Evidence from Hf and O isotopes in Mississippi detrital zircons

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Detrital zircons from the Mississippi River have been analyzed for U-Th-Pb, Lu-Hf and O isotopes to constrain the rate of growth of the preserved North American continental crust. U/Pb dates on zircons mounted in epoxy resolved six major periods of zircon crystallization: 0-0.25 Ga, 0.3-0.6 Ga, 0.95-1.25 Ga, 1.3-1.5 Ga, 1.65-1.95 Ga and 2.5-3.0 Ga. These age ranges match the ages of the recognized tectonic units of the North American continent in the hinterland of the Mississippi River. Ninety-six zircons mounted on tape, which show no age zonation, were selected to represent the six U/Pb age time intervals and analyzed for Lu-Hf and O isotope by laser ablation MC-ICP-MS and SHRIMP II, respectively. Zircons derived from juvenile crust, which we define as having mantle d^{18}O (4.5 - 6.5 ‰) and lying within error of the Hf depleted mantle growth curve, are rare or absent in the Mississippi basin (Fig. 1). The overwhelming majority of zircons crystallized from melted pre-existing continental crust, or mantle derived magmas that were contaminated by continental crust. The average time difference between primitive crust formation and remelting for each of the recognized lithotectonic time intervals, which is defined as crustal incubation time in this study, is 890 ± 460 Myr.

If the zircons are weighted by the area of North America covered by the six recognized periods of zircon crystallization the average Hf model age is 2.35 Ga, which compares favorably with a weighted by area Nd model age of 2.36 Ga. Our preferred approach is to use the measured O isotope values to constrain variations in the ^{176}Lu/^{177}Hf ratio of the granitic source region from which the zircons crystallized, making the assumption that zircons with mantle like O isotopic ratios have higher ^{176}Lu/^{177}Hf than zircons with higher O isotope values. This method gives an average Hf model age of 2.53 Ga, which is 180 Myr older than the constant ^{176}Lu/^{177}Hf calculation. The area weighted zircon Hf model ages show two distinct periods of crust formation for the North American continent, 1.6 to 2.2 and 2.9 to 3.4 Ga. At least 50% of the preserved North American continental crust was extracted from the mantle by 2.9 Ga and 90% by 1.6 Ga. Two similar periods of crustal growth are also recognized in Gondwana (Hawkesworth and Kemp, 2006), suggesting that these may be periods of global continental crustal growth.

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Early crustal evolution deduced from monazite geochronology and geochemistry

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Knowledge of early crustal evolution is central to deciphering the evolution of the young Earth. Mt. Narryer and Jack Hills metasediments in the Narryer Gneiss Complex of Western Australia are of particular importance for the study of early crustal evolution because they yield Hadean (>4.03 Ga) detrital zircons; no crustal rocks have been found from the first 500 Myr of Earth’s history. To better understand the tectonothermal history and provenance of these ancient metasediments, we have undertaken in-situ LA-ICPMS geochronology and geochemistry of monazites from the metasediments.

Our data reveal multiple periods of metamorphic monazite growth in the Mt. Narryer metasediments during tectonothermal events, including metamorphism at ~3.3–3.2 and 2.7–2.6 Ga and a hydrothermal alteration at 3.2–3.1 Ga. These results set a new minimum age of 3.2 Ga for deposition of the Mt. Narryer sediments, previously constrained between 3.28 and ~2.7 Ga. Despite the significant metamorphic monazite growth, detrital monazites survive with a relatively high proportion in a Fe- and Mn-rich sample. This could be primarily due to its Fe- and Mn-rich bulk composition leading to the efficient shielding of old monazite by garnet. By contrast, the metamorphic monazite growth in the Jack Hills metasediments was insignificant, suggesting the lack of high-grade metamorphism in the region.

The detrital monazites provide evidence for the derivation of Mt. Narryer and Jack Hills sediments from 3.6 and 3.3 Ga granites, likely corresponding to Meeberrie and Dugel granitic gneisses in the Narryer Gneiss Complex. Importantly, no monazites older than 3.65 Ga have been identified. This can be interpreted as indicating that the source rocks of the >3.65 Ga detrital zircons contained little monazite, thereby providing no evidence for the presence of granites (sensu stricto) on Hadean Earth. An alternative interpretation is that although the source rocks may have contained monazite, this phase completely dissolved/recrystallized during <3.65 Ga metamorphism or was eliminated during prolonged sedimentary recycling.

Figure 1. 207Pb/206Pb age histograms of concordant and <5% discordant monazites for Mt. Narryer metasediments (a) MN051, (b) MN074, (c) MN080, (d) MN090, and (e) MN100 and Jack Hills metasediments (f) EH26 and EH27. Columns are coded according to internal structure under backscattered scanning electron imagery.
He, Ne and Ar in peridotitic and eclogitic paragenesis diamonds from the Jwaneng kimberlite, Botswana – constraints on diamond formation

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Research goals in noble gas geochemistry include understanding the structure of the Earth’s mantle and the creation of a coherent model of its evolution. In this regard, noble gas compositions in mid-ocean-ridge basalts (MORBs) and ocean island basalts (OIBs) have provided very useful information on the mantle. However, virtually all these data are from samples that are effectively of zero-age and, therefore, only give information about the present composition of mantle noble gases. If noble gas measurements are made on mantle-derived samples of different ages, these can allow further refinement of models concerning mass transport in the mantle.

Diamonds have unique characteristics which make them potentially very useful as sources of noble gases from the mantle: (1) most diamonds appear to be derived from 150 km to 200 km depth in the Earth, (2) diamonds cover a wide range of crystallization ages of between 1.0 and 3.5 billion years, and (3) diamonds have suffered little interaction with crust or atmosphere. Thus, diamonds provide a direct window into the ancient mantle.

We have undertaken helium, neon and argon analyses of eleven polycrystalline diamonds from the Jwaneng kimberlite pipe, Botswana, with known diamond paragenesis. In contrast to the findings of crustal noble gases in framesites from the same kimberlite pipe (Honda et al., 2004), the Jwaneng polycrystalline diamonds appear to have similar noble gas, particularly neon, isotope compositions as observed in MORBs, regardless of their parageneses (Fig. 1). This implies that the Jwaneng polycrystalline diamonds may have formed in recent times, and are possibly as young as kimberlite emplacement (~ 235Ma). In contrast, Jwaneng framesites could be as old as sulphide inclusions in diamonds, which have model Re-Os ages of ~2.9 Ga. Furthermore, as shown in Figure 1, neon isotope compositions in the mantle where Jwaneng diamonds formed, appear to have changed over this time period from crustal Ne (as observed in the framesites) to MORB-like Ne (as observed in the polycrystalline diamonds).

The apparent difference of neon isotope compositions and formation ages between the Jwaneng polycrystalline diamonds and framesites may imply that primordial noble gases in the upper part of the mantle were outgassed at an early stage of the Earth’s formation, and that crustal noble gases could have been introduced into the diamond stability field of the sub-continental mantle by subduction-related processes. Subsequently primordial noble gases were continuously supplied from the lower to upper part of the mantle in order to form MORB-like Ne compositions in the upper mantle.
Noble gases and halogens in metamorphic, magmatic and hydrothermal systems

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Fluid inclusions enable crustal fluids to be sampled from deeper and hotter environments than can be sampled by direct means and have been trapped throughout Earth’s History. Therefore fluid inclusions enable us to investigate the noble gas systematics of magmatic and metamorphic systems that have never been investigated previously. Analysis of unirradiated samples maximises information from He, Ne, Ar, Kr and Xe isotopes while complementary analysis of irradiated samples enables halogen determination (Ar-Ar methodology) meaning the fluid inclusions Ar concentration can be determined from its salinity and the measured Ar/Cl value. Combining these approaches has proven powerful because it enables the noble gases to be studied in tandem with other volatiles including the halogens, H2O, CO2 and CH4.

Current projects applying these tools to important ore systems in the Mt Isa Inlier and Yilgarn Terrane of Australia have demonstrated it is a powerful tool for testing exploration models. In addition the work has lead to new insights on how noble gases are transported through the crust. We now understand noble gases are partially coupled to the major volatiles and unravelling mixing systematics can provide information on both fluid source and water-rock interactions. Measuring noble gas concentrations in the actual fluid is essential to a complete understanding and we are now developing methods to determine fluid inclusion salinity and Ar content independently. New research projects apply these techniques to subduction related metamorphic rocks and promise to transform our understanding of the noble gas volatile cycle.
Solar-wind exposure effects on lunar grains:

oxygen diffusion in iron metal

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Most of the mass in our Solar System, more than 99.8% [1], is cumulated in our Sun, which is believed to reflect the original composition of the solar nebula, and yet little is known about its isotopic composition. Analysing the surface of lunar soil grains is an attempt to identify the isotopic oxygen signature of the solar wind and the Sun. The oxygen isotopic composition - oxygen having three stable isotopes: $^{16}$O, $^{17}$O and $^{18}$O - is commonly plotted in a three-isotope oxygen plot. Previous analyses on solar wind implantation in lunar grains show very different results, from $^{16}$O-enriched [2, 3] to $^{16}$O-depleted [3, 4] compositions.

This research focuses on the stable isotope signature of implanted ions in the surface of lunar grains, predominantly metal spherules in the soils with a main focus on oxygen isotopes. The main goal is to understand solar wind exposure effect on lunar soils and the implications for oxygen isotopic fractionation.

A new generation of SHRIMP, optimized for stable light isotopes (SHRIMP SI), will be used to characterize the isotopic composition of oxygen, nitrogen and carbon implanted on the surfaces of individual grains and analyses on the Noble Gas Mass Spectrometer at RSES will provide noble gas isotopic and abundances, helium and neon, on single grains for correlation of measured abundances and isotopes to characterise the composition of the solar wind.

In order to gain further knowledge on the issue of oxygen diffusion in iron an experimental approach is in progress to address this matter. This aims to provide a depth profile of oxygen in various iron metals after heated to different temperatures, simulating conditions on the Moon’s surface and to gain a reliable timescale for oxygen diffusion for lunar metal grains.


**Successes and limitations of extinct nuclide initial abundances in meteorites by in-situ analysis**

$^{53}$Mn in Angrites and Pallasites

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The abundances of extinct radioactive nuclides in the early Solar System provide constraints on the stellar environment of formation and are used for obtaining relative ages of meteorites. For some isotope systems these initial abundances serve as accurate and precise meteorite chronometers, but even reliable isotope systems sometimes turn up uncooperative samples. We have developed a technique to measure Cr isotopes by ion-probe in meteoritic olivine. Correlations between Cr isotopic composition ($^{53}$Cr/$^{52}$Cr) and the inter-element ratio ($^{55}$Mn/$^{52}$Cr) indicate the abundance of the extinct isotope $^{53}$Mn (which decays to $^{53}$Cr, $t_{1/2}$ 3.7 My). This is reported as the initial $^{53}$Mn/$^{55}$Mn. We have applied this method to meteorites from two different environments: angrites, which are crustal rocks crystallised from magma near the surface of a small body, and a pallasite, which is a mixture of planetary mantle olivine and core metal.

For volcanic angrites, initial $^{53}$Mn/$^{55}$Mn is at the level of $\sim 3-4 \times 10^{-6}$. Plutonic (slowly cooled) angrites have a lower abundance, $\sim 1 \times 10^{-6}$. In a pallasite, we find apparent initial $^{53}$Mn/$^{55}$Mn of $2.6 \pm 0.9 \times 10^{-5}$, in agreement with previously reported ion-probe results from a different laboratory (Hsu 2005). Mn-Cr systematics in angrites are well understood in terms of chronology; angrite magma is sequentially isolated from a parent reservoir (e.g. the bulk asteroid/planet) while $^{53}$Mn decays over a period of several My, resulting in differences in initial $^{53}$Mn/$^{55}$Mn.

However, pallasite results pose a problem for Mn-Cr dating, because initial $^{53}$Mn/$^{55}$Mn at the level of $10^{-5}$ translates into an unrealistic age based on intercalibration between Mn-Cr and absolute ages for angrites. Such high concentrations of $^{53}$Mn are only expected in the molecular cloud or interstellar medium (initial $^{53}$Mn/$^{55}$Mn for the Solar System is $\sim 8.5 \pm 1.5 \times 10^{-6}$; Scott and Sanders 2009). Pallasite absolute ages are not well known but are probably about the same as angrites and in any case they are not presolar. We conclude that microscale Mn-Cr systematics of some pallasites do not reflect initial $^{53}$Mn/$^{55}$Mn and are the product of a complex history.


Tectonic sequence diagrams used to characterise the evolution of the ductile movement zones in NW Himalaya

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The Himalaya is characterised by a sequence of large thrusts, each of which can be poorly extrapolated from place to place because of the rugged nature of the terrain, and the lack of continuous exposure. Previous work has extrapolated the Main Central Thrust over vast distances, but there is often little data to support the detail of the correlation. Work conducted during the 2006-2009 field seasons suggests that the areal extent, and the location, of individual thrusts (and thrust-related shear zones) is not as well defined as might be expected.

Although the Main Central Thrust in principle should juxtapose the Greater Himalayan crystalline rocks against the Lesser Himalaya, complexities and misunderstanding are increased within the Lesser Himalaya due to the existence of many smaller (?) but still laterally extensive thrust faults. One region where this is of importance is in the NW region of the Himalaya near the town of Shimla, where one of the anastomosing faults has been mislabelled as the Main Central Thrust. The Jutogh Thrust carries the Shimla klippe, allowing us to reassess the nature and timing of movement in one of the most intensely deformed movement zones along this tectonic boundary.

Tectonic Sequence Diagrams were used to establish the complex deformational and metamorphic history of this movement zone, ensuring that all field and thin-section data is included of this information, recording the timing relationships between folding, metamorphic mineral growth events and the different ductile shear zones that could be identified. Previous studies on this particular area have placed an emphasis on folding. There is a general consensus that there were three episodes or styles of folding. However results from this study suggest that these were not all distinct, separate events. A sequence diagram from a garnet-rich zone where both folding and shear zone movement has occurred shows that shear zones affected the second and possibly third folding event, and that these later fold events may be linked. Garnet-grade Barrovian metamorphism overprinted earlier formed crenulations, and ongoing shear zone operation transposed these structures and developed spectacular pressure shadows. The initial garnet porphyroblasts acted as nucleation sites for subsequent episodic garnet growth. Mineral growth alternated with shear zone activity. NE-directed shear bands may be conjugate to SE-directed ones, and conjugate crenulations may have formed as well. ⁴⁰Ar/³⁹Ar geochronology is being undertaken to constrain the timing of individual events within the sequence diagram.

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Figure 1. Garnet millipede structure where an initial garnet growth overprints crenulations. The concave rims suggest a later garnet growth over a simultaneously deflecting schistosity (XPL, x1.6 objective). This later phase is correlated with ‘F3’ in the TSD below.

Figure 2. The tectonic sequence diagram described in the text, correlated with prior deformation schemes, with folding (F1, F2, F3) and metamorphic (M1, M2) history as shown. A crenulation cleavage formed in the axial plane of isoclinal folds, followed by an upper greenschist metamorphism defined by garnet growth. Garnet growth continue during the with the operation of an overall SW-directed shear zone with both SW- and NE-directed S-C' fabrics, and recumbent folding with axial planes parallel to the shear zone. Biotite grew in the low stress zones around rotating porphyroblasts where microdilational sites opened during shearing. With continued deformation conjugate crenulations started to form, and were overprinted by yet another garnet growth episode (see millipede structure in Figure 1). The conjugate crenulations develop a weak differentiated fabric. Late near-static garnet growth may have occurred without any significant associated deformation.
Important of uranium isotope variations for chronology of the Solar System’s first solids

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The $^{238}\text{U}/^{235}\text{U}$ ratio must be known for accurate determination of $^{207}\text{Pb}-^{206}\text{Pb}$ ages. This ratio was thought to be invariant until recent discoveries of uranium isotope variations in terrestrial rocks and in Ca-Al-rich refractory inclusions (CAIs) in carbonaceous chondrites. CAIs are considered the oldest Solar System objects and their $^{207}\text{Pb}-^{206}\text{Pb}$ age has been used as our best absolute age for the beginning of our Solar System’s formation, but their Pb isotopic ages don’t fit well in the emerging consistent pattern of the early Solar System chronology. It is possible that some of the differences in formation time intervals between various early Solar System objects, obtained from extinct nuclide chronologies and from $^{207}\text{Pb}-^{206}\text{Pb}$ dates, are caused by variations of the $^{238}\text{U}/^{235}\text{U}$ ratios. We report the first combined high precision $^{238}\text{U}/^{235}\text{U}$ and $^{207}\text{Pb}-^{206}\text{Pb}$ data for a large CAI from the Allende meteorite, and U isotopic data for chondrules and representative whole rock samples of the same meteorite. The difference of 0.129±0.046 in the $^{238}\text{U}/^{235}\text{U}$ ratio between the CAI and chondrules and bulk Allende meteorite increases the $^{207}\text{Pb}-^{206}\text{Pb}$ age difference by ~1.4 million years, yielding an accurate CAI-chondrule time interval, which is also more consistent with the extinct nuclide data. The U isotopic variations are not caused by the presence of $^{247}\text{Cm}$, but may be related to isotope fractionation or nucleosynthetic anomalies. Our data support the growing evidence that small $^{238}\text{U}/^{235}\text{U}$ variations in planetary materials are pervasive, and can make significant changes in $^{207}\text{Pb}-^{206}\text{Pb}$ ages at the current precision of dating. It is clear that any geo- and cosmochronological study using the $^{238,235}\text{U}-^{206,207}\text{Pb}$ isotopic system must include precise determination of the $^{238}\text{U}/^{235}\text{U}$ ratio when the ultimate precision and accuracy of the age is needed.

Figure 1. Pb-isotopic data for acid-washed fractions from Allende CAI SJ101, plotted in a $^{207}\text{Pb}/^{206}\text{Pb}$ vs. $^{204}\text{Pb}/^{206}\text{Pb}$ isochron diagram.

Figure 2. Uranium isotopic compositions of USGS standard rocks, fragments of the Allende meteorite, an aliquot of an assorted Allende chondrule population, and Allende CAI SJ101.
Argon geochronology and microstructural analysis: a unique and reliable duo

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$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology is the only geochronometer that allows structural geologists and tectonists to directly date the complexity of deformation in a single sample, as well as acting as a geospeedometer that allows calculation of rates and the duration of events and processes. This of course cannot be done unless a number of criteria are met. In particular the sample must be taken from an ancient "argon partial retention zone" in which case there is a strong correlation between microstructure and the age spectrum that will be obtained.

To analyse such material, the sequence of events that affected the rock must be determined by microstructural analysis: these may include mineral growth, and recrystallisation of minerals associated with distinct deformational events and the overprinting effects. The pressures, temperatures and duration of the individual events will have a major influence on the resultant apparent age spectra that is produced during incremental heating of the sample during diffusion experiments. It is often not a simple matter to correlate between the different parts of the apparent age spectrum and the observed microstructural elements. Laser in situ analysis is not useful because argon diffusion is clearly multiscale, and spot analyses eliminate almost all useful information.

The science of "cooling ages" has in the past dominated the science of $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. In reality, few terranes get so hot that "cooling ages" have much relevance, and most argon analyses are not at all amenable to this classic method of interpretation. The much sought after "plateau" in the apparent age spectrum may not exist. Nor has the concept of "closure temperature" any particular theoretical relevance. And in many cases, a "plateau", if it exists, means something quite different than classical theory would allow (see figure). In fact, unless a sample is from very hot rock and/or subject to a simple history, it can be expected that the argon system will retain multiple gas populations and information on multiple events during the history of the grain/s.

In traditional argon analysis these 'disturbed spectra' are often cast aside, but in fact much information can be obtained from samples where older gas population are at least in part preserved and only partially reset during the on-going evolution. Now, with increasingly routine application of the method of tectonic sequence diagrams to conduct fabric and microstructural analysis, and with routine application of the method of asymptotes and limits to analyse apparent age spectra obtained from carefully designed sequences of step-heating experiments, the VG1200 argon facility at ANU is producing reliable, precise and accurate age determinations of a variety of complex scenarios.

In terms of the science of the argon partial retention zone, argon geochronology and microstructural analysis offer a unique and reliable duo.
How efficiently does the crust melt?
A geochronological investigation of melting in migmatites

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The Earth’s crust is constantly melting in regions where high thermal conditions are reached, as for example the deep roots of mountain buildings, i.e. migmatites. This process is an important component of the secular chemical evolution of the crust and ultimately the planet. Migmatites (rocks that recorded melting) now exposed on the crust surface offer the opportunity to investigate the dynamic of the melting process through geological times. The timing of melting has been investigated in a well-exposed migmatitic terrane in the Alps, through U-Pb dating of the accessory minerals zircon. Over a series of samples, individual melt-related zircon domains yielded ages ranging over 10 million years (32 to 22 Ma ago). Multiple melt episodes could be analyses within a single grain indicating that the same rock reached melting temperatures more than once over that period. The chemistry of the zircon domains allows discriminating between melts formed at different conditions (temperature and chemical environment). The distribution of ages also indicates that melting occurred at different times in samples a few meters apart because of the local rock composition and localized influx of fluids; and that repeated melting was localized in particular levels with a favourable composition (leucosomes), whereas vast areas were unaffected.

This detail study has important implications for the dynamic of the crust during melting. Melting persisted over a long period, much longer than what previously thought, but was scattered throughout the terrain. The proportion of leucosome present in outcrops is the cumulative result of several melting episodes. During the protracted high temperature history, the migmatites in the Central Alps never contained significant amounts of melts at any given time. The lack of large melt volumes at any given time implies that the rheological behaviour of the crust was not profoundly affected by the melting process, opposite to what argued by some tectonic models.

Full details in the online article:
http://www.springerlink.com/content/38k0273620335873/
Age of volcanism and its migration in the Samoa Islands

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Potassium-argon (K-Ar) ages on whole rock samples have been measured on lavas from the subaerial Samoa Islands, which form a broadly linear volcanic chain that extends from the ESE to the WNW for about 360 km. The Manu’a Islands near the southeast limit of the chain exhibit youthful ages, with most <0.4 Ma, in keeping with the geological observations. Tutuila consists of several volcanoes and previous work yielded a mean K-Ar age of 1.26 ± 0.15 Ma for the shield-building volcanism. Upolu, to the WNW of Tutuila, gives a mean age of 2.15 ± 0.35 Ma for the shield-building phase, represented by the Fagaloa Volcanics, with much of the island covered by significantly younger volcanic rocks. Savai’i, further to the WNW, is dominated by youthful volcanism, extending into historic times. In a restricted area, adjacent to the NE coast of Savai’i, previously thought to have volcanic rocks correlating with the Fagaloa Volcanics of Upolu, the ages are much younger than those on Upolu, lying between 0.32 and 0.42 Ma. Considering only the subaerial volcanism from Ta’u to Upolu, but also including Vailulu’u, the volcanism has migrated in a systematic ESE direction at 130 ± 8 mm/a over 300 km in the last 2.2 Ma. This rate is nearly twice that obtained from GPS measurements of Pacific Plate motion of 72 mm/a at N64ºW in this area. However, if the much older age of shield-building volcanism from the submarine foundations of Savai’i is included, the regression yields a volcanic migration rate of 72 ± 14 mm/a (Figure 1), in keeping with the measured GPS rate and consistent with a hotspot origin for the island chain. This suggests that the volcanic migration rates determined from the age of subaerial volcanism can be considerably overestimated, and this is now evident in other Pacific Ocean island chains. Clearly, the age of the main shield-building volcanism from subaerial volcanism are minima, and if the older submarine lavas can be measured, these may yield a migration rate more in keeping with current plate motions.


Earth Environment

Introduction

The year proved quite challenging for us all, especially with the Geochemistry, Mineralogy and Petrology Review. This forced us to examine our research directions and priorities including also our performance. Basically, Earth Environment’s research is on the response of the Australian landscape and the oceans in our region to past, present and future climate change and human impacts, with four broad specific themes focussing on:

- Ocean chemistry and climate change
- Coral reefs and global change
- Landscape evolution and terrestrial impacts of climate change
- Human evolution, linked to the environment, both in Australia and abroad.

These research themes reflect strengths that are based around a combination of leading expertise and analytical technologies, the latter predominantly developed or enhanced in-house. The recent addition of the new radiocarbon facility, a joint RSES-RSPhysE project funded through an ARC LIEF and ANU MEC grants, stands to play a vital role in understanding processes that operate in the oceans and in particular changes in carbon cycling within the Southern Ocean. Earth Environment houses outstanding analytical facilities, spanning multi-collector ICP-MS for high precision U-series dating and stable isotope geochemistry, laser ablation ICP-MS, TIMS, and oxygen/carbon-isotope mass spectrometry, to cosmogenic isotope, OSL, ESR and palaeomagnetic dating. All are vital for achieving current and new goals set by the Earth Environment. To further enhance our capabilities for environmental reconstruction and fundamental research into ocean processes, we are in the process of purchasing a new oxygen/carbon isotope mass spectrometer through the MEC and new state-of-the-art MC-ICPMS through the ARC LIEF grant scheme.

A new focus for Earth Environment is on culturing marine organisms [from microscopic calcareous and siliceous plankton to sponges, and perhaps corals] in controlled conditions to develop new and validate existing chemical proxies for the reconstruction of past environmental conditions. In combination with the development of new B isotope and trace metal proxies to link past changes in ocean carbonate chemistry and pCO2, these are providing new insights into the threat of oceanic acidification from anthropogenic CO2 under different emission scenarios.

Changes also occurred among our group with the departure of Professor Malcolm McCullogh who accepted the prestigious position of Premier’s Fellow at the University of Western Australia. He is accompanied by Dr Julie Trotter. Several of his PhD students and Dr J-A. Mallela (Postdoctoral Fellow), appointed by Malcolm, remain at RSES. Dr Tim Barrows also left for a position at the University of Exeter and Dr K. Fitzsimmons is about to depart for a position in Germany. Dr B. Walther left for a position in Texas and was replaced by Dr Mallela. Dr Alibert recently rejoined our group to work with Dr Eggins.

Several PhD students submitted their thesis this year, and many have now been awarded their degrees.

With respect to teaching, Earth Environment provides a core component to the Marine Science undergraduate teaching program and to the BGOS degree, which is attracting high-performance undergraduate students. Other EE staff are involved in teaching and supervision of the newly established Master’s course on Archaeological Science.

We are keen to investigate the possibility of developing a new MSc program in "Environmental Geoscience". This program would draw on the large pool of expertise within Earth Environment and provide the basis for pedagogic training for postdoctoral fellows and postgraduate students, and has the potential to attract significant numbers of full-fee paying students.
360 million-year-old giant predator discovered on the South Coast

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Sedimentary rocks of Devonian age (~416-360 million years ago) are well exposed along the south coast from near Bermagui to the Victorian border. This geological period has been called the ‘Age of Fishes’, because fossil vertebrate remains became abundant for the first time. During that period the first forests evolved, and our fish-like vertebrate ancestors moved onto the land. Reconstructions of ancient atmosphere indicates a dramatic drop in concentrations of CO₂ during the Devonian Period, as diverse terrestrial ecosystems became established.

Fossil fish and plant remains, and preserved trackways of unknown amphibians, have been discovered at a number of localities in SE Australia and adjacent Victoria (summarised by Young, 2007). The trackways represent the oldest definite evidence for land animals in the Southern Hemisphere. Under an Australian Research Council Discovery Grant (DP 0558499: ‘Australia’s exceptional Palaeozoic fossil fishes, and a Gondwana origin for land vertebrates’) we conducted new field investigations along the coastal outcrops, some of which were covered by scientific permits when within the area of Ben Boyd National Park.

In 2008 we excavated a near-complete specimen of a placoderm (armoured) fish from the coastal outcrop south of Eden, NSW. At the same time we exposed a large tooth about 45 mm long associated with adjacent large bones that extended deeper into the rock. In April, October, and December, 2008 we used rock saws and drills to remove numerous blocks and pieces. Over 100 collected samples and larger blocks were brought back to the laboratory, prepared mechanically, then glued together and reassembled into about 30 larger blocks. Where the bone was very weathered it was removed by treating with acid so impressions could be cast with rubber latex. Many hundred or hours work in the laboratory during 2009 demonstrated that we have collected the front half of a very large predatory lobe-finned fish, including most of the skull, palate, cheek, jaws, and shoulder girdle. The lobe-fins were the fish group that gave rise to the first land animals, the fleshy lobes in the fins being modified into limbs. Reassembly of the new specimen shows that the two jaws meet at the front in the midline, with other bones of the skull and cheek slightly displaced.

A total jaw length of 45-50 cm for these associated skull remains makes this the biggest such bony fish ever found in Devonian rocks from anywhere in the world. With fangs nearly 50 millimetres
long, the fish was perhaps up to four metres in total length; it would have been the top predator in the big river system that deposited the red mudstones forming the coastal cliffs between Eden and Merimbula. It will be described as a new genus and species of lobe-finned fish.

Reference

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Figure 3. Blocks containing the lower jaws of the giant predator reassembled on a table, with some of the surrounding bones labelled.
Higher silicon concentrations in the Pacific sector the Southern Ocean during glacial times

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Fundamental to understanding changes in CO2 variability across the last glacial-interglacial transition is the reconstruction nutrient concentrations in the deep Southern Ocean. Such reconstructions have typically been based on nutrient proxies such as $d^{13}C$, Nd isotopes, Cd/Ca, Ba/Ca, $^{231}Pa/^{230}Th$, but with conflicting results. Glacial Cd/Ca and Ba/Ca benthic foraminiferal results suggest that there was little change palaeo-nutrient concentrations, whereas the $d^{13}C$ and Nd isotope results suggest palaeo-nutrient concentrations were higher as a result of a reduction in Northern Component deep water feeding into the Southern Ocean. In our study we determined the silicon isotope ($d^{30}Si$) composition of sponge spicule and found that the distribution of silicon within the deep Southern Ocean not homogeneous during the last glacial period; rather the glacial concentration of silicon in the Pacific sector was higher compared to the Atlantic sector. At face value, this result suggests that the Antarctic Circumpolar Current (ACC) was less efficient in mixing Pacific and Atlantic deep and bottom waters. Possible scenarios leading to such heterogeneities may be linked to changes in the position and intensity of the ACC. A change in the position of the westerly winds may lead to increased stratification which would increase the invasion of nutrient-rich deep Pacific water into this region.
Diverse pollen and spore assemblages, spanning the Late Eocene preglacial–glacial transition, have been recovered from Ocean Drilling Program cores from Prydz Bay, East Antarctica. These microfloras are mostly in situ and provide an unparalleled record of terrestrial plant communities growing in Antarctica during the earliest stages of ice-cap formation. The evidence provides a basis for assessing the phytogeographic relationships of the Antarctic floras with other high-latitude floras in the southern hemisphere, including possible migration routes for some taxa. Preliminary studies (Macphail and Truswell 2004a) suggested the Late Eocene vegetation at Prydz Bay was floristically impoverished rainforest scrub, similar to Nothofagus–gymnosperm communities found near the climatic treeline in Patagonia and Tasmania. Re-evaluation of the microfloras indicates the diversity of shrubs, especially Proteaceae, was underestimated and the Late Eocene vegetation was a mosaic of dwarfed (krumholtz) trees, scleromorphic shrubs and wetland herbs, analogous to the taiga found in the transition zone between the boreal conifer forest and tundra biomes across the Arctic Circle. Microfloras similar to although much less diverse than the Prydz Bay assemblages occur in coreholes from the Ross Sea region on the opposite side of Antarctica. Interpretation of the latter is complicated by reworking and low yields but the combined evidence points to the collapse of taller woody ecosystems during the Eocene–Oligocene transition and their replacement by tundra-like or fell-field vegetation during the Oligocene and Neogene. This temperature-forced regression seems to have been broadly synchronous across the continent. The high-palaeolatitude location (~70°S) means that the Prydz Bay flora was adapted to several months of winter darkness and short-summer growing seasons. The nearest living relatives of identifiable woody taxa suggest year-round high humidity, with an annual precipitation between ~1200 and 1500 mm. Palaeotemperatures are more difficult to quantify although the inferred humid microtherm climate is consistent with mean annual temperatures less than 12°C and freezing winters.
Lead isotopic evidence for an Australian source of aeolian dust to Antarctica at times over the last 170,000 years

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Systematic analysis of Pb, Sr and Nd isotopes of 23 fluvial clay samples (<2µm fraction) from many of the major tributaries of the vast (1.10^6 km^2) Murray Darling Basin (MDB), located in semiarid southeastern Australia, display similar isotopic values between some MDB clays and dust from several ice core samples from the EPICA Dome C in Antarctica. Close scrutiny of several ratios of the four Pb isotopes, and in particular ^208Pb/^207Pb versus ^206Pb/^207Pb, show that several samples from the Darling-sub-basin of the MDB display similar values for the same isotopes for Dome C samples [see figure1] from different ages, and more particularly during wet phases in Australia [Marine Isotopic Stages 5e, 3 and 1]. The combination of Nd and Sr isotopic ratios from the same MDB fluvial clays clearly eliminates the Murray-sub-basin, and supports the Darling sub-basin as a potential source of aeolian material to Antarctica. Overall, the Australian dust supply to Antarctica predominantly occurred during interglacial periods.

Our work shows that aerosols generated in southeastern Australia can travel to parts of West Antarctica and this is supported by atmospheric observations and models using the HYPLIT program. In addition, evidence of Australian dust in Antarctic ice cores further implies dust deposition in the Southern Ocean would have occurred in the past. Current meteorological observations also imply that the east Antarctic sector of the Southern Ocean would frequently receive aeolian dust components originating from southeastern Australia.
Sediment transport in the Murray Canyons offshore South Australia

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We have examined some of the most spectacular canyons that are located offshore Kangaroo Island, and these are linked to ancient courses of the River Murray which would have flowed across the very wide Lacepede Shelf during periods of low sea level. During the AUSCAN-1 project held in 2003, modern sedimentation was assessed using a multi-tracer approach on interface sediments from 350 to 2,500 m water depth.

The presence of freshly deposited particles, tagged by 234Th in excess, 210Pb-based sediment accumulation (0.03 - 0.13 cm y-1) and 230Th-based focusing ratios support the occurrence of significant advection of marine sediments within these canyons. In the absence of direct riverine inputs, the shelf, being the site of intensive carbonate production, is the main supplier of material.

The presence of incised channels in the eastern portion of the Murray Canyons Group [MCG] [see figure 1] indicates recent to sub-recent activity along the courses. The presence of underwater slides in the western side of the MCG confirms that sediment transport to the abyssal plain does occur.

Based on our preliminary investigation and by synthesizing previous work on other canyons, we provide a conceptual model for sediment focusing and transfer within the canyons offshore Australia.
Kalkowsky's association of stromatolites and oolites - re-evaluation and geological significance

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Three world-wide used geologic terms derived from the area around the north German Harz Mountains: “Oolithi” [1] and nearly two hundred years later “Ooid” and “Stromatolith” [2]. These terms all describe carbonate grains and rocks of the Lower Triassic Buntsandstein Group. The widespread Buntsandstein Group of central Europe consists of red and variegated sandstones and mudstones which stretch from Lorraine in France to the Holy Cross Mountains in eastern Poland. It is a typical dominated by red beds deposited in a large inland basin, the Central European Basin. Braided and meandering rivers brought siliceous grains and mud from the hinterland towards the centre of the basin. At times the inflow of water led to large but shallow lakes at the centre of the basin. When the rainy seasons vanished, the water of the lake evaporated. Microbial calcite-producing communities flourished in the absence of higher organisms. Calcite ooids formed in the shallow environment under the impact of wind and wave action bars or shoals which are now preserved at the margin of the basin and palaeohighs from the Netherlands to Poland. Eventually the lakes vanished and small ephemeral rivers reached the centre and brought only mud with them.

The sediments of the Lower Buntsandstein, are nearly devoid of fossils, body fossils as well as trace fossils. The reason of this scarceness may be not abnormal salinity, but rapidly changing environmental conditions as the shallow playa lake has no buffer capacity against fluctuations of various environmental parameters. The etched surfaces of stromatolites are because of the decay of organic matter under a cover of clay or living mat led to formation of CO₂, lowering the pH and consequently to acidification of the water and dissolution of carbonate.

Some prerequisites of stromatolitic growth can be deduced from observations in the field. Muddy water or mud layers excluded stromatolites or terminated their growth. The microbial community did not survive a mud cover or muddy water. This effect may be the reason for their restriction to the Eichsfeld Palaeohigh. Here, the sandy and muddy sediments were diverted west and east of the high on their way towards the basin. The more extended areas of oolites indicate that the ooid producing microbes are not so sensitive. The position of stromatolites at top of oolite beds seems to reflect a directional evolution, most likely of the water chemistry, e.g. alkalinity or supersaturation in respect of calcium carbonate.
The observed photoautotrophy points to cyanobacteria, at least as a component of the microbial community. There is a high potential of preservation by the absence of grazers and browsers and an early lithification, although the latter cannot be proved.

There was a long-lasting discussion in the scientific community about the formation of ooids. During the 19th and 20th century most scientists thought of inorganic origin, a precipitation due to supersaturation in regard of calcium and carbonate. Calcite or aragonite may precipitate around a nucleus of a quartz or carbonate grain. Only Kalkowsky (1908) thought of an organic origin produced by colonies of lime secreting phyto-organisms. During the last twenty years an increasing number of indications are found that organic biofilms are involved in the formation of ooids.

To summarize, Kalkowsky (1908) stated that

p. 100 § 64 Regarding the environment of the oolites in the north German Bunter Sandstone, it is generally assumed that they have formed in a shore facies. One could easily be tempted to think already now of salt lakes as area of their formation.

p. 118 § 88 Stromatolites were always associated with oolites.

p. 123 § 94 Ooids resemble growing bacterial colonies as observed in a Petri dish. Ooids are therefore probably produced by colonies of lime secreting phyto-organisms.

p.124 § 96 We have to assume that simple plants gave rise to limestone precipitation.

My aim has been to show that the oolites and stromatolites of the north German Bunter Sandstone are inherently of organic origin.

Fifty years after Kalkowsky published the classic paper Richard Chase recognized the first convincing modern analogues of “stromatoliths” around the shores of Hamelin Pool, Western Australia [6]. Recent investigations of both localities reveal a number of interesting parallels between the environment of Hamelin Pool and that of the Basin in which the association described by Kalkowsky. In both cases stromatolites grow on stable or firm ground in turbulent environments characterized by low sedimentation rates, little fine grained sediment, virtually no terrigenous input, rapid cementation and abnormal or fluctuating salinity.

Kalkowsky's stromatolites occur on the surface of oolite beds. Laminated crusts (called stromatoid by Kalkowsky and interpreted as being formed by syndepositional cementation) also occur in these rocks. Both stromatolites and laminated crusts are concentrated in specific layers traceable throughout quarry faces. In places the stromatolites are clearly syndepositional with rippled ooid sand. Spongy-fenestrate and fan-like stromatolitic microstructures can be distinguished, and both have undergone intense sparitization. The upper surfaces of some stromatolites are pitted due to syndepositional dissolution. The stromatolites may incorporate variable amounts of ooids, quartz grains and other material.

Hamelin Pool stromatolites also occur associated with ooid sands [3,8]. Subtidal stromatolites grow on rock substrate or crusts formed by penecontemporaneous cementation of marine sands, and are surrounded by mobile oolitic rippled sands and sand waves. The subtidal stromatolites have a laminoid fenestral fabric consisting of ooid and other carbonate sand grains cemented by micritic cements [3]. Micritisation of sand grains begins soon after deposition and gradually destroys the original structure of the incorporated ooids and other grains [9,10]. Stromatolites in the intertidal zone are thought to be subtidal forms stranded by sea-level fall and modified by intertidal microbial communities [11]. While the Buntsandstein stromatolites originated in a hypersaline lake environment during the high stand of water level, and the Hamelin Pool stromatolites a forming in a hypersaline marine embayment during a period of regression, there are many environmental similarities. In both cases conditions favourable for ooid formation precedes the initiation of stromatolite growth, but the stromatolites co-exist with ooid sands, and incorporate ooid grains into their structures. The morphology of the many of the subtidal Shark Bay stromatolites is clearly influenced by the erosive effects of ooid sand waves migrating around them. Once formed, early diagensis progressively obliterates the structure of ooid grains incorporated into the stromatolites. The association of stromatolites and ooid sands is of considerable geological significance. In another present-day environment the stromatolites of Lee Stocking Island in the Bahamas show a similar association with migrating ooid sand waves to that found in Hamelin Pool [12]. The association of stromatolites and oolites dates back to the Archean. One of the oldest occurrences of the association is known from the 2, 72 Ga. Tumbiana Fm., Fortescue Gr. Pilbara Block in Western Australia.

Even the first stromatolites known to science are associated with oolitic limestones, for, 25 years before Kalkowsky's work was published, James Hall had formally named Cryptozoon proliferum, from the oolitic Cambrian Hoyt Formation of Saratoga Springs, New York State [13].

References


Fate and transport of chemicals in an ACT municipal wastewater treatment plant, its effluent, and receiving waters

An Actew/ANU initiative

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In times of changing climate, increased urbanization, industrial development, and changes in land use practices, the Australian Water Industry faces a significant challenge to maintain a safe and sustainable water supply in the midst of an overall reduction of water quality via anthropogenic contamination. Aquatic wildlife is particularly at risk, as the aquatic environment is a natural sink for waterborne contaminants derived from human activity. These can enter waterways via several sources, however wastewater treatment plant (WTP) effluents are thought to be a major contributor of contaminants to riverine systems. Most conventional WTP's are not specifically designed to remove EDC's and pharmaceuticals from wastewater. Detailed chemical characterization of WTP effluents is especially important for inland systems, as they are often a primary source of water for downstream users, especially in low-flow scenarios; aquatic wildlife and population centres down-catchment are directly impacted by WTP effluent quality.

Contaminants of concern include a wide range of endocrine disruptive compounds (EDC's) such as industrial chemicals, pharmaceutical and personal care products, pesticides, natural and synthetic estrogens and organochlorine compounds. Endocrine Disrupting Compounds have been formally defined by the World Health Organisation as ‘exogenous substances that alter function(s) of the endocrine system and consequently cause adverse health effects in an intact organism, or its progeny, or subpopulation(s)’. The detection and removal of these potentially harmful substances is essential for the water industry to maintain an adequate supply of potable water to Australian communities; the major concern associated with the presence of EDC's in surface waters is not necessarily acute effects on human health, but imperceptible effects on aquatic life and humans resulting from chronic, low-dose exposure. Ultimately, these endocrine effects effects can accumulate to induce profound changes.

This work will investigate a representative set of EDC's (and their metabolites) that contribute to the total estrogenic activity of LMWQCC effluent measured by previous researchers, and the movement and fate of these compounds through the sewage treatment works and in the Molonglo catchment (see Fig 1). Chemical analysis of wastewater and biosolids using novel, advanced mass spectrometric methods will be undertaken with the aim of ultimately constructing a detailed mass balance for target analytes around the STP. It is anticipated that more specific information on the chemical signature of LMWQCC effluent, as well as the concentration, movement, transformation and sorption characteristics of priority compounds will be of value to Actew Corporation water quality officials, ecotoxicologists, engineers and policymakers alike, and may assist in decision making regarding the need to modify current treatment practices.

Currently, laboratory training for complex pre-analysis sample treatment is underway, and a full 12 month sampling program is being assembled to begin in 2010. From the beginning of the project in March 2009 to present (nine months), much reading and research has been undertaken to establish the research direction, alongside detailed planning of laboratory work. This has been accompanied by conference attendance, Actew workshops and the organisation of ANU National Water Week.
The boron geochemistry of biogenic silica
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The boron content and isotopic composition ($\delta^{11}$B) of marine carbonate organisms can be linked to the pH of the seawater in which they have grown, making carbonates a useful tool for palaeo-seawater pH reconstruction. A study by Furst (1981) documented unusually high boron concentrations in siliceous sponge spicules, in range from hundreds to a thousand ppm. This observation and the potential for preferential incorporation of the tetrahedral borate species into biogenic silica raises the question as to whether the boron chemistry of biogenic silica might also be influenced by seawater pH. We have measured the boron concentration and isotopic composition of siliceous sponges from the Southern Ocean region, with a view to (1) confirming the observations of Furst (1981), (2) assessing the factors that control boron incorporation and isotopic compositions of sponge silica, and (3) investigating the potentially significant role of siliceous sponges in the marine boron cycle. The measured boron concentrations in a diverse range of both demosponge and hexactinellid sponges confirm the high boron concentrations previously reported. The boron isotope compositions of these sponges vary from around $+2\%$ to $+25\%$ and greatly exceed the range in marine carbonates. This isotopic variation is inconsistent with seawater pH control but is correlated with ambient seawater silicon concentration, in a manner that suggests a link to silicon uptake kinetics and demand by sponges.

Figure 1. Boron isotope ($\delta^{11}$B) vs silicon isotope ($\delta^{30}$Si) signatures of siliceous sponges from Southern Tasmania and George V Land, Antarctica. Si isotope fractionation corresponds with the uptake and deposition of silica; the correlation between $\delta^{11}$B and $\delta^{30}$Si suggests that B uptake is related to these silica formation processes in sponges.
Direct dating of fossil human remains
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Our research focuses on decomposing the ESR spectra observe in fragments of human tooth enamel crystal from the CO$_2^-$ radicals defect. Studies on tooth enamel fragments have shown that the ESR spectra are significantly more complex than previously assumed (Figure 1A, Joannes-Boyau et al. in press). The ESR signal of the $\text{CO}_2^-$ radical in hydroxyapatite has been used for the assessment of the past radiation dose, which in turn is converted into numerical age estimates, once the dose rate parameters are assessed. ESR dating studies are conventionally carried out on powdered samples, and it has repeatedly been demonstrated that the ESR spectra recorded from fossil samples are qualitatively similar to those generated by laboratory irradiation.

However, when attempting non-destructive ESR analysis, which is essential when working on fossil human remains, measurements are carried out repeatedly on tooth enamel fragments. Because of the anisotropic nature of hydroxyapatite, the ESR spectra show strong angular dependencies (Figure 1B Joannes-Boyau et al. 2009). In contrast to powders, the ESR spectra of fossil samples are significantly different to those generated by laboratory irradiation. Because of unstable components, it was initially suspected that all ESR age estimations could be underestimated (Joannes-Boyau et al. 2009). At the present point, the study focuses on the enamel structure to understand where the different components are located within the crystal.

The enamel structure is exceptionally complex. Our studies have so far revealed a composite organisation of crystal clusters, in prismatic and inter-prismatic configurations, both having different ESR responses (Figure 1C). At the same time Kinetics studies undertaken are showing complex transfer process and radicals disappearance that could threaten the fundamentals of ESR dating of tooth enamel (Grün et al., 2008).


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Figure 1. (A) ESR Spectra of human tooth enamel fragment; (B) Angular dependency of ESR spectra; (C) Differing ESR responses based on crystal structure.
Extinction implications of a chenopod browse diet for a giant Pleistocene kangaroo

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Kangaroos are the world’s most diverse group of herbivorous marsupials. Following late-Miocene intensification of aridity and seasonality, they radiated across Australia, becoming the continent’s ecological equivalents of the artiodactyl ungulates elsewhere. Their diversity peaked during the Pleistocene, but by ~45,000 years ago, 90% of larger kangaroos were extinct, along with a range of other giant species. Resolving whether climate change or human arrival was the principal extinction cause remains highly contentious.

In this study we combine craniodental morphology, stable-isotopic and dental microwear data to reveal that the largest-ever kangaroo, Procoptodon goliah, was a chenopod browse specialist, which may have had a preference for Atriplex (saltbushes), one of a few dicots utilizing the C4 photosynthetic pathway. Furthermore, oxygen isotope signatures of P. goliah tooth enamel show that it drank more in low-rainfall areas than its grazing contemporaries, similar to modern saltbush feeders. Saltbushes and chenopod shrublands in general are poorly flammable, so landscape burning by humans is unlikely to have caused a reduction in fodder driving the species to extinction. Aridity is discounted as a primary cause because P. goliah evolved in response to increased aridity and disappeared during an interval wetter than many it survived earlier. We suggest that hunting by humans, who were also bound to water, may have been the more decisive factor in the extinction of this giant marsupial.

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Seventeen inorganic germanium and silicon concentration profiles from the Atlantic, the Southwest Pacific and the Southern Oceans were collected. A plot of germanium concentration versus silicon concentration produced a near-linear line with a slope of 0.760 x10-6 (± 0.004) and an intercept of 1.27 (± 0.24) pmol/L (r²=0.993, p<0.001). When the germanium to silicon ratios (Ge/Si) were plotted versus depth and/or silicon concentrations, higher values are observed in surface waters (low in silicon) and the ratio decreased with depth (high in silicon). Germanium to silicon ratios in diatoms (0.608-1.03 x10-6) and coupled seawater samples (0.471-7.46 x10-6) collected from the Southern Ocean show clear evidence for Ge/Si fractionation between the water and opal phases. Using a 10-box model (based on PANDORA) Ge/Si fractionation was modelled using three assumptions: (1) no fractionation, (2) fractionation using a constant distribution coefficient (KD) between the water and solid phase and (3) fractionation simulated using Michaelis-Menten uptake kinetics for germanium and silicon via the silicon uptake system. Model runs indicated that only Ge/Si fractionation based on differences in the Michaelis-Menten uptake kinetics for germanium and silicon can adequately describe the data. The model output using this fractionation process produced a linear line with a slope of 0.76 x10-6 and an intercept of 0.92 (± 0.28) pmol/L thus, reflecting the oceanic dataset. This result indicates that Ge/Si fractionation in the global ocean occurs as a result of subtle differences in the uptake of germanium and silicon via diatoms in surface waters.
Coral calcification and ocean acidification in the central region of the Great Barrier Reef

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Coral reefs are exceptional rich environments of great commercial and natural value. The construction of these reefs relies on the accumulation of limestone skeletons from corals and other organisms. Coral reefs are at risk to climate change and human imposed stresses including increased nutrient and sediment loading, direct destruction, overfishing, habitat modification, and contamination. In addition, ocean acidification, caused by the increase in atmospheric CO2, has recently been added as a possible coral stressor. Laboratory experiments have shown that a decrease in pH causes a decrease in calcification rates.

This project aims to analyze the effects of ocean acidification during the last ~50 yrs in coral calcification across a transect from inshore to offshore in the central section of the Great Barrier Reef. Emphasis will be placed on the possible effects of the "acidic" flood plume from the Burdekin River in inshore corals.

Changes in coral calcification, will be obtained from three growth parameters including; (1) skeletal density (gr cm\textasciitilde{}3), (2) annual extension rate (cm yr\textasciitilde{}1), and (3) calcification rates (gr cm\textasciitilde{}2 yr\textasciitilde{}1). The boron isotopic composition (\textdelta{}\textsubscript{11}B) will also be measured in selected coral samples along the growth axis and can be used as a proxy for pH changes. This information will be complemented with trace elements analyses by LA-ICP-MS of some coral samples.
Figure 1. Black and white images of five corals from the inshore reefs of Havannah and Pandora showing the luminescent bands used to measure the linear extension rates. Some high intensity bands related to high river discharge episodes are highlighted.
Late Quaternary radiolarians as proxies for past environmental conditions in the eastern and southern sectors of the Indian Ocean

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I examined the silica tests (the hard parts or "skeletons") of a group of plankton called Radiolaria. Firstly, I counted the tests appearing in the tops of sediment cores taken from 100 sites in the eastern and southern sectors of the Indian Ocean - around 600 tests per core-top and about 400 species in all. I was able to relate the distributions of the species to the currents in the eastern Indian Ocean (EIO) and to the inter-frontal zones of the southern Indian Ocean (SIO). I was also able to establish statistical relationships between the radiolarian counts and a number of physico-chemical oceanic variables (temperature, salinity, etc) over a range of depths from the surface to around 500 metres below sea level.

Next, I performed census counts on samples taken from four SIO sediment cores from between the Kerguelen Plateau and the Southeast Indian Ridge. From these data and the relationships established with the present-day physico-chemical environment, I was able to reconstruct the palaeoceanic conditions at the core sites over approximately the last 40,000 years and, hence, an indication of how the ocean fronts moved over that period. In addition, I attempt to find reflections of interactions between the Southern Ocean and the North Atlantic as reported by Sicre et al. (2005). There was some evidence in the radiolarian-based reconstructions of sea-surface temperature that warming in the SIO coincided with Heinrich Events H1 and H2 but the possible associations with earlier Heinrich Events were tenuous.

I also examined the statistical techniques commonly used for the analysis of plankton census counts and concluded that a number of the traditional methods are unsuitable for regions as complex as the Indian Ocean and that Weighted-Averaging - Partial Least Squares (ter Braak and Juggins, 1993; ter Braak et al., 1993) was the most efficient technique available given the number of core-tops I investigated.


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Silicon isotopic fractionation in marine sponges: A new paradigm and model for understanding silicon isotopic variations in sponges

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The modern Southern Ocean plays a pivotal role in determine the air-sea balance of CO₂ and global biological production. However, there is debate regarding nutrient utilisation in Southern Ocean surface waters and how this transfers through to the deeper Southern Ocean, especially during the past. To fill this gap we have determined the silicon isotope composition of deep-sea sponges collected from near Antartica, subantarctic waters (Tasmania Seamounts) and subtropical waters north of New Zealand with the aim of developing a new paleo-nutrient proxy. For deep-sea sponges, δ³⁰Si values widely between 0.87 ‰ and -3.40 ‰ (vs NBS). Depth profiles show that sponge δ³⁰Si compositions trend to lighter values with increasing depth. This is exemplified by sponges from the Tasmanian Seamounts which vary from 0.87 ‰ to -3.13 ‰ over a depth range from 100 to 1200 m. We find that silicon isotope fractionation (δ³⁰Si sponge - δ³⁰Si seawater) varies with seawater silicon concentration with more fractionated (lighter) isotope values being associated with specimens collected from water high in silicon. A mass-balance based model for silicon isotope fractionation is consistent with δ³⁰Si fractionation driven by changes in the difference between the silicon influx and efflux from the sponge. At higher seawater silicon concentrations efflux is correspondingly higher, and with δ³⁰Si having an apparent greater internal fractionation, this results in lighter δ³⁰Si spicule values. This model can also explain δ³⁰Si fractionation in diatoms and be used to reconstruct past seawater silicon concentrations from the δ³⁰Si signature of fossil sponges and diatoms.

Figure 1. Depth profiles of Si concentration in seawater, d³⁰ Si in seawater (d²⁹ Si values from Cardinal et al. (2005) for Stotions CTD17 and CTD124,64 were divided by 0.5092 to obtain d³⁰ Si values) and d³⁰ Si in sponges from 3 locations in the Southern Ocean; Tasmania (a - circles), Antarctica (b - squares), and New Zealand (c - diamonds). Si concentration in the New Zealand profile were obtained from the WOCE database for location 173.49E, 30.086S.
The Quaternary comes in from the cold

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Although the name “Quaternary” has long been used by geologists to describe the period of time known as the Ice Ages, it was only in 2009 that the Quaternary Period was finally ratified as a formal subdivision of geological time by the International Union of Geological Sciences (IUGS).

The Quaternary Period, comprising the Pleistocene and Holocene Epochs, is marked by the waxing and waning of large continental ice sheets in the Northern Hemisphere during the last 2.6 million years. At the height of the most recent glacial period, about 20,000 years ago, large ice sheets covered Canada and northern USA, Scandinavia and northern Europe (including most of Britain) and Siberia - the Greenland Ice Sheet is the last remaining remnant of these once extensive Northern Hemisphere ice sheets. Small mountain glaciers also existed in the highest parts of Kosciuszko National Park and over large areas of central and western Tasmania, and with world sea levels up to 150 m lower than present, it would have been possible to walk across Bass Strait, Bering Strait and across the English Channel. Some 50 such glaciations, and subsequent interglaciations (such as the present, or Holocene interglaciation) occurred during the Quaternary, the period of time which also saw the rise and spread of the human species. During the last glaciation, iconic animal species, such as woolly mammoths, roamed across vast areas of the northern continents (Fig 1).

Ratification of the Quaternary came after intense lobbying by the International Union for Quaternary Research (INQUA), particularly over the last 5 years, and prolonged negotiations between INQUA and the IUGS commission that is responsible for managing the geological timescale, the International Commission for Stratigraphy (ICS) – see Pillans & Naish (2004), Aubry et al. (2005), Pillans (2007) and Ogg & Pillans (2008).

A paper describing the formal ratification of the Quaternary is about to be published (Gibbard et al. in press).

References


Coral and Speleothem Reconstructions of Ocean-Atmosphere Dynamics in Southern Indonesia during the 8.2 ka event

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A variety of natural archives have been interpreted as indicating major changes in the strength of the Australasian monsoon and El Niño-Southern Oscillation (ENSO) through the Holocene. Geochemical tracers in coral skeletons are particularly well suited for reconstructing coupled ocean-atmosphere climate systems at seasonal to interannual timescales. The high temporal resolution offered by corals is especially important to study the variability of parameters such as sea surface temperature (SST) and the hydrological cycle on ENSO-monsoon timescales. However, most coral studies have focussed on the past millennium because coral aragonite is prone to diageneasis, and it is difficult to find pristine corals in the early to middle Holocene when the monsoon and ENSO may have been quite different from what we know today.

In the first instance, we performed stable isotope ($\delta^{18}$O, $\delta^{13}$C) analysis of the corals at 5-year resolution to detect any changes in the mean climate state. Our preliminary results, from the analysis of several well-preserved massive Porites corals from Alor (southern Indonesia), with U-series ages of 8.5 to 7.9 ka (thousand years ago), show a double cool/dry-snap with SSTs reaching minima at 8.3 and 8.0 ka. These rapid coolings (2-3°C in 30 years) are synchronous in time, length and strength, with sharp increases in the $\delta^{18}$O of speleothems from the nearby island of Flores.

Based on this result, specific periods have been targeted for high-resolution isotope analysis to document how ENSO and monsoonal rainfall change in response to abrupt changes in the mean climate state. With these high-resolution analysis, we were able to reconstruct the annual $\delta^{18}$O cycle for several time periods during the modern time and the early Holocene (mean climate state, onset of the cold snap and the cold snap). These results show that during the early Holocene, the australasian monsoon was weaker than today, but there is no real evidence for a weaker monsoon during the 8.2 ka event.

Thus, it appears that the 8.2 ka event in the Australasian region would have been only a cold event and not a dry one as suggested by previous studies.
Knowledge of coral recruitment patterns helps us understand how reefs react following major disturbances and provides us with an early warning system for predicting future reef health problems. We have reconstructed and interpreted historical and modern-day recruitment patterns, using a combination of growth modelling and in situ recruitment experiments, in order to understand how hurricanes, storms and bleaching events have influenced coral recruitment on the Caribbean coastline of Tobago.

Whilst Tobago does not lie within the main hurricane belt results indicate that regional hurricane events negatively impact coral recruitment patterns in the Southern Caribbean. In years following hurricanes, tropical storms and bleaching events, coral recruitment was reduced when compared to normal years (p = 0.016). Following Hurricane Ivan in 2004 and the 2005–2006 bleaching event, coral recruitment was markedly limited with only 2% (n = 6) of colonies estimated to have recruited during 2006 and 2007. Our experimental results indicate that despite multiple large-scale disturbances corals are still recruiting on Tobago’s marginal reef systems, albeit in low numbers.

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http://rses.anu.edu.au/people/mallela_j/

**Figure 2.** The estimated year of recruitment for all coral colonies in this study 1980–2006 (solid black line), solid arrows indicate when hurricanes, tropical storms (TS) and bleaching events occurred. Dashed arrows indicate events which may have impacted Tobago’s reefs but were not cited in records. The histogram underneath gives the estimated year of recruitment for dominant coral species: *Colpophyllia natans* (green), *Diploria labyrinthiformis* (dark grey), *Diploria strigosa* (yellow), *Montastrea cavernosa* (light grey), *Porites astreoides* (white), *Siderastrea siderea* (black). (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)
High resolution Sr concentration and isotope distributions in a Neanderthal tooth from Payre (Ardèche, France) using laser ablation ICP-MS

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We have mapped Sr elemental concentrations as well as \(^{87}\text{Sr}/^{86}\text{Sr}\) isotope distributions in a Neanderthal tooth from the Middle Palaeolithic site of Payre using laser ablation ICP-MS. The tooth is an unerupted molar of a three year old child. The dentine shows a clear overprint of Sr with the isotopic composition of the Jurassic bedrock in which the site is located. In enamel we observe a relationship between Sr concentration and isotopic composition that also indicates a secondary overprint. Nevertheless, certain domains in the enamel seem to preserve the original isotopic signature. These results indicate that the individual grew up in a significantly different geochemical rock province to where it was found. Analyses of the bioavailable Sr in the surrounding areas of the site point to a metamorphic province, some 50 km to the SW of Payre, as possible origin of this Neanderthal individual who must have moved to the to the site shortly before its premature death.
Figure 2. A: $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition. B: Relationship between Sr concentration and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition. The general trend of lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with increasing Sr concentration can be explained through a diagenetic overprint of soluble Sr with an $^{87}\text{Sr}/^{86}\text{Sr}$ composition close to the bedrock. C: Results of Sr analysis of plants of the rock provinces in the vicinity of Payre (circled). Abbreviations: Alluv: Alluvium, Cret: Cretaceous, Jur: Jurassic, Mioc: Miocene, Olig: Oligocene, Volc S: volcanic sediment. The dotted lines mark the approximate boundary between metamorphic rocks (Massif Central and Alps) and Triassic to Quaternary sediments. Areas of possible origin are coloured.
A new chronology for sea level highstands during the penultimate interglacial

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Understanding the precise phase relationships of changes in sea level, temperature, and greenhouse gas concentrations during previous interglacial periods provides us with critical knowledge to evaluate the future response of the climate system to anthropogenic forcing. Absolutely-dated sea level archives that document the response of ice sheets to changes in temperature and atmospheric CO₂ become increasingly rare as we look beyond the last interglacial due to the combined effects of alteration, physical superposition of multiple sea level oscillations, and challenges related to temporal limitations of geochronometers.

We have studied a suite of submerged stalagmites from Argentarola Cave, Italy collected across a depth range of -18 to -21 m to improve the absolute chronology of several sea level highstands during MIS 7, also referred to as the penultimate interglacial (Fig. 1). The spectacular feature of speleothems recovered from Argentarola Cave is the occurrence of alternating layers of biogenic calcite and spelean calcite that result from multiple sea level oscillations in the past. The biogenic layers are composed of serpulid calcite secretions that encase the speleothems during seawater submergence while the spelean calcite growth only occurs when the cave is emergent, or above sea level. We have used U-series dating techniques to determine the precise timing of speleothem growth that brackets each serpulid calcite layer to ascribe a chronology to three sea level highstands during the penultimate interglacial. The second highstand, also known as marine isotope stage (MIS) 7.3, is observed to peak at a lower elevation than the other two highstands and appears delayed in timing relative to peak northern hemisphere insolation. We postulate that this behaviour results from the intense cold period preceding MIS 7.3 that was associated with significant development of ice sheets in the northern hemisphere.

Our findings underpin the importance of cryosphere state as a critical factor determining the sensitivity of sea level response to insolation forcing. While records from submerged speleothems such as this are rare, they are archives that have enormous potential to shed light on the dynamics of climate and sea level in the past, and also to inform us about the interplay of these variables as we head into the future.

More details can be found at Nature Geoscience.

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Rhodoliths as environmental proxies in the marine realm,
or how red algae could help fill the climatic gap between the tropics and the poles.

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Rhodoliths are free-living forms of calcareous, coralline red algae that can be found worldwide, from low to high latitudes, in relatively shallow (0->250m) waters. They can live hundreds of years and form a high-Mg calcite skeleton that presents periodical growth bands.

Recent studies on rhodoliths-forming coralline red algae show that the variation of specific trace elements along these periodical growth bands appear to reflect, through time, the variations of ambient seawater temperature and river discharges. This project aims to assess this reliability of rhodoliths as a new proxy to record past environmental changes for subtropical to temperate waters. Two study sites were chosen, one in the lagoon of New Caledonia (subtropic) and one offshore Victoria (temperate) for comparison of environmental parameters. Trace elements analyses by Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA.ICPMS) and δ¹⁸O by Sensitive High Resolution Ion MicroProbe (SHRIMP) will be performed across growth transects on selected rhodoliths to obtain this high-resolution record of past environmental conditions.

Figure 1. Rhodolith bed covering the seafloor. Point Addis Marine National Park (Victoria). Image courtesy of Parks Victoria.

Figure 2. Preliminary results from LA.ICPMS, showing variations of Mg/Ca (orange) and Sr/Ca (blue) ratios along a rhodolith section of 28.5 mm, collected in New Caledonia. 24 points smoothed data are presented in plain lines.
Reconstructing the history of hydrologic change and drought in Australia
Evidence from Lake George, New South Wales

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Temperate southeastern Australia is one of the regions hardest hit by the drought which has prevailed on the continent for more than ten years from 1997-2009. It is unclear how the present relatively arid, warm conditions relate to the cold, dry climate responsible for desert expansion during the late Quaternary period, or to the current severe droughts. This knowledge gap is primarily due to the fact that there are few systematic records of regional aridity and drought in Australia. The key to understanding the development of aridity is to produce a chronological framework for terrestrial aridification. Recent and continuing work at the luminescence dating laboratory in the Research School of Earth Sciences aims to produce such a chronological framework, focusing on key sites which preserve landscape features responsive to aridity, such as dunes and lake shorelines.

The Canberra region, in particular, has experienced record low precipitation in response to the current drought. Lake George, a closed basin located approximately 50 km from Canberra and once mainland Australia’s largest freshwater lake, has completely dried in response to this recent drought. The lake has intermittently filled to a shallow depth, and dried out, eight times during the period since European arrival 200 years ago. The timing of these events matches that of historically documented droughts. The lake acts as a palaeo-rain gauge for the region, providing past context for present and future potential climatic conditions. Lake George therefore represents one of the most complete and valuable records of hydrologic variability as a response to drought and potentially increasingly dry conditions in southeastern Australia. However, regional hydrologic and environmental change over longer timescales - throughout the Holocene and Pleistocene - remains poorly resolved, lacking a comprehensively dated stratigraphic sequence. Consequently, it is difficult to identify how the present drought relates to past conditions.

At Lake George, hydrologic change brought about by climatic variability is expressed in lake shorelines. The lake has intermittently dried and filled to depths of up to 37 m several times during the late Quaternary period. Chronologies for lake level change fundamentally underpin interpretations of palaeoclimate. Our work addresses the existing limitations to reconstructing Holocene palaeoenvironmental change at Lake George by applying optically stimulated luminescence (OSL) dating to stratigraphic sequences along previously occupied shorelines. These represent the last phases of significantly high lake levels prior to present conditions and document changing hydrologic conditions through the Holocene. OSL dating circumvents many of the issues associated with earlier radiocarbon chronologies by directly dating when sediments were deposited. We construct a chronologic framework using OSL for hydrologic variability in southeastern Australia throughout the Holocene, and place the 1997-2009 drought conditions in the context of climate change (Fitzsimmons and Barrows, in press). We have assessed the luminescence behaviour of the samples with respect to depositional context and age (Fitzsimmons et al., in press). We are also presently seeking to extend the chronology beyond the limits of conventional SAR OSL dating through the use of thermally-transferred OSL (Tsukamoto et al. 2008), and are contributing to the development of this new technique.

The OSL chronology indicates three distinct periods of permanent lake conditions up to 15-18 m depth over the Holocene period, at approximately 10-8, 6-2.4 and 0.7-0.3 ka, with lower lake levels occurring in between those events (Fitzsimmons and Barrows, in press) (Figure 1). There appears to be a trend towards lake regression over this period despite relatively recent high lake
levels. The chronology is broadly synchronous with comparable records of Holocene climatic variability across southeastern Australia. The preliminary OSL chronology for events older than the Holocene period shows a striking correlation between lake filling at Lake George and permanent lake conditions/ high water tables across humid, semi-arid and arid Australia. The Holocene and oxygen-isotope stage 5 filling events at Lake George correspond to warm sea-surface temperatures. Lake filling events also appear to correspond to relatively humid periods between major arid episodes in the desert dunefields of central Australia, also identified by OSL dating in the luminescence laboratory at the Research School of Earth Sciences (Fitzsimmons et al. 2007).


Link to Fitzsimmons et al. (in press), Quaternary Geochronology
http://www.sciencedirect.com/science/article/B83WJ-4V999672/2/4c57a7dab6759817446c66824f98c8a

Link to Fitzsimmons et al. (2007), Quaternary Science Reviews
http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VBC-4P9T9VH-1&_user=554534&_coverDate=10%2F31%2F2007&_alid=1083904081&_rdoc=1&_fmt=high&_orig=search&_cdi=5923&_sort=r&_docanchor=&view=c&_ct=2&_acct=C000028338&_version=1&_urlVersion=0&_userid=554534&md5=c0ea3123deabc41e87c55327ff6b499

Figure 1. Holocene hydrological variability at Lake George.
Which climate signals are captured in tropical speleothem records?

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Speleothems are calcium carbonate cave deposits, such as stalagmites, which potentially yield annual to decadal records of past climate change. In the tropics, changes in the oxygen isotopic composition (δ¹⁸O) in speleothems, which is related to the composition of local rainfall, indicate that rapid shifts occur in tropical hydrology during the so-called “Heinrich events.” The last glacial period (between 100 and 200 thousand years ago) was punctuated by these abrupt cool periods that result from massive iceberg discharges into the North Atlantic. Changes in oxygen isotopic ratios in speleothems are often interpreted in terms of changes in rainfall amount. Throughout the monsoon regions, isotopic shifts in speleothems during these climatic excursions have been interpreted as a widespread drying though the Northern Hemisphere and a wetting in the south.

We examine the climatic controls of oxygen isotopes in tropical precipitation using the GISS ModelE general circulation model. Using this climate model, we simulate a collapse of the North Atlantic overturning circulation as an analogue to a Heinrich event. Figure 1 shows the changes in precipitation amount and isotopic composition of rainfall during this simulation. A decrease in monsoon intensity is simulated over East Asia and India and an increase in intensity is simulated over South America and Australia. The drivers of variability in isotopic compositions are found to be complex and dynamic, linked to large-scale changes in monsoon strength, water vapour transport, atmospheric mixing and changes in the source of precipitation to a site, and do not simply reflect local precipitation amount and temperature effects. Ultimately, oxygen isotopes are a useful recorder of tropical hydrological changes, which can be understood in more detail using climate models that include water isotope tracers.
Earth Materials and Processes

Introduction

The Earth Materials and Processes area comprises research groups in Rock Physics, Experimental Petrology, and Structure & Tectonics. Our research centres around laboratory based measurements under controlled conditions, simulating those occurring in nature, but these activities are complemented by a rich array of analytical equipment and are supported by extensive field-based observations, often in collaboration with scientists from other institutions, nationally and internationally. Through such investigations we aim to develop understanding of the structure and chemical composition of planetary interiors, and the processes by which planets evolve. Our interests start at the very beginning of solar system history with how the Earth and other rocky planets accrete, and then cover the ongoing processes of mantle convection, volcanism, metamorphism, global tectonics and the formation of ore deposits.

Areas of current research activity include:

- The making of terrestrial planets. Chemical constraints on the accretion of the Earth and similar planets from the solar nebula, and the processes of core formation; mineralogical and chemical properties of the deep mantle and their influence on global tectonics.
- The nature of the Earth's upper mantle. Experimental studies and thermodynamic modelling of the phase equilibria relevant to upper mantle melting and ultra-high-pressure metamorphism associated with crustal thickening and subduction; experimental and microstructural studies of phenomena associated with lattice defects and grain boundaries including incorporation of water into nominally anhydrous minerals and microscopic mechanisms of seismic wave attenuation; experimental studies and modelling of grain-scale melt distribution and its implications for melt transport, rheology and seismic properties.
- Oxidation state and coordination of metal ions at high temperatures. Studies of crystals, melts and hydrothermal solutions by X-ray absorption spectroscopy, using synchrotron radiation. Studies of silicate glasses and melts to very high temperatures under controlled redox conditions. Analysis of hydrothermal solutions trapped in synthetic fluid inclusions is providing important basic information on metal complexes at high temperatures.
- Coupling between fluid flow and fault mechanics in the continental crust. Field-based studies of a normal fault system in Oman, along with complementary stable isotope and other geochemical studies of associated calcite vein systems, are being used to explore how fault-controlled fluid flow is localized among components of regionally extensive fault networks. Field-based and microstructural studies in two examples of intrusion-related ore systems (Porgera, PNG, and North Parkes, NSW) are providing insights about the dynamics of growth of fracture-controlled hydrothermal systems and localization of ore deposition in these settings. Laboratory studies of the seismic properties of the cracked and fluid-saturated rocks of the upper crust.
- The mission to planet Earth in which we construct a virtual time machine (in collaboration with U. Sydney) to provide a spatio–temporal context that will allow a greater understanding of planetary tectonics from the point of view of plate-scale physical processes. This infrastructure development is supported by the NCRIS AuScope initiative. To provide critical data for the tectonic reconstructions, "listening posts" are being established that provide samples that can be analyzed and dated using 40Ar/39Ar and U-Pb geochronology in the Earth Chemistry.
Environmental Tracers in Waters of the Lower Murrumbidgee Catchment, New South Wales

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The semi-arid Lower Murrumbidgee catchment in south-central New South Wales hosts agricultural and horticultural industries that generate more than one billion dollars in crops annually. Irrigation water in the region is predominantly sourced from the Murrumbidgee River, with supplemental water extracted from local aquifers.

During the first year of a three-year ARC-Linkage grant held by ANU and Parsons Brinckerhoff, a field program was initiated in 2009 to sample water from irrigation extraction bores, environmental monitoring bores, and rivers throughout the Lower Murrumbidgee to characterize and quantify groundwater dynamics in the region. To date, over 150 water samples have been collected and analysed for a major, minor, and trace elements as well as select stable and radio isotopes. This research has produced the most comprehensive and largest-scale hydrogeochemical data set available for the region.

Environmental tracer concentrations in water samples have been reviewed for insight into processes influencing groundwater quantity and quality. Analytical results illustrate that groundwater chemistry evolves in the direction of groundwater flow from an Na-HCO₃-Cl type water to an Na-Cl type water at higher TDS concentrations.

Cl/Br ratios and ²H/¹⁸O isotope concentrations indicate that the increase in groundwater TDS is primarily the result of evaporation and transpiration of meteoric waters, consistent with the findings of studies conducted in adjacent catchments. A significant finding is that mixing of surface waters and shallow groundwater is most pronounced in aquifers under the main irrigation areas, adjacent to the...
Murrumbidgee River, and in areas of groundwater discharge. Regions outside of the irrigation areas exhibit no significant evidence of surface water/groundwater mixing.

Preliminary results from this research were presented at the 10th Australasian Environmental Isotope Conference & 3rd Australasian Hydrogeology Research Conference held from 1-3 December 2009 in Perth, WA. Future research includes the continuation of the current sampling protocol to identify seasonal trends in water quality, and the selection of characteristic sites within the Lower Murrumbidgee for higher-frequency sampling.

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Dynamic permeability and the evolution of fluid pathways in fault networks

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At elevated temperatures, and especially in the presence of reactive pore fluids at depth in the Earth’s crust, permeability in rocks may be destroyed rapidly by compaction, pore cementation and crack healing and sealing processes. The repeated re-generation of fracture-controlled permeability therefore plays a critical role in governing fluid escape from overpressured reservoirs (such as prograding metamorphic crust, subducting slabs, crystallizing magmatic bodies and compacting sedimentary basins), and redistribution of those fluids within the crust.

The migration of aqueous fluids through active fault networks impacts on a number of important Earth processes. These include the generation of hydrothermal ore deposits and the deformational response of the crust to tectonic plate interactions. For example, fluid overpressures can play a critical role in driving brittle failure and are implicated in earthquake processes in some geodynamic settings. However, our fundamental understanding of growth and behaviour of fluid pathways in active fault systems at depth in the crust is limited. Key questions concern the relative roles of stress and fluid pressure in driving the formation of fracture-controlled permeability networks at various scales, and how these different drivers influence the evolution of hydraulic connectivity and fluid pathways.

In actively deforming, reactive fluid-rock systems, permeability is a dynamic, time-variant parameter controlled by competition between various permeability-destruction processes and deformation-induced, or fluid-pressure-induced, permeability-creation processes (Cox, 2005). In seismogenic fault zones, for example, large and sudden permeability enhancement can occur during earthquake rupture events. In contrast, the much longer interseismic period is characterised by gradual permeability destruction associated with fracture healing and sealing (Tenthorey & Cox, 2006; Giger et al, 2007). Repeated breaching of fluid reservoirs by earthquake ruptures, followed by hydrothermal sealing of pathways and shut-off of flow, should foster the development of episodic, rather than continuous, flow regimes. Little is known about how such “toggle-switching” of permeability (Miller & Nur, 2000) might impact on the evolution of fluid pathways during ore genesis in fault systems, and more generally in fracture-controlled flow networks during upper crustal deformation. “Toggle switching” of permeability should lead to repeated changes in fluid pathways as failure events migrate around fracture systems. This has important implications for network connectivity, and may result in segments of fracture-controlled flow networks switching repeatedly from above to below the percolation threshold. As there are likely to be feedbacks between localisation of fluid migration and nucleation of seismicity, understanding the nature of coupling between dynamic permeability, fluid flow rates, fluid pressure states and deformation processes is critical for understanding how fluid pathways may evolve in space and time. This knowledge is critical also for understanding what factors favour the extreme flow localisation required to form many types of hydrothermal ore deposits in brittle deformation regimes, and for understanding the possible roles of fluids in affecting how seismicity patterns evolve in space and time.

In light of these observations, key motivations for this project are the following questions:

- How do interactions between stress states, fluid pressures, permeability and fluid-rock reactions
influence the growth, time-dependent permeability structure, and evolution of fluid pathways in fault-related fluid flow networks?

- What are the implications of these interactions for fluid redistribution processes in the crust, especially in relation to their impact on epigenetic ore formation, the mechanical behaviour of the crust, and seismicity patterns?

Many vein systems that are preserved in exhumed fault zones represent ancient, fracture-controlled fluid pathways. Vein systems are developed at various scales, and range from localised arrays of veins associated with small faults to regional-scale vein networks or swarms. The chemistry of vein minerals has potential to reflect the composition of the fluids from which they grew. Importantly, changes in vein mineral chemistry during incremental vein growth can preserve a record of changes in fluid chemistry in space and time. Barker et al (2006) used high spatial resolution isotopic and trace element analyses to document progressive changes in isotopic compositions, rare earth element (REE) concentrations, and redox states during growth of one vein. In this project, this approach is being extended across a regionally-developed, fault-related vein system to explore spatial and temporal variations in vein mineral chemistry during advective flow, and thereby use geochemical tracers to explore aspects of the dynamics and evolution of fluid pathways during growth of a fault system.

A key factor in using geochemical tracers to explore the operation of flow systems is that, as fluids migrate downstream along pathways, isotopic and element exchange occurs between fluids and the rocks through which they percolate. As externally-sourced fluids react progressively with rocks along the flow path, their compositions become more rock-buffered towards the downstream parts of the system (Figure 1). Reactive transport modelling of isotopic profiles in veins and wall-rocks along flow paths can be used to constrain flow directions and fluid fluxes. The shapes and positions of geochemical fronts are influenced by parameters such as flow rates and net fluid flux, temperature-dependent exchange rate constants, and effective reactive surface areas. In continuous flow regimes, geochemical fronts migrate with time in the fluid flow direction (Figure 1). In contrast, in episodic flow regimes, each batch of migrating fluid may react separately with wall-rocks and the position of the geochemical front will be dependent on the fluid flux during each pulse of fluid flow (Cox, 2007).

Calcite-rich vein systems formed in upper crustal regimes in limestone sequences provide great potential for preserving the record of fracture-controlled flow. In low temperature (150-300°C) environments, C/O isotope, trace element, and Sr-isotope signatures in veins and host rocks can exhibit negligible re-equilibration after vein formation (eg, Barker et al, 2006; Cox, 2007). Additionally, fluids derived from reservoirs outside limestone sequences are usually substantially out of chemical equilibrium with limestones, and leave a distinctive signature in vein calcite deposited prior to fluids becoming rock-buffered along their pathways. Finally, high precision, high spatial resolution analytical techniques now allow the chemical signature of fluids to be examined cost-effectively at very fine scales during incremental growth of veins. This opens the way to produce high resolution records of spatial and temporal variations in fluid chemistry during formation of vein systems in fracture-controlled, advective flow regimes.

Coupling geochemical tracer analysis with a physical understanding of how fracture-controlled percolation networks may evolve, accordingly has potential to provide new insights about how fracture-controlled flow networks evolve and influence fluid redistribution in the crust.

In this project, we are conducting structural and microstructural studies of exceptionally well-exposed, calcite-rich vein systems that are hosted by a system of normal faults in a limestone sequence in the Jebel Akhdar dome in Oman. The structural studies are being combined with high spatial resolution C/O stable isotope, Sr isotope, and trace element analysis of vein calcite, to map spatial and temporal variations in the chemistry of vein calcite throughout the fault system. The study uses the 4D variations in vein mineral chemistry to map the distribution of reactive flow paths as the fault system evolved. In particular, vein mineral chemistry will be used to map, at various scales, how the positions of geochemical fronts migrated with time within vein systems. The geometry and distribution of geochemical fronts will be used to constrain flow directions. Reactive transport modelling of geochemical profiles along fluid pathways will be used to map 4D variations in fluid fluxes.

In summary, the project is advancing understanding of:

- structural controls on the distribution of fluid flux within individual, fluid-conductive fault zones;
- how the dynamics of growth of fracture-controlled flow systems at depth in the crust influences hydraulic connectivity, the distribution of fluid flux, and changes in fluid pathways with time in flow systems associated with the growth of fault networks;
- feedbacks between fluid flow and rock mechanics in the seismogenic regimes of the continental crust;
fundamental aspects of coupling between deformation processes, fluid transport and reaction, how these processes may influence redistribution of fluids during crustal deformation, and impact on seismicity patterns and flow localisation associated with ore deposition in fracture-controlled hydrothermal systems.

References
Laboratory Studies of Rock Deformation, Dislocation Recovery and Attenuation

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As part of an ongoing study of dislocation damping as a possible mechanism for seismic wave attenuation in the Earth’s upper mantle, we focused this year on the preparation of natural (San Carlos) olivine cylindrical fine-grained polycrystalline specimens and their deformation by dislocation creep. These specimens differ significantly from their fully synthetic (sol-gel) counterparts by being more coarse-grained and containing a broad inventory of trace elements. Specimens of each type have been successfully deformed both in compression (ANU) and torsion (University of Minnesota). Infrared spectroscopy indicated that the specimens are essentially dry (< 20 wt ppm water). The specimens were deformed in torsion to a shear strain of 0.5 at 170 and 200 MPa shear stress (Fig. 2a). Micro-structures viewed under the light microscope show strong crystal preferred orientation - most notable in the fine grained sol-gel olivine (Fig. 2b).

We have also begun a study of the recovery of dislocation micro-structures in a compressionally deformed San Carlos specimen during high temperature annealing - designed to complement our previous work on the sol-gel material. Preliminary results show that the dislocation recovery rate is not affected by trace elements in olivine nor grain size (see Fig. 1). However, comparison with previous results on dislocation recovery in natural olivine conducted nearly 20 years ago using a light microscope and an older generation scanning electron microscope, reveals a marked contrast - possibly attributable to the significant difference in resolution at which dislocations are counted and measured (1000x versus 8000x). Completion of the micro-structural study and planned attenuation measurements on both types of material, undeformed or pre-deformed in either compression or torsion, should contribute significantly to our understanding of dislocation damping and hence the interpretation of seismological models for the upper mantle.
Figure 2. (a) Sol-gel olivine, specimen T0436, deformed in torsion. Twist direction is anti-clockwise when viewed from above. (b) Light microscope image of the torsionally deformed sol-gel specimen. The sense of shear and direction of preferred orientation of [100] crystal axis are indicated.
A versatile facility for rock physics research

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The presence of fluids is expected to profoundly influence the seismic properties of the cracked rocks of the Earth’s upper crust in situations ranging from earthquake nucleation and recurrence, to geothermal power and CO\textsubscript{2} sequestration. In particular, the seismic wavespeeds and attenuation are expected to be strongly frequency dependent under these conditions, placing a special premium on laboratory measurements at seismic frequencies. To this end, we have modified unique equipment for low-frequency torsional oscillation studies of shear mode behaviour under high-pressure conditions to allow complementary work on compressional mode behaviour by flexural oscillation (Fig. 1, upper panel).

Another important change has been development of the capacity to perform such forced oscillation measurements under conditions of independently controlled confining and pore fluid pressures. Exploratory measurements have demonstrated the necessary sensitivity to low-amplitude flexural oscillation (Fig. 1, lower panel). In parallel with the development of the laboratory capability, we have undertaken finite-difference and finite-element modelling of the flexure of the experimental assembly that reveals close consistency with the experimental data. Having thus demonstrated the viability of the new technique, we are now planning exploratory studies of thermally cracked rocks and ceramic analogues, to be tested dry or saturated with a pore fluid - either argon or water in the first instance.
Effects of stress states and fluid pressure regimes on fluid pathways and evolution of fluid compositions within intrusion-related hydrothermal systems.

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Fluid pathways and hence localisation of ore in intrusion-related hydrothermal systems, are controlled by the development of fracture networks and by ongoing competition between (1) fracture sealing processes and (2) stress-driven and fluid-pressure-driven opening of fracture permeability. This project explores how stress fields evolve during gold mineralisation in the Porgera Intrusive Complex (PIC) and examines the controlling role that changes in both stress field orientations and failure modes have on mineralisation styles. The Porgera gold deposit is located in the Enga province at 2500m elevation in the highlands of Papua New Guinea. Emplacement of the PIC occurred at 6.0 ± 0.3 Ma at a depth between 2-4km (Richards, 1997). Mineralisation occurred between 6.0 Ma and 5.6 Ma and regional uplift commenced around 4 Ma.

On the basis of cross-cutting relationships, mineralisation at Porgera is separated into 4 main episodes: pre-stage 1, stage1, stage 2 and post-stage 2. Only stage 1 and stage 2 are economically significant. Stage 1 mineralisation is hosted by widely distributed extension veins. Most veins are moderatly to steeply dipping, but mutually overprinting relationships with a second population of gently dipping stage 1 veins indicates that there were repeated changes in the orientation of the near-field σ3 from a gently plunging to steeply plunging attitude during Stage 1. Repeated reorientation of stress fields in the PIC during stage 1 is interpreted to be associated with either (1) magma inflation-deflation cycles in a deeper level magma chamber, or (2) inflation-deflation cycles driven by fluid leakage repeatedly interrupting accumulation and pressurization of volatiles in a reservoir at the top of the magma chamber.

The transition from stage 1, low grade, distributed mineralisation to stage 2 localized high grade mineralisation was associated with the growth of the Romane Fault network. This fault network accessed magmatic-hydrothermal fluids at depth and localized fluid flow through faults and their damage zones. Compositional banding in stage 2 veins indicates cyclic changes in fluid chemistry. The formation of implosion breccias is interpreted to indicate sudden fluid de-pressurisation associated with fault slip events. Microstructures indicating multiple episodes of opening and sealing of some veins and breccias suggest that episodic, fracture-controlled flow may have been controlled by co-seismic permeability enhancement and interseismic permeability destruction in the stage 2 fracture systems. Transiently high flow rates, large transitory fluid pressure gradients, and large chemical gradients, during pulses of fluid redistribution, were associated with repeated breaching of the deep-level magmatic-hydrothermal fluid reservoir and are interpreted to be key factors promoting flow localisation and efficient gold precipitation during stage 2.


Angela Halfpenny webpage
http://rses.anu.edu.au/people/halfpenny_a/

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Figure 1. The internal structure of a composite stage 1 and stage 2 vein. Sections 1 and 3 represent the stage 2 mineralisation, which exhibits quartz and roscoelite-rich bands. The gold is associated with the roscoelite-rich bands and a patch of gold is marked by the white arrow. Section 2 is a coarse-grained stage 1 vein.
In most areas of the world, high population centres and heavy industry are located along river systems and provide a catchment wide source of heavy metal pollution along the length of the river system. These anthropogenically derived heavy metal pollutants enter the freshwater river systems and are transported downstream as part of the suspended sediment load. Such metals combine with the suspended sediment such that there is a higher concentration of heavy metals with the finer grained, clay-rich component of the transported sediment. In such cases, the ultimate depositional environment of contaminated sediments bears little relation to the distant source regions of anthropogenic pollution.

In an arid country like Australia, there are numerous coastal estuaries that are supplied with sediment transported down catchments that lack both industry and significant population centres. However such coastal estuaries are undergoing rapid population growth, even though for such regions the upstream catchment is notably lacking in population centres and industry. This provides an opportunity to study heavy metal additions and contamination in a post-depositional estuarine saline environment, in which relatively uncontaminated freshwater sediments are input into the system, mainly during seasonal flood events.

We used a range of conservative elements, especially rare earth elements, to show that heavy metal contamination does not correlate wholly with sediment grain size, but also correlates with proximity to local townships surrounding part of an estuary. Heavy metals such as Pb can then clearly be discriminated in terms of original, transported sediment compositions and local pollutant sources in an estuary. This shows that heavy metal pollution correlates in proximity to urban development, rather than with upstream contamination and transported sediment type.
Experimental constraints on chlorine behavior in subducted sediments
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It is widely accepted that a fluid phase released from the subducted slab fluxes partial melting in the overlying mantle wedge, however, the nature of “subduction fluid agent” remains a matter of debate. The Cl concentration in “subduction fluid agent” is also poorly constrained, although experimental studies have shown that complexation with chlorine (and possibly other halogens) at high concentration might produce a strong effect on relative HFSE vs. REE/LFSE partitioning (Brenan et al., 1995; Keppler, 1996).

Detailed chemical analyses of oceanic crustal material have revealed that subducted sediments are the dominant host of LILE in the slab. The significance of such a role is further supported by considering that the composition of the “slab fluid agent” which migrates from the subducted slab to the mantle wedge is assumed to be buffered by the subducted sediment residue component located at the slab-mantle interface. Therefore, determining accurate sediment-derived fluid and melt compositions at high P are critical for understanding mass transfer from the slab to mantle wedge (e.g., Hermann and Spandler, 2008).

We have conducted an experimental study on hydrous Cl-brearing synthetic pelite over a pressure and temperature range of 25-45 kbar and 650-850°C respectively. The starting composition contains 6.65% water and 0.05% chlorine, equivalent to ~1wt.% NaCl solution. Apatite was found to be the major chlorine carrier with Cl concentrations ranging from ~0.1%-1.2%. While Cl in apatite shows a consistent trend of increasing concentration with increasing temperature, a decrease in Cl concentration was found to occur with increasing pressure. The chlorine content in the coexisting melt or aqueous fluid phase was determined by both analysis and mass balance calculations. From the resultant data we were able to obtain a set of chlorine partition coefficients between apatite and melt/aqueous fluid (D_{Cl^{ap}}^{liq}) and while these values show a general increase with increasing temperature, they are found to decrease with increasing pressure. Chlorine partition coefficients between apatite and melt, D_{Cl^{ap}}^{melt}, are found to vary from 1.5 to 14, while partition coefficient values for aqueous fluid are found to be less than 1, suggesting chlorine has a strong partitioning preference for aqueous fluid. Our results show that Cl in apatite can be a very useful sensor for the Cl concentration in subduction zone fluids.

References:


Figure 1. Backscattered electron images of experiment C3314 at 25kb, 660°C (a) and experiment C3269 at 25kb, 800°C (b). Abbreviations: Amp, amphibole; Phen, phengite; Q, quartz; Grt, garnet; Ky, kyanite; Rut, rutile; Ap, apatite; F, quench product from aqueous fluid. (a) Fine-grained hydrous quench powder was present in the run products. (b) Hydrous melt coexisting with phengite, garnet and accessory minerals.
The oxidation state of terrestrial basalts revisited

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In order to better understand the oxidation state of planetary mantles and their partial melting products, we have developed and calibrated a method to estimate the relative oxygen fugacity (fO2) of mafic volcanic rocks based on the relative partitioning of V and Sc between olivine phenocryst and basaltic melt (Fig. 1). The method relies on the high sensitivity of the partitioning of V on oxygen fugacity (Mallmann & O'Neill 2009) and has two fundamental advantages relative Fe wet chemistry analyses: 1) it records the oxidation state of a basalt at the time when olivine forms or, in other words, very early in its magmatic cooling history, and 2) it can be applied to any planetary olivine-phyric mafic rock independent of their oxidation state (either highly reduced or highly oxidized). Preliminary assessment indicates accuracy in relative fO2 between 0.2 to 0.5 log units, but precision typically better than ±0.2 log units.

The method was applied to 41 mid-ocean ridge (MORB), 34 ocean island (OIB), and 24 island arc (IAB) basalts from a variety of geographic locations. The results indicate that MORBs and OIBs record a very restricted range of relative fO2s, between QFM and QFM+1 (where QFM stands for the quartz-fayalite-magnetite oxygen buffer), with no clear distinction between them. On the other hand, IABs record consistently more oxidizing conditions, with relative fO2s ranging from QFM+1 to QFM+3 (average = QFM+1.6). The average relative fO2 determined for MORBs is about 1 log unit higher than previous results obtained by Fe wet chemistry (Fig. 2), but in excellent agreement with new Fe XANES measurements (Mallmann et al., unpublished data). The average relative fO2s of Hawaiian OIBs is in excellent agreement with previous determinations, but show much less variability, indicating that the ferric/ferrous iron ratios in these samples have been altered by late-stage processes. Whilst our results suggest that IABs are oxidized relative to MORBs and OIBs at the time they crystallize olivine, we believe these more oxidizing conditions are the result of late-stage (shallow depth) processes since no distinction exists in the bulk V/Sc ratios (which record the oxidation state of the source, Mallmann & O'Neill 2009) between these different types of terrestrial basalts. Hence, the oxidation state of the asthenospheric upper mantle must be uniform within 1 log unit.

Mallmann & O'Neill (2009)
http://petrology.oxfordjournals.org/cgi/content/abstract/50/9/1765
Figure 2. Histograms (top) and probability (bottom) plots for the oxygen fugacity (relative to the quartz-fayalite-magnetite buffer, QFM) of terrestrial mid-ocean ridge (MORB), ocean island (OIB) and island arc (IAB) basalts determined by V/Sc olivine-melt partition. Literature data obtained by other methods based on the oxidation state of iron are also shown.
Ni Partitioning Between Olivine and Silicate Melt

Compositional effects due to Fe variation

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As the acquisition and interpretation of trace element partition coefficients has been pursued since the late 1960’s it may be expected that, after countless studies regarding natural and experimental systems, the application of partitioning data for simple mineral-liquid pairings such as Ni in olivine and silicate melt, would be relatively uncontroversial. Such is not the case. It appears that a complete understanding of effects relating to all intensive parameters on divalent cation partitioning remains elusive.

By conducting a series of carefully designed one atmosphere experiments, we have investigated Ni partitioning between metal, silicate melt and olivine phases, over a range of (reduced) $f_{O_2}$ conditions using a single starting composition and Fe:Ni:Co metal alloy components with variable Ni:Fe ratios.

While a significant negative dependence for $D^{Ni}$ values on the MgO content of silicate liquids has been observed in several prominent studies (i.e. Hart & Davis, 1978; Leeman & Lindstrom, 1978), our results show a reverse trend (positive correlation).

Li et al. (2003) also reported a similar positive correlation between $D^{Ni}$ and MgO glass content derived from analysis of a series of fresh MORB samples, a trend which they subsequently attributed to loss of available Ni$^{2+}$ in total Ni figures due to NiS complexing in the melt.

As a further line of evidence, Li et al. (2003) present the correlation between the two-element distribution coefficient $K_{D}^{Ni-Mg}$ ($K_{D}^{Ni-Mg}$=$[MgO_{melt}/MgO_{ol}]/[NiO_{melt}/NiO_{ol}]$) and Sulphur as being a function of NiS complexing in silicate liquids, thus reflecting its strong influence on $D^{Ni}$ figures.

As can be seen in fig 1, the positive dependence of $D^{Ni}$ on MgO-glass content shown in the S-free experiments (series 1-5) of this study reflect a similar trend to that produced by Li et al. (2003) from their MORB analyses; a compositional trait that was attributed to the effects of NiS in the liquid phase.

It has long been inferred from the sulphur contents of MORB glasses that the sulphur content at sulphide saturation (SCSS) of silicate melt increases with increasing FeO in natural magmas (Wallace & Carmichael, 1992, Mavrogenes & O’Neill, 2002). It appears that the S-related correlations observed by Li et al. (2003) may in fact be masking the underlying and controlling role of Fe, observed in the $K_{D}^{Ni-Mg}$ values. The results determined ($K_{D}^{Ni-Mg}$ vs. FeO$_{glass}$) in our S-free system, appear to support this conclusion.
References:


The CO2 paradox in subduction zones
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Understanding the carbon recycling into deep Earth reservoirs and its connection to the exogene carbon cycle is crucial to understand the evolution of climate throughout geological time. Along subduction zones, carbon from exogene reservoirs is buried into the deep Earth. The main input materials of carbon are sediments (organic matter and carbonate-rich sediments) and carbonates formed during seafloor alteration of the oceanic crust. Some of the carbon is recycled back to the Earth’s surface as CO2 via arc volcanism on a time scale of a few million years, whereas other parts can be subducted into the lower mantle and remain locked up for hundreds of millions of years. So the key question is: How much of the carbon goes deep down and how much is recycled through arc volcanism.

Two methods have been applied to understand if carbon in the subducting slab is transported into the deep mantle or recycled back to the surface. (i) The analysis of the CO2/3He and isotopic composition of the volcanic gas have suggested that 80% of the carbon originates from the metamorphism of the down-going slab (Varekamp et al., 1992; Marty and Tolstikhin, 1998). (ii) Experimental studies of the stability of carbon-bearing phases in H2O-CO2-bearing basaltic compositions show that carbon remains trapped in carbonates up to 6 GPa and the fluid at sub-arc depth is, therefore, dominated by H2O (Poli et al., 2009). Consequently, results from both methods contradict each other and the origin of CO2 emitted in arc volcanoes is not well constrained.

During seafloor alteration, the oceanic crust is not only enriched in H2O and CO2 but also in K. At high pressures, such altered basalts are thus characterized by the assemblage garnet + omphacite + glaucophane + phengite + epidote + carbonate (Fig. 1). Solidus experiments were conducted with a starting material composition of K, CO2 and H2O-bearing basaltic composition as a proxy of the altered oceanic crust at 2.5 and 3.5 GPa, 750-850°C in order to study CO2 liberation during subduction.

The experimental results indicate that the solidus occurs at a temperature below 750°C. At T≥750°C, a high proportion of melt coexists with a carbonate phase, omphacite, garnet, epidote, rutile ± coesite and phengite (Fig. 2). Between 750 and 800°C, the carbonate phase is dolomite and above 800°C, it is replaced by Mg-rich calcite. The evolution of phase proportions with increasing temperature suggests the following melting reaction:

Epidote+Phengite+Carbonate+Omphacite+H2O+Quartz/Coesite = Garnet + hydrous, CO2 bearing melt

The following conclusions can be drawn from these results. (i) The solidus of the altered oceanic crust occurs below 750°C at 2.5 and 3.5 GPa, which is similar to the solidus in CO2-free (700<T<750°C, Schmidt and Poli, 1998) basaltic and pelitic systems. (ii) Such a low solidus temperature suggests that the fluid composition is H2O-rich at the solidus. (iii) The melting reaction is associated with the destabilisation of the carbonates phases, which leads to the release of CO2, most likely dissolved in the hydrous melt. (iv) These results suggest that the altered oceanic crust, which is preferentially located at the top of the slab, may partially melt at sub-arc depths. This provides an explanation on how CO2 is efficiently released from the subducted slab and suggests that a much larger portion of CO2 can be recycled through arc volcanism than what previous experimental studies have predicted.
References


Accretion of seamounts and oceanic islands in subduction zones

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Oceanic islands and seamounts are common products of intra-plate volcanism in the oceans, with recent estimates suggesting a population of ~95'000 seamounts in the Pacific Ocean (Hillier & Watts, 2007). Once formed, seamounts and oceanic islands migrate with plate tectonics toward subduction zones and are ultimately driven into the mantle at a present subduction rate of ~0.34 seamount km⁻¹ Ma⁻¹ along the Pacific. Subducting seamounts have a major impact along convergent margins and notably affect seismogenesis, supra-subduction magmatism and processes of accretion and subduction erosion. Although some of these effects are clearly of fundamental interest for the evolution of convergent margins, mechanisms controlling the subduction, accretion and extend of preservation of seamounts along subduction zones is still poorly understood.

Our study provides new constraints on subduction processes based on the characterization of fragments of seamounts and oceanic islands preserved in recent and ancient accretionary complexes. We studied accretionary complexes along the Middle American Trench through a multi-disciplinary approach that includes extended field mapping, geochemistry of the igneous rocks, remote interpretations based on satellite imagery and biochronologic dating. Our results indicate that the outer parts of the convergent margin include km-sized slices of accreted oceanic islands and seamounts, some of which represent unusually large fragments of ancient intraplate volcanoes (fig. 1). Based on the nature and arrangement of these slices we reconstructed the development of the margin from the subduction initiation (~75-73 Ma) to the Oligocene (~30 Ma). The margin underwent a ~45 Ma-long history of repeated shifts between accretion and subduction erosion.

More recently, we initiated a new study on a Permian accretionary complex exposed along the Paleo-Tethys Suture Zone in Iran. We identified distinct seamounts and oceanic islands that became exhumed during the closure of the Paleo-Tethys Ocean. Good exposures allowed efficient mapping of the accretionary complex by satellite (fig. 2). The results show that large slices of seamounts and oceanic islands can be subducted to considerable depth in subduction zones.
An experimental study of the upper mantle melting behaviour of recycled carbonate eclogite at 3.5-5.5 GPa

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Altered, carbonated oceanic crust may be recycled through subduction zones into the deeper convecting mantle, where it may contribute components to mantle-derived partial melts such as carbonatites, Kimberlites and other silica-undersaturated magmas. We used a high pressures experimental approach to investigate the melting behaviour of carbonate eclogite (modelling high pressure, altered, carbonate-bearing, recycled oceanic crust) in the upper mantle at depths of 100-170 km, which correspond to pressures of 3.5-5.5 GPa. We aim to test the possible involvement of such material in formation of rare and exotic rocks as Kimberlites and Carbonatites.

The aim of the study is to locate the solidus positions, partial melt compositions and trace element partitioning of carbonate-bearing eclogite as functions of pressure, temperature and SiO₂ content. The initial composition GA1 [1] represents altered oceanic basalt (eclogite) to which 10% of calcite (10%cc) was added. The second composition Volga+10%cc is identical to GA1 but with 6.5% less SiO₂. This models subducted mafic crust which may have lost a siliceous component during dehydration and/or silicate melting in the subduction zone. Both mixes were doped with a mixture containing 30 trace elements in an average amount around 100-150 ppm.

Experiments were conducted in piston-cylinder presses over the range of pressures (3.5-5.5 GPa) and temperatures (1000-1400 °C). The main findings are:

- The mixes crystallize under sub-solidus conditions at 3.5 GPa as garnet + clinopyroxene + carbonate + rutile ± K-feldspar ± apatite (fig. 1)
- At 3.5 GPa the solidus of GA1 is less than 1050°C. At 4.5 and 5.0 GPa the estimated solidus is lower. The solidus of Volga+10%cc for all the examined pressures is at least 100°C lower than in GA1, which is in a good agreement with silica-undersaturated composition SLEC1 [2]
- Carbonate-silicate liquid immiscibility (fig. 2) is detected at all the pressures (3.5, 4.5, 5.0, 5.5 GPa) and its field expanded from low to higher pressures reaching 150°C at 5.0 GPa.
- Depending on the temperature and pressure, CO₂ or CO₃²⁻ may be present, dissolved in silicate melt, in carbonate melt; in solid carbonate or as a fluid, transporting incompatible elements from the crystalline run product into the graphite capsule
- Initial melts are highly siliceous, K-rich compositions, probably with considerable dissolved carbon. Early melting is probably dominated by components from accessory phases such as K-feldspar, coesite and carbonate. This is an important contrast with earlier, similar studies in low –K or K-free systems, in which initial melts were calcio-dolomitic carbonatites [1,3], and highlights the important influence on early melts of accessory phases such as coesite and K-feldspar.
- Trace element partition coefficients between garnet, clinopyroxene and silicate melt are similar to previously reported [3]. D_Cpx/melt in equilibrium with carbonatic melt reveals different patterns with high values for HFSE, as Ta, Zr, Hf and Ti.
References


squeezing out the upper mantle: melt evolution of voluminous mafic layered intrusions

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many of our technological advances and devices that we take for granted in our daily life require noble metals, making these group of elements a substantial and highly valuable resource, and by that, a fundamental cornerstone of the world’s economy. the majority of the world’s noble metals that are stored near the earth’s surface - and thus accessible for mining - are hosted by mafic layered intrusions (mli). these large igneous bodies comprise a stratified sequence of voluminous upper mantle-derived melts, with most of them predominantly archean to early proterozoic age. despite decades of research on mli, their genesis, including their tectonic settings, melting origins, evolution of melts, and the cause for specific noble metal distributions are still not completely understood. the key to unraveling these questions and to more efficiently access these ancient treasures is the study of mli melt evolution using petrologic and geochemical investigations.

our research is focusing on one of the world’s largest mli, the windimurra-narndee igneous complex (wnic; ~2.8 ga old) forming part of the archean yilgarn craton, located in the west australian desert. the complex is unique among mli as it was not affected by crustal contamination during magma ascent and opens a crystal-clear window in the long-gone, ancient mantle beneath australia. we use petrogenetic tools (such as the electron microprobe for major elements chemistry, laser-ablation in-situ trace element analyses, and isotope investigations by isotope dilution for dating and source tracing) on two long drill cores of the upper sequences. one goal is to better understand the nature of iron enrichment in uppermost mli, and its role in controlling the oxygen fugacity in melts, a parameter that is crucial for the distribution of some key elements such as v, s or e.g., the ferric-ferrous ratio. an important feature therein is the overall absence of water (or hydrous phases) in the melts. this is fairly uncommon in most mli as many of them experienced various degrees of crustal assimilation. in the future, isotopic investigations will give us not only a better constraint on the emplacement age of the intrusion and its role in the formation of the yilgarn craton, but will also provide us with source information of the intrusion. its crustal contamination-free nature means it is ideally suited for study of the mantle source using sr-nd-hf isotope systems. we can also study the effect of parent-daughter element fractionation during extensive mantle melting on crustal formation, and potentially discover the true nature of the depleted mantle at around 2.8 ga before present.
Peridotites from a submarine volcanic front arc volcano: a global first

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Research Voyage SS06/2007 (WeBiVE) of the Marine National Facility recovered a suite of basalt-coated peridotite xenoliths from three cones to the northwest of Ritter Volcano, on the volcanic front of the New Britain-West Bismarck Island Arc (Fig. 1). The Ritter suite is the first global occurrence of peridotites sampled from an active submarine volcanic arc front edifice. In 1888, the former ~800m Ritter cone collapsed, triggering a tsunami that devastated the nearby islands of Sakar and Umboi. Since 1888, an active submarine vent has grown in the throat of the collapsed volcano.

The peridotites range from harzburgite to lherzolite in composition, are generally coated by basalt, and occur as rounded and angular blocks and fragments. The host basalt is a Cr spinel-olivine-bearing, medium-K, low-Fe tholeiite. It is the most MgO-rich basalt (~15wt%) discovered in the West-Bismarck-New Britain Arc system; the high-MgO might derive in part from the cumulative and/or xenocrystic nature of the olivine crystals. The mineralogy of the host basalt includes olivine (Fo91.9-82.4), diopside-augite, and spinel. The spinel is highly refractory with Cr/(Cr+Al) > 0.8, akin to spinel in boninites. The peridotites have complex textural relationships between the main minerals olivine, orthopyroxene, clinopyroxene, and spinel; deformation textures are prominent, and include deformation banding in olivine and wavy deformation of exsolution lamellae in the pyroxene. The Cr/(Cr+Al) of the spinel ranges from ~0.4 to some of the highest and most refractory (0.9) values ever reported for peridotite assemblages. The mineralogy and geochemical characteristics of the peridotite suite will give insight into the lithospheric mantle forming the overriding plate of the New Britain-West Bismarck arc system.

Melt transport in the mantle

Transition from dunite channels to pyroxenite dykes in the upper mantle section of New Caledonia

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In oceanic spreading zones, new crust is formed by basaltic melts extracted from the mantle. Previous research has shown that dunite channels play a fundamental role in this magma transport (Kelemen et al. 1995). These channels are relatively porous and were thought to allow the transfer of large amounts of melts from the mantle to the crust. Once established, there is little interaction of melt passing through the channels with the surrounding peridotite rocks.

We have investigated in detail melt transport in the uppermost mantle section of the New Caledonia ophiolite. Dunite channels are widespread in the harzburgite and crosscut the dominant tectonite foliation. However, field studies of the uppermost part of the mantle section show an evolution of the channels as the crust mantle boundary is approached (Fig.1). In some places, dunite channels (Fig.2a), normally formed only of olivine, start to precipitate pyroxenes by consuming olivine. This reaction leads to the formation of proto-pyroxenite channels cross-cutting the mantle (Fig.2b). In the uppermost part of the mantle, the replacive proto-pyroxenite channels gradually transform into pyroxenite dykes indicating a more brittle behavior of the surrounding mantle rocks (Fig.2c). These dykes, which are widespread in many ophiolites all around the world, can occasionally show fractionation trends in the last few hundred meters below the crust-mantle boundary. Closer to the crust mantle transition, it is common to see gabbro dykes with pyroxenite walls (Fig.2d) cutting through the peridotite. Pyroxenes from the walls are identical to pyroxenite dykes whereas the gabbro has similarities with the cumulate gabbros forming the oceanic crust. These gabbro dykes are reaching the crust-mantle transition zone and act as feeders for mafic melts forming the oceanic crust. The evolution from dunite channels to pyroxenites to gabbro dykes shows that melt transport in oceanic spreading zone is highly focused. However, the variety of rocks observed provide evidence for multiple dissolution-precipitation processes acting during the melt transport. Additionally we show that fractionation of mafic magma can occur in the uppermost mantle before the melts reach the crust-mantle boundary.

Figure 2. a. Dunite channel (Dun) in layered harzburgite (Hzb). b. Proto-pyroxenite channel (PPx) in harzburgite. c. Pyroxenite dyke (Px) 25m from proto-pyroxenite 2b. d. Gabbro dyke (Gab) with pyroxenite walls (Px) in harzburgite (Hzb). All pictures taken in the Massif du Sud, New Caledonia.
Archaean asteroid impacts, banded iron formations and sulphur MIF-S anomalies.

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The origin of the abrupt end-Archaean - early Proterozoic (c. 2.45 Ga) transition from an oxygen-poor to an oxygenating atmosphere remains one of the outstanding problems in early Earth history. A change in mass-independent fractionation of sulphur isotopes (MIF-S) ($\delta^{33}$S) about 2.45 Ga is commonly interpreted in terms of the termination of UV-triggered chemical reactions under oxygen-poor atmosphere conditions. Late-Archaean (~2.7–2.5 Ga) and mid-Archaean (~3.2 Ga) sequences in the Pilbara craton (Western Australia) and Kaapvaal Craton (South Africa), in which MIF-S data were measured, contain asteroid impact ejecta units dated as 2.48, 2.56, 2.63, 3.24, 3.26 and 3.47 Ga-old. The scale of the impacts is estimated by mass balance calculations based on Iridium and $^{53}$C/$^{52}$Cr isotopic anomalies and on impact spherule (microkrystites. see figure) size distribution, suggesting projectiles several tens of kilometres in diameter. In view of an incomplete preservation of impact ejecta units, the above represents a minimum rate of the Archaean impact flux. High UV flux due to low ozone levels in the Archaean atmosphere may have been enhanced by large impacts, accentuating MIF-S anomalies. The appearance of iron-rich sediments above late and mid-Archaean impact ejecta units may be related either to to microbial oxidation of ferrous iron or, alternatively, photochemical oxidation of ferrous to ferric iron. Similar MIF-S anomalies may have been associated with Proterozoic and Phanerozoic impacts, although to date little evidence exists in this regard. Detailed sampling and isotopic analyses across the impact ejecta fallout units are required in order to test possible relationships between Archaean impacts and MIF-S anomalies.
A Monte Carlo study of short- and long-range order of tetrahedral cations in sapphirine and khmaralite

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Stability of the mineral assemblage sapphirine + quartz is an indicator of metamorphism under ultrahigh-temperature (> 950°C) conditions, but it is still uncertain how far down in temperature this assemblage persists, or how it is affected when the major elements (Mg, Al, Si, Fe²⁺) of sapphirine are substituted by minor amounts of components such as Fe³⁺ or Be. It is known that current thermodynamic databases do not correctly predict the stability of other exotic assemblages such as sapphirine+forsterite and sapphirine+kyanite, and that the problem is likely with the activity model used for sapphirine solid solutions: the complex sapphirine crystal structure has many distinct cation sites, some of which show full long-range order (LRO) while others show some disorder. However, NMR spectroscopy indicates that there is considerable short-range order (SRO) between neighbouring “disordered” sites. The enthalpy of the mineral is very sensitive to the degree of short-range order, which will also tend to reduce the entropy below what would be expected from long-range site occupancy data.

Al-Si order is made difficult in sapphirine because it has a chain of linked tetrahedrally coordinated cations which are 60–70% Al. Although energetically unfavourable Al-O-Al links and Si-O-Si can be minimised in number, they cannot be eliminated completely, as they can in many other rock-forming silicates. Because the chain has an unusual “winged” geometry, in which equal proportions of tetrahedra link to 1, 2 or 3 neighbours (Q¹, Q², Q³), short-range linkage patterns couple strongly to long-range site occupancies. Favourable Al-O-Si links can be maximised if the minority component Si is concentrated in the Q³ sites. However, since the two such sites are adjacent, there is a limit as to how much LRO is possible.

A computer simulation of the tetrahedral chain of sapphirine, with energy minimised by the Monte Carlo method, has been used to demonstrate that the observed amount of Al-Si order in sapphirine is much greater than can be driven by tetrahedral linkage enthalpies alone, even though the Al-Si exchange enthalpy is of the order of 2RT. Interactions with the surrounding octahedral (Al, Mg) are at least as important. However, substantial Be is readily incorporated in the chains via the substitution (BeSi)(AlAl)−¹, which ultimately leads to the mineral khmaralite, which shows rearrangement of the LRO scheme. The ordering pattern of khmaralite has also been simulated, as a minimum-energy solution for a small number of near-neighbour and chain-matrix interaction terms. Be outcompetes Si for the Q³ sites.
because Be-O-Be avoidance is much more enthalpically significant (Be-Al and Be-Si exchange enthalpies \(= 7RT\)) than Al-O-Al/Si-O-Si avoidance. The model predicts a major reorganisation of site occupancies and increase in enthalpy when Be > 1.7 atoms per 12 tetrahedra, which is probably why the maximum observed content in nature is about half of this value. The chain-doubled superstructure in khmaralite is not due to within-chain interactions, but aligns the Be-rich sites of back-to-back chains and links them to a cluster of octahedral Fe\(^{2+}\)-rich sites.

The simulation can be used to calculate the effect of short-range order on configuration entropy, comparing chains with no SRO with those where SRO is maximised for a given state of LRO. It appears that SRO reduces configurational entropy by only 17-18% in either sapphirine or khmaralite


Figure 3. Predicted Be contents of the 12 tetrahedral sites of khmaralite as a function of the total Be. Q\(^1\) sites indicated by circles, Q\(^2\) by diamonds, Q\(^3\) by triangles. Below 1.7 Be per formula unit, the Be can be confined almost exclusively to two Q\(^3\) sites. Above that threshold, this abruptly ceases to be the case, and the number of unfavourable Be-O-Be linkages grows rapidly.
Asteroid impact connections of crustal evolution

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Advances in isotopic age determinations increasingly point to an episodic nature of crustal evolution. Field and geochemical evidence indicate that at least some large impact episodes may have been associated with, and possibly triggered, magmatic and tectonic events. Correlations are observed between isotopic age frequency peaks and asteroid impacts records (~3.47, ~2.63, ~2.56, ~2.48, ~2.023 Ga [Vredefort] and 1.85 Ga [Sudbury]). Evidence for major dynamic and thermal effects of a large impact cluster on the early Precambrian crust is provided by ejecta fallout units associated with: (i) unconformities; (ii) tsunami boulder debris; (iii) compositional contrasts between supracrustal sequences that underlie and overlie the ejecta units; (iv) onset of episodes of iron-rich sedimentation; and (v) near-contemporaneous intrusion of granitoid magmas. An impact cluster at ~3.26–3.24 Ga, documented in the Barberton greenstone belt, South Africa, is associated with unconformities and granite activity correlated with unconformities and olistostromes in the Pilbara Craton, Western Australia. In both cratons a 300 Ma period of evolution of greenstone–granite terrains is abruptly terminated by unconformities overlain by impact ejecta, turbidite and banded iron-formation. The 3.26 and 3.24 Ga terminations involve major faulting, uplift, erosion, and the onset of high-energy sedimentation, which includes detrital components from contemporaneous granites. The onset of ferruginous sedimentation, including banded iron-formation, in the wake of the ~3.47,~3.26,~3.24,~2.63 and~2.56 Ga impacts, suggests weathering and soluble transport of ferrous oxide under low-oxidation atmosphere and hydrosphere conditions, possibly reflecting extensive mafic volcanic activity triggered by the impacts. Extensive dyke formation during 2.48–2.42 Ga (Matachewan, Scourie, Karelian, Widgiemooltha, Bangalore, Antarctica dykes) may be related to deep crust/mantle fractures triggered by the ~2.48 Dales Gorge mega-impact. Tentative observations are consistent with, but do not demonstrate, possible overlaps between Phanerozoic impacts and the onset of faulting and plate tectonics episodes.
A probable end-Eocene impact structure under the Timor Sea

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The end-Eocene (c. 35 Ma) constitutes a period of major extraterrestrial impacts, including the Popigai (D=100 km; 35.7 ± 0.2 Ma), Chesapeake Bay (D = 85 km; 35.3±0.1) and a major tektite strewn field in northeastern America. The end-Eocene is also a key period at which the Drake Passage (Chile - Antarctic Peninsula) opened, the Antarctic ice sheet began to form, sharp global cooling occurred accompanied with mass extinction of about 10 percent of species. Here we report the discovery of a new, hitherto unknown, asteroid impact structure of end-Eocene age. New seismic reflection data and petrological studies of drill cuttings from the Mount Ashmore structural dome, west Bonaparte Basin, Timor Sea, suggest the dome represents the central uplift of an extraterrestrial impact of end-Eocene, pre-Oligocene, age. The dome is located below a major unconformity. Isopach maps and reconstruction of structural depths reveal kinematic deformation patterns and structural orientations consistent with centripetal deformation toward the domal axis, as well chaotic megabreccia structures. A study of early Oligocene to early Jurassic drill cuttings from the Ashmore 1B petroleum exploration borehole reveals a dominance of flow-textured comminuted microbreccia with particles ranging to submicron scale, referred to as pseudotachylite. X-ray diffraction analysis indicates the microbreccia includes about one third of poorly-diffracting particles, likely derived from carbonate and clay-dominated material. The microbreccia contains corroded relic quartz grains which display heavy irregular fracturing and incipient planar fractures. Similar pseudotachylite fragments occur in basal Oligocene sediments, likely representing erosion of the structural dome which protrudes above the pre-Oligocene unconformity. Scanning electron microscopy (SEM) coupled with Energy Dispersive Spectrometry (EDS) indicate the pseudotachylite consists of micron to tens of micron-size particles with low-totals and non-stochiometric heterogeneous compositions, including Si, Al-Si, Si-Ca-Al, Si-Al-Ca, Si-Mg, Fe-Mg-Ca, Fe-Mg-Ca, Fe-Mg and carbonate-dominated particles (see figure). No volcanic material or evaporites are encountered in the core, which militates against interpretations of the structure in terms of volcanic or salt dome origin. The chaotic seismic structure of the domal core, the centripetal sense of intra-domal deformation, the micro-brecciated flow-textured nature of the cuttings, the poorly diffracting nature of the pseudotachylite matrix and the heavily fractured state of quartz grains are consistent with an interpretation of the Mount Ashmore dome in terms of a central rebound uplift of an impact structure.

Figure 1. Scanning Electron Microscope image of Mount Ashmore pseudotachylite, showing fragments of microbreccia embedded in microbreccia. Qz - quartz fragments; kf - K-feldspar fragment; FeS - pyrite fragment; SiAl - Silica and alumina-dominated non-stoichiometric fragments; Ca - Ca-dominated non-stochiometric fragment; F - fossil foram shell.
The Nb-Ta chicken-egg problem
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The continental crust is generally enriched in incompatible trace elements but shows a pronounced negative anomaly in Nb and Ta compared to Th and La. During partial melting of the mantle all these elements are similarly incompatible and thus are not fractionated. Hence, it has been speculated that the fractionation occurs during subduction of oceanic crust. Fluids liberated from the subducted slab trigger partial melting in the mantle wedge and impose a “slab signature” in terms of trace elements onto the volcanic arc rocks that represent newly formed continental crust. Nb and Ta highly partition into the high-pressure phase rutile (TiO$_2$) in deeply subducted crust and are potentially retained when these fluids are liberated from the slab.

We have performed high-pressure and high temperature experiments at conditions relevant for slabs at sub-arc depth in order to test whether such residual rutile is ultimately responsible for the negative Nb-Ta anomaly in the continental crust. The experiments were performed on a subducted sediment composition because these rocks dominate the incompatible trace element input into subduction zones. All the experiments contained residual rutile (Fig. 2). However, trace element analyses of the produced fluid phase showed that Nb and Ta are not depleted with respect to the starting material and showed a similar behaviour to Th and La (Fig. 1). The main reason for this is that the accessory phases allanite and monazite (Fig. 2) retain Th and La as efficiently as rutile does with Nb and Ta. Therefore, it seems that in subduction settings Nb and Ta are not easily fractionated from Th and La and we are faced with a chicken-egg problem. Detritus from the continents dominates the trace element composition of the subducted sediments, which are thus already characterized by a negative Nb-Ta anomaly. The partial melting of the subducted sediments and the interaction of these fluids with the mantle wedge will then transfer this negative Nb-Ta anomaly into newly formed crust at volcanic arcs. While our study shows how to maintain a “status quo” it also (re-)opens the question: When and how was the negative Nb-Ta anomaly in the continental crust established?
Figure 2. Electron back scatter images of experimental run products. a) Rutile (rt) coexists with partial melts at 800°C, 2.5 GPa. Also present are other important phases that control the trace elements such as phengite (phe), allanite (all), zircon (zir), and apatite (apa). b) Idiomorphic rutile is in contact with a hydrous melt at 800°C, 3.5 GPa. Monazite is stable instead of allanite. Scale bar represents 10 µm.
Paleomagnetic results from the ignimbrite-rich Carboniferous succession of the Tamworth Belt, Southern New England Orogen (SNEO), eastern Australia, indicate an Early Carboniferous northward excursion over about 30 degrees of latitude, culminating during middle-late Visean. The excursion is identifiable also in paleomagnetic data from the Australian craton and the Tasman Orogenic System (TOS) and may have started in Early Devonian. By middle-late Visean, the promontory of the Australian Craton in central New Guinea reached latitudes of 30 - 40 degrees N (Figure 1G), well within the paleolatitudinal range of the Central Asian Orogenic Belt (CAOB) of then southern Laurasia. Devonian-Carboniferous convergence and collision of Australia, as part of northeastern Gondwana, with the CAOB is proposed as the cause of contemporaneous, Variscan, tectonism along, and in the hinterland of, the northern and southern margins of the Paleoasian Ocean. That is within the CAOB of southern Laurasia and throughout Australia (Alice Springs, Quilpie and Kanimblan Orogenies).

Convergence-related compressional deformation of Australia was essentially confined to a “compression box”, extending southward from the central New Guinean craton promontory and bounded by the Lasseter Shear Zone in the west and the future East Australian Rift System in the east (Figure 1A). Convergence-driven north-south compression, weak heated crust in the Larapintine Graben and the oceanic basement of the TOS (Figure 1B), and the “free” oceanic boundary of the Paleopacific, constituted Variscan Australia-Asia conditions comparable to the Cenozoic India-Asia indentation and extrusion process (Royden et al. 2008, Burchfiel et al. 2008). Tectonic extrusion of ductile lower crust, and partial melt, from the Larapintine Graben caused eastward displacement of mainly the Thomson Orogen and the Northern New England Orogen (NNEO), perhaps in association with slab rollback of Paleopacific subduction. Upper crustal displacement was guided in the north by the Diamantina River Lineament-Clarke River Fault Zone and in the south, more complexly, by the Darling River/Cobar-Inglewood Lineaments and Cato Fracture Zone, and by the Lake Blanche-Olepoloko Fault Zones and Lachlan Transverse Zone (Figure 1B).

The tectonic extrusion hypothesis offers provocative new avenues for interpreting aspects of the Late Paleozoic evolution of Australia: (i) Different tectonic grains of the Alice Springs Orogeny (E-W) and the Quilpie and Kanimblan Orogenies (N-S) represent diverse effects of the Australia-Asia convergence/collision on the brittle upper crust and on the ductile lower crust. Direct north-south compression through the upper crust led to the Alice Springs Orogeny of east-west tectonic grain, whereas in the ductile lower crust hydraulic fanning out of north-south compression toward alignment with the east-west pressure gradient near the free boundary of the Paleopacific, led to the Quilpie and Kanimblan Orogenies of north-south tectonic grain; (ii) East-west fanning out of azimuthal anisotropy (Figure 1E) and continental-like velocities in the lower crust/upper mantle of more internal parts of the TOS (Figure 1C, 1D), indicated by surface wave tomography, traces lower crustal tectonic extrusion from the Larapintine Graben into and through the TOS; (iii) Prominent negative magnetic anomalies in the Larapintine Graben and the TOS (Figure 1H) may represent hematite-residing Kiaman reverse polarity remanence (Figure 1F) in lower and upper crust and outline lower crustal flow throughout the TOS; (iv) Extent of lower crustal flow may be outlined further by mapping the extent of seismically highly reflective lower crust, assuming that its planar anisotropy represents horizontal ductile flow rather than vertical magmatic underplating; (v) The widespread Namurian sedimentary lacune may represent thermal expansion resulting from lower crustal ductile flow, with denudation products transported from the elevated “compression box” into the non-elevated New England Orogen (NEO) and western Australian basins; (vi) Formation of the Kanimblan Highlands during Late Carboniferous may reflect this thermal expansion process, with latest Carboniferous-Permian thermal relaxation leading to its demise; (vii) A Late Carboniferous heat flux may explain the fission track and low-temperature isotopic disturbance record without the need for extensive burial and denudation; (viii) A Stephanian change to clockwise rotation of Gondwana caused northward telescoping of the SNEO against the eastward displaced buttress of the NNEO, facilitated by structural detachment of the SNEO from the Lachlan Orogen along the northward progressing Eastern Australian Rift System, leading to formation of the Texas-Coffs Harbour and Manning Oroclines.


Figure 1. (a) Topographic and bathymetric image of the Australian plate in its surrounding setting, reproduced courtesy of Geoscience Australia, with the outline of the “compression box” hatched in white (Klootwijk, in prep., figure 12a). (b) Schematic overview of tectonic extrusion during the Alice Springs Orogeny. Red arrows indicate compression from Australia-Laurasia convergence during the Devonian-Carboniferous. Orange arrows indicate ductile flow of lower crust from the Larapintine Graben into mainly the Thomson and Lachlan Orogens. Major ENE-WSW fault zones, in red, guided up to 200 km upper crustal eastward displacement of the Thomson Orogen and the Northern New England Orogen. Yellow compartments (after Shaw et al. 1996) indicate at large the heated, weaker, crust of the Larapintine Graben and the weaker, originally oceanic, crust of the TOS (Klootwijk in prep., figure 12B). (c) Rayleigh wave speed anomalies of central and eastern Australia at 100 km depth, relative to the ak135 model (Kennett et al. 1995), after Fischwick et al. (2008, figure 3a). (d) Image of the horizontal gradient of surface wave velocity of central and eastern Australia at 100 km depth, after Fishwick et al. (2008, figure 4a). (e) SV azimuthal anisotropy at 100 km depth (Debayle & Kennett 2000a, plate 2a). Azimuths of red line segments indicate fast directions, their lengths indicate strengths of anisotropy. (f) Duration of the “Kiaman” Permo-Carboniferous Reverse Superchron, after Menning (1995) and Roberts et al. (2003), (Klootwijk in prep., figure 22a). (g) Schematic view of paleolatitudinal evolution of the central New Guinean promontory of the Australian Craton during the Carboniferous (Klootwijk in prep. figure 22b). (h) Comprehensive model of the Oersted and CHAMP scalar residual field model CM4 at 400 km altitude, after Sabaka et al. (2004, figure 14b).
Tectonic reconstruction using deformable plates

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AuScope is part of the National Collaborative Research Infrastructure Strategy (NCRIS). As part of that effort the simulation, analysis and modelling community (AuScope SAM) is constructing a "software machine" consisting of several interoperable components. The tectonic reconstruction component is being developed at U.Syd. and ANU. The RSES component is Pplates, the first ever deformable-plate, global- to regional-scale, tectonic reconstruction code.

The workflow is illustrated here.

The Pplates code is now almost fully functional, and is available for download as a ".dmg" disk image. Click here to obtain a working copy of the program along with elementary datasets. New in Pplates v 1.3 (a new release) are many improvements that enhance the user experience and modified implementation of many of the features of Pplates with an eye to moving to new API libraries. In particular:

1) Faster handling of gridded data.
2) Higher screen resolution for topography.
3) Performance improvement with larger projects.
4) Better menu design for handling project files - including a "Save All" option.
5) Improved mesh shaper performance -- moving a mesh shaper has been enabled.
6) Stress eigenvector calculation and display where previously only strain eigenvectors were available.
7) Map window viewing preferences stored with project.

Please Email joe.kurtz@anu.edu.au or sam.hart@anu.edu.au with comments and suggestions.
Dating a major shear zone in the Central European Alps - The Forcola Fault

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The Central European Alps have been subject to geological studies for now more than 150 years with a prolific array of data available. Even though the timing of deformation is one of the most important keys to resolve the geological history of a mountain belt few studies have focused on ascertaining the timing of major movement zones in the area. The Forcola normal fault is a major displacement zone in the Central European Alps and is often regarded as the Eastern boundary of the Lepontine gneiss dome. This dome is a window into deeper crustal levels of the Alpine nappe pile and the most prominent structure in the Central Alps, but the origin of this gneiss dome is still contentious with several hypothesis proposed during the last decades. We suggest that none of the present hypotheses explain either the published observations, or our observations, in a satisfactory manner. One important step towards a better understanding of the formation of the Central European Alps, is the direct dating of deformation events inside and around the Lepontine dome. The ⁴⁰Ar/³⁹Ar geochronology furnace step-heating dating technique on K-bearing minerals like micas or K-feldspar, enables us to date recrystallisation of major fabric forming minerals, and thus determine the timing of deformation directly.

Preliminary results from ⁴⁰Ar/³⁹Ar geochronology experiments on white micas from rocks deformed in the Forcola fault are now available from samples collected during the field summer 2008. Results show that these rocks recrystallised between 21 and 22 million years ago (see apparent age spectra) during an intense deformation event (mylonitization of an orthogneiss). The relative flat “plateau” in the spectra indicates that the white micas in the sample recrystallised completely and lost all their previous accumulated radiogenic argon during the deformation event. This complete resetting of the argon system correlates with the last event that can be verified at the microstructural-scale. These ages are the first direct evidence for the timing of shearing events at the Eastern border of the Lepontine gneiss dome.

This study on the deformation of the Forcola Fault is just the beginning of a greater project. The overall aim is to analyse several of the major movements zones in the Central Alps, helping to understand the complicated processes of mountain range formation, continental collision and continental convergence in greater detail.
Evolution of the subducting Solomon Sea Plate

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The Papua New Guinea and Solomon Islands region is located within the transition zone between SE Asia and the SW Pacific, one of the best-endowed metallogenic belt and most actively deforming areas on Earth. Interactions between the WNW-moving Pacific Plate and the NNE-moving Australian Plate give rise to a complex convergent zone exhibiting numerous microplates, volcanic provinces, island arcs and some of the fastest relative plate motions on Earth.

Some of this complexity has been unravelled using earthquake hypocentre data to create a 3-D model of the Wadati-Benioff zone associated with the subduction of the Solomon Sea Plate at the New Britain Trench. We report the presence of a large aseismic zone, herein termed the New Ireland aseismic zone, located in the ‘apex’ of the subducting slab, the margins of which initially record a dip of 30°, before steepening to over 75° at depth. Steeper slab dips are seen both to the east and west of the slab apex, particularly the eastern section of the slab, which appears to have been overturned (i.e. dip exceeds 95°).

In the light of this discovery existing tectonic models must be reassessed. The 3-D geometry appears to require slab-tearing during roll-back, and by implication must have stranded formerly attached segments of the subduction zone. Alternative models for the aseismic zone, such as the subduction of an aseismic ridge, do not provide a satisfactory explanation for the inferred geometry, and implicit deformation, of the Solomon Sea slab. In contrast, the roll-back and slab-tearing hypothesis is consistent with the current 3-D geometry, although it has significant ramifications for the tectonic evolution of the region. Roll-back and slab-tearing require a modification of palaeogeography and 3-D structure with time.
Evidence of (subduction-related?) magmatism after "the collision" of India and Eurasia

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The concept of “the collision” in relation to the accretion of India to Eurasia dominates the literature on the Himalayan orogen. Current controversy surrounds its timing. One hypothesis suggests that this event took place at ~54-50 Ma, whilst other hypotheses suggest that it occurred earlier (~75 Ma), or later (~35 Ma). Most of this controversy is associated with the simplified view that the accretion of India to Eurasia was more important in terms of magmatism, metamorphism and deformation than the accretion of other island arcs and terranes during the closure of Tethys. The current paradigm suggests that Indus Suture Zone marks the boundary between the Indian and Eurasian plates (Figure 1).

New U-Pb SHRIMP dating of zircons from a granodiorite in the Karakorum Batholith indicate crystallization occurred north of the Shyok Suture Zone at 32 Ma. There is also other evidence of magmatism at this time along strike of the Shyok Suture Zone, this includes porphyry Cu, Mo and Au deposits in eastern Tibet. Various models are invoked to account for this magmatism. However, as the evidence of magmatism at these times does not fit the paradigm of “the collision” marked at the Indus Suture Zone at ~54-50 Ma, tectonic models that suggest this magmatism could be the result of partial melting caused by dehydration of a down-going slab at (or before) this time are ignored. We therefore suggest that the Indus Suture Zone (at least in NW India) may not mark the boundary between the Indian and Eurasian plates, and the concept of “the collision” needs to be revised.

Figure 1. Digital elevation model of the Himalaya derived from Shuttle Radar Topography Mission (SRTM) data showing the location of major structures and suture zones, as well as the location of crystallization ages of granites, granodiorites and porphyry Cu-Mo-Au deposits north of the Indus and Shyok Suture zones.
Diffusional rims and moats around ilmenite inclusions in garnet and their significance for garnet geospeedometry

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Geospeedometry is a rapidly developing field. The technique is used to constrain the duration of thermal pulses during metamorphism. For example, diffusion modelling of element profiles in garnet. Garnet geospeedometry involves measurement of diffusive loss of an element during the entire heating and cooling history, giving information as to the time-integrated thermal response to the heating and cooling history. Currently, garnet geospeedometry is plagued by the difficulty of differentiating between growth zoning, as a result of Rayleigh-Taylor fractionation, and diffusion profiles. Development of a new geospeedometer that utilises the exchange of Fe-Mn between garnet and ilmenite inclusions will aid in solving this problem.

The garnet-ilmenite system, if properly calibrated, will allow the determination of the duration of both heating and cooling during the tectonometamorphic evolution of a particular rock. This is possible because of the temperature dependence of the Fe-Mn partition coefficient of the garnet-ilmenite system (Pownceby et al. 1987). This allows exchange of Fe and Mn at the boundary between garnet and ilmenite with the diffusion coefficient of garnet controlling the efficiency of exchange; the diffusivity of ilmenite does not need to be taken into account due to its rapidity. The rate of diffusion dictates the efficiency of exchange, with a quadratic relationship between the length of the diffusion profile and timescale. Ilmenite operates as a sink for Mn during the period of heating above the growth temperature; during cooling the ilmenite acts as a source for Mn, expelling it into the garnet. The ability of ilmenite to act as a diffusional sink on the heating path is greater than its ability to act as a source on the cooling path because as temperature decreases the systems potential for diffusion rapidly drops. This process produces diffusional features that vary in length and a bimodal diffusion profile is created. According to these theoretical considerations the Mn diffusion profile should have a sharp increase in concentration adjacent to the ilmenite inclusion then a Mn moat surrounding the ilmenite inclusion. The diffusion profile for Fe theoretically mirrors this behaviour. This profile has been observed in electron microprobe transects across ilmenite inclusions in garnet.

Gravity drives Great Earthquakes

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It is evident that the most violent of Great Earthquakes are driven by ruptures on giant megathrusts. Current theory suggests that the rupture harvests (and thus releases) elastic energy that has been previously stored in locked segments of the megathrust, and that this energy is stored as the result of relative motion of the adjacent stiff elastic tectonic plates. However it is clear that this mechanism fails to explain many first order aspects of large earthquakes. The energy source for strain accumulation can also be found in gravitational collapse of orogenic crust and/or in the foundering (or roll-back) of an adjacent subducting lithospheric slab.

Analysis of the geometry of aftershocks allows distinction of two types of failure. The classic view is that megathrusts fail in compression, with motion analogous to that expected if accretion takes place against a rigid (or elastic) backstop. This type of megathrust behaviour may well have applied to the southern segment of the Sumatran megathrust, from whence emanated the rupture that drove the 2004 Great Earthquake. The northern segment (beneath the Andaman Sea) admits to no such explanation. The geometry of aftershocks suggest that the crust above the initial rupture failed in an extensional mode.

Therefore westward roll-back of the subducting Indian plate, and the consequent gravity-driven movement of the over-riding crust and mantle can be implicated in the origin of the tsunamigenic Great Sumatran Earthquake of 2004. The edge of the Indian plate is foundering, with slab-hinge roll-back in a direction orthogonal to its motion vector. Aftershocks show that this motion may have driven afterslip in the Andaman segment of this giant megathrust-related earthquake.

The crust and mantle above major subduction zones is mechanically weakened by the flux of heat and water associated with subduction zone processes. In consequence the lithosphere of the over-riding orogens can act more like a fluid than a rigid plate. Such fluid-like behaviour has been noted for the Himalaya and for the crust of the uplifted adjacent Tibetan Plateau, which appear to be collapsing. Similar conclusions as to the fluid-like behaviour of an orogen can also be reached for the crust and mantle of Myanmar and Indonesia, since here again, there is evidence for arc-normal motion adjacent to rolling-back subduction zones.
Introduction

The Research School of Earth Sciences includes substantial activities in geophysics. The main research themes are Geodynamics, Geodesy, Geophysical Fluid Dynamics, Mathematical Geophysics and Seismology. These span observational, theoretical, laboratory, computational and data oriented studies, all directed towards understanding the structure and physical processes in the earth’s interior, the crust or the earth’s fluid envelope.

In 2009 Professor M. Sambridge was awarded the J.C. Jaeger Medal by the Australian Academy of Science for achievements in Earth Science. Dr M. Roderick was awarded the Australasian Science Prize by the journal Australasian Science for his work on the Earth’s hydrologic cycle and showing how pan evaporation rates in Australia have decreased over time with global warming. Professor R. Griffiths joined the Australian Research Council College of Experts (Physics, Chemistry, Earth Science panel).

RSES continues to take a major role in the National Cooperative Research Infrastructure Strategy (NCRIS): “Structure and Evolution of the Australian Continent”, which is managed through ‘AuScope’. RSES hosts activities in Earth Imaging through support of portable instrumentation and transects, Geospatial through gravity measurements and testing of portable equipment for satellite laser ranging, and Simulation & Modelling through ‘pPlates’ software for tectonic reconstruction. As a linked activity between three AuScope components (Imaging, Geospatial and Access and Interoperability), the Terrawulf II cluster computer at RSES (Centre for Advanced Data Inference) provides capability in geophysical inversion and the computation reduction of observational data. RSES also continues the management of the Warramunga Seismic and Infrasonic Research Station near Tennant Creek in the Northern Territory, as a primary station in the International Monitoring System for the Comprehensive Nuclear-Test-Ban Treaty Organisation.

Research in geodynamics and geodesy has focused on measuring deformation of the Earth from both terrestrial and space-based observations. Estimates of total water storage from the GRACE space gravity mission were compared to terrestrial estimates of surface, soil and ground water in a study of the multi-year drought in the Murray-Darling Basin. The finding that a significant component of water loss had come from groundwater reserves generated considerable media interest. Other results were a demonstration of the non-stationary nature of geophysical signals observed by GRACE, that positive gravity anomalies in Enderby Land (Antarctica) are not related to glacial isostatic adjustment, and improvements in GPS analysis strategies that lead to a better agreement between GPS- and GRACE-based surface deformations than reported in previous studies. Terrestrial gravity measurements have been made using an absolute gravimeter and tidal meters in order to quantify the surface deformations caused by ocean tide loading.

In geophysical fluid dynamics, laboratory experiments have been used to examine the three-dimensional flow in mantle subduction zones, and the interaction of ascending mantle plumes with subduction zones, with a view to explaining the history of volcanism in the Columbia River Basalts, the Lava High Plains and Yellowstone hotspot of the northwest USA. Modelling of the combined chemical and thermal evolution of the Earth’s mantle has been extended to Venus’ mantle to test ideas about the operation of plate tectonics on Venus and whether the ‘basalt barrier’ mechanism can explain the outburst of volcanism that completely resurfaced Venus about 500 Myr ago. Another highlight is an explanation of the energetics of the global meridional overturning circulation of the oceans, which shows that energy supplied to irreversible turbulent mixing from the winds and tides (or other sources) must be in balance with the available potential energy supplied by the surface buoyancy fluxes. Hence the energetics indicate that the rate of overturning is governed by both the buoyancy fluxes and the mixing rate, as previously argued on the basis of dynamical considerations. Numerical solutions from a general circulation model were also found to be different depending on whether it was run in the usual hydrostatic and low-resolution mode, or in non- hydrostatic mode with an extremely high resolution resolving the vertical convective motions. In closely related work aimed at understanding both turbulent mixing and the global circulation, new experiments were carried out to obtain additional information about the nature of mixing in exchange flows over topographic sills. The results indicate that the proportion of energy input that goes into raising the potential energy by mixing is in the range 5–10%, efficiencies much smaller than the 20% often assumed in analyses of global ocean energy balances. Work also continues in high-resolution modelling of flow in the Southern Ocean, designed to determine the dynamics driving the circulation in this region. The latest results give a clearer indication of the likely response of the Southern Ocean to climate change.

In parallel with the gravity satellite research, and the ocean studies, we conduct detailed studies on the hydrologic cycle. Of principal interest here is the development of a theoretical framework that can provide physical understanding of the possible changes in the hydrologic cycle with global warming, at both global and local scales. One highlight this year was the publication of “The Global Water Atlas” (by ANU ePress), which documents model predictions contributed by international climate modelling groups to the 2007 4th Assessment Report of the Intergovernmental Panel on Climate Change. Activities in seismology in 2009 included extensive field-based deployments of seismic instrument arrays, data analysis and theoretical development, for studies of Earth structure from the crust to the core. Much of the activity centred on the WOMBAT experiment, a rolling-array deployment that has been in operation since 1998 and is currently focused on achieving
high resolution imaging of the crust and upper mantle beneath south-eastern Australia, including the Flinders ranges and the Murray Basin. The results show little evidence for the Palaeozoic building blocks of the southeast Australian continent that had been inferred from geological mapping. By utilizing differential PcP-P times from WOMBAT, high resolution imaging of the core-mantle boundary is also possible and current efforts are directed at mapping variations in core-mantle boundary geometry and D' velocity. New global observations of waves reflected from the Earth's inner and outer core (PKiKP and PcP waves), originating from earthquakes and nuclear explosions, were used to place bounds on density ratio between the inner and outer cores. Other arrays were deployed in the region around Mt Isa in Queensland and between the Eyre Peninsula in southern Australia and Tennant Creek in northern Australia, in order to examine the transition between the northern and southern Australian cratons. The new Seismic Data Centre (SDC) now provides easy access to all current and past seismic data collected by RSES in a variety of user-friendly formats. Model structures for the inner core were re-examined using our Antarctic permanent stations as well as the temporary SSCUA deployment operated by the RSES during 2002-2005, and provide evidence against a proposed cylindrical structure in the outer core tangent to the inner core in the southern hemisphere.
A portrait of the Bárdarbunga volcano, Iceland, earthquake and insights into the kinematics of the caldera drop

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The Bárdarbunga volcano lies beneath the 500-m-thick Vatnajokull icecap, the largest glacier in Europe. An earthquake with Mw=5.6 occurred beneath the caldera on 29 September, 1996 and produced an unusual radiation that cannot be explained by a shear slip on a planar fault. A peculiarity of this earthquake was that it was the first in a sequence of seismic and magmatic events and that it was followed, not preceded or accompanied, by a major eruption, which ultimately led to a breakout flood from the subglacial caldera lake. It was hypothesized that the observed source mechanisms results from slip on an outward-dipping cone-shaped ring fault beneath the caldera, as a result of a change in pressure in the volcano’s shallow magma chamber. The earthquake was recorded well by the Iceland Hotspot Project seismic experiment.

The absence of a volumetric component in the source mechanism is surprising, however a possible mechanism that can produce an earthquake without a volumetric component involves two offset sources with similar but opposite volume changes. We show that although such a model cannot be ruled out, it is unlikely. We simulated different caldera geometries and rupture scenarios on the walls of a conical surface. These experiments support a super-shear rupture extending unilaterally across one-half perimeter of the caldera or a bilateral rupture extending across full perimeter of the caldera as likely scenarios for the Bárdarbunga earthquake.

If studied in different frequency bands, synthetic seismograms based on a point source approximation fail to simultaneously explain the observed data, and this indicates the existence of finite-source effects. Using a 3D model of the Icelandic crust and upper mantle, we perform a probabilistic finite source inversion. One of the most robust outcomes of this is a well-constrained source duration with approximately equal amount of energy radiated by individual segments. This indicates that the caldera dropped coherently as a single block. We also hypothesise that a smaller subglacial eruption that triggered the caldera collapse occurred and went unnoticed. The caldera drop could have increased the pressure in the magma chamber thus inducing the principal eruption. The major eruption after the earthquake is consistent with the classical model where the ring fault is located above the magma chamber.

Link to the online article:
http://www.bssaonline.org/cgi/content/abstract/99/5/3077
As part of a wider AUSCOPE project 67 short-period seismometers were deployed across the Gawler and Curnamona Cratons in South Australia. Station spacing was approximately 60 km and covers the area from the Streaky Bay in the east to the New South Wales border in the west. The north-south extent of the array runs from Cameron Corner to Port Lincoln. Stations recorded continuous three component data for a period of 6-8 months. The instruments are capable of recording data from both local and distant earthquakes.

The primary aim of these arrays is to increase data coverage in this part of Australia for seismic imaging. There are few permanent seismographs in the region covered by this array. The area covered is currently of particular interest for the supply of geothermal energy and there are many ongoing industry projects in the area. This area of South Australia is also seismically active and local earthquake data recorded on this array will help improve our ability to locate and characterize these events.

Currently the data are being used for receiver function analysis to locate seismic discontinuities such as the crust-mantle boundary (Moho). This is contributing the the ongoing AusMoho project mapping the Moho beneath the Australian continent (figure 1).

Curnamona Craton seismic stations

Gawler Craton seismic stations

Figure 1. Current AusMoho map. Contours show the depth to the crust-mantle boundary in kilometers. Data points from short-period receiver functions are shown as circles, data points from broadband receiver functions are shown as diamonds and reflection/refraction line data are shown as triangles.
High Resolution Imaging of the Core Mantle Boundary with PcP-P Differential Travel Time Residuals

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Southeastern Australia is favorably positioned relative to much of the Pacific Rim and SE Asian subduction systems for detection of PcP phases from subduction zone earthquakes, which are best recorded between approximately 25-75°. The subduction zones of Indonesia, Papua New Guinea, Tonga/Kermadec, Philippine, Izu-Bonin-Mariana, and Japan are all within 25-75° of SE Australia. As such, any seismic stations deployed in this area have potential for detailed PcP-P travel time studies. Using data from a large rolling seismic array in southeast Australia, we obtain unprecedented high-resolution coverage of the core-mantle boundary in this region.

Surface projections of PcP bounce points are clustered directly beneath the large region spanning central and northern Australia, the Arafura Sea, north of Papua New Guinea, and the Tasman Sea. There is an overall predominance of negative residuals throughout the region, particularly near Sulawesi, western Indonesia, central Australia, and west of New Zealand. In particular, results under the Tasman Sea show a transition from large and negative residuals to moderate and positive residuals, which could be suggestive of remnant subduction signals at the CMB from the Tonga/Kermadec region.

With the remaining analysis using the rest of the >500 short-period stations in SE Australia and >100 stations in Sumatra, we aim to produce high-resolution images of the lower mantle and core-mantle boundary. We will focus on the regions of central Australia and the Timor and Tasman Seas in particular as they have the densest raypath coverage. Using traveltime tomography, waveform coherence, any precursory phase analysis, and amplitude information, we will investigate the trade-off between velocity structure and interface depth at the core-mantle boundary.
Figure 3. Surface projections of PcP-P bounce points. Points are scaled by PcP-P residual, black circles are negative, red triangles are positive. Inverted blue triangles are stations used in the study.
Detailed images of Rayleigh wave group velocity are derived from ambient seismic noise recorded by WOMBAT, a large rolling seismic array project in southeast Australia (see Figure 1). Data from 282 stations deployed as part of seven separate array movements are used, with a maximum of 57 stations recording at any one time. Group velocity maps sensitive to shallow crustal structure (Figure 2) reveal the presence of low velocity regions associated with sedimentary basins and the Newer Volcanic Provinces of western Victoria, and high velocities associated with regions of outcropping metamorphic and igneous rocks in the Great Dividing Range. Distinct and well-constrained patches of low velocity within the Murray Basin, a large Tertiary intra-cratic basin, point to the presence of infra-basins, the existence of which have been confirmed by drilling, but whose spatial extent is poorly understood. In a broader tectonic context, our results show little evidence for the Palaeozoic building blocks of the southeast Australian continent that have been inferred from geological mapping and potential field data. For example, the transition from the Delamerian to the Lachlan Fold Belt is not marked by a change in group velocity, nor is the so-called Tasman Line, which supposedly separates Precambrian western Australia from Phanerzoic eastern Australia. In the latter case, the new results support the contention that the change from an accretionary orogenic terrane in the east to a much older cratonic terrane in the west is likely to be gradual rather than distinct.
High Frequency Po/So and the nature of the oceanic lithosphere

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It has long been recognised that high frequency seismic body waves can travel for substantial distances through the oceanic lithosphere. In the western Pacific such Po and So phases are very common from shallow events in the various subduction zones, and have been recorded at more than 3000 km from their earthquake source. Usually So is stronger and longer duration than Po when recorded on seismometers, but weaker when a hydrophone is used as the sensor. A combination of multiple propagation legs within the lithosphere reinforced by more rapid reflection processes in the water and sediments helps to carry such Po and So energy to long distances. The complex observed waveforms with long tails can be well simulated by numerical models that include heterogeneity in the lithosphere with much large horizontal than vertical extent.

Despite the generally good propagation to stations in the western Pacific where poor propagation is inked to source location in the back arc region, the situation is more complex in the east. The underwater observatory H2O on an old telephone cable between Hawaii and the Mainland USA only records So from events on Hawaii, and even these arrivals are relatively weak compared with Po. A survey of Po/So properties across the Pacific (Fig 1) highlights the differences in propagation characteristics. It appears that the poor transmission of Po and So may be related to the presence of the major transform fault systems in the eastern Pacific that are likely to be linked to changes in lithospheric thickness. These effects are being investigated through detailed analysis of the signals and numerical modelling of the high frequency wavetrains. Oblique incidence on a major step in lithosphere thickness is likely to have a significant effect on the complex wave packets.

Figure 1. Compilation of Po and So propagation characteristics in the Pacific showing the clear propagation of Po and So in the western pacific and the relatively poor propagation in the east where paths traverse major transform faults systems.
Eddy response of the Southern Ocean to climate mode forcing

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The Southern Ocean consists of some of the most dynamically complex ocean currents in the world. Not only does it include the Antarctic Circumpolar Current (ACC), which is among the world’s strongest in terms of transport, but also contains a network of vigorous small-scale eddies. As a transit point for the exchange of water masses between the other major oceans, the Southern Ocean plays a crucial role in the climate of our planet, and these currents can have a significant impact on the state of world oceans.

The consequences of this active eddy field have yet to be fully understood. For example, the ACC transport has been shown to be largely insensitive to wind forcing in high resolution models. Rather, such forcing tends to produce a more vigorous and spatially inhomogeneous eddy field. Modeling work of the GFD group at ANU has shown that this eddy field is sensitive to standard modes of climate variability, specifically the Southern Annular Mode (SAM) and ENSO. In particular, ENSO can have a modulational effect on SAM, either amplifying or suppressing the eddy response in specific regions across the Southern Ocean (Figure 1). Such an inhomogeneous and time-dependent eddy field directly impacts the mixing and large-scale transport of water throughout the Southern Ocean, and can lead to long-term impacts on the world’s oceans.

Figure 1. Wind forcings based on the Southern Annular Mode (SAM) and La Niña are applied over a two year period (below dashed line), producing eddy kinetic energy (EKE) responses with dramatic spatial and temporal variability. Despite a dominant SAM mode, La Niña can enhance (90W, Pacific) or suppress (30E, Atlantic) the SAM response.

Figure 2. This snapshot of the pressure field from numerical modeling reveals an active eddy-rich flow along the fronts of the Antarctic Circumpolar Current. Variations in wind forcing are transferred predominantly to these small-scale structures.
Mixing in flows between ocean basins

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Underwater cascades carrying huge volumes of water are common in the oceans. They occur where water overflows from sea and ocean basins into neighbouring basins over bottom ridges, or through channels and straits. When the overflow water is dense enough, it falls down the slopes to the bottom of the ocean as a turbulent current. The extent to which the cascading water mixes with its new surroundings influences the density stratification in the oceans, and we have previously argued that this mixing also influences the global rate of overturning of the oceans, hence the poleward heat transport.

Overflows, or hydraulically-controlled density-driven exchange flows, have been set up in the Geophysical Fluid Dynamics Laboratory at ANU. The amount of mixing was measured to see whether it depends on sill height, bottom slope, or density difference (figures 1-3). These experiments also serve as a case study of the fundamental nature of turbulent mixing more generally, and may help to improve climate models by allowing us to develop a better description of mixing in the oceans.

Figure 1. Dye visualizations of exchange flow experiments. Fresh water (yellow) flows from left to right and salt water solution (blue) from right to left. Exchange takes place through a pure lateral constriction (situated between the two bands of vertical lines) in the first case, and across a bottom sill located in the constriction in the second case. The third case shown has a higher topographic sill and a larger Reynolds number. Strong interfacial disturbances lead to turbulence and mixing.
The global ocean overturning: what pushes must pull
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What governs the rate at which cold water from the ocean surface sinks at high latitudes, passes through the deep ocean, is reheated and returns to the surface? This is an important question because the overturning circulation redistributes heat and helps to regulate the Earth’s climate.

Oceanographers argue about the relative importance of heat fluxes through the sea surface (heating of the upper ocean at low latitudes and cooling it at high latitudes) and mixing within the ocean. Some ask whether the dominant factor is the “push” from the buoyancy of the dense sinking water at high latitude or the “pull” associated with the downward mixing of heat and buoyancy over much of the area of the oceans.

In a paper in the Journal of Physical Oceanography we have shown how surface buoyancy fluxes generate available potential energy (figure 1). The density of the ocean water can be altered only by irreversible mixing and surface buoyancy fluxes. Hence the energy transports associated with these two processes must balance (in a steady circulation). In other words, both the surface heat fluxes and sources of kinetic energy for turbulent mixing - commonly associated with winds and tides - are simultaneously necessary to maintain the observed ocean overturning circulation. The analysis of energy transformations shows that “pushing” and “pulling” cannot be separated, a point we have previously argued based on models of the forces and momentum balance of the circulation.

As a corollary, aspects of the ocean overturning circulation predicted by general circulation models are strongly influenced by the nature of the model computation. In particular, the circulation (figure 2) is influenced by whether vertical convective motion is parameterized, or whether these motions are fully resolved by using extremely high-resolution computations. Parameterisation of convection and an assumption of hydrostatic flow are commonplace in climate models, but do not correctly describe the energy changes.

These concepts are being further examined in laboratory experiments with overturning forced by salt and freshwater fluxes at the surface. In the experiments turbulent mixing is generated by horizontal bars, which are traversed up and down through the depth of the water, and the flow is allowed to reach an equilibrium state before the density stratification and circulation flow velocities are measured. The results, particularly the dependence on vertical diffusivity owing to mixing, will be compared with theoretical solutions and with the behaviour of ocean general circulation models.
Internal gravity waves and convection

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Coherent propagating waves have been discovered to be a ubiquitous feature in numerical simulations of convection that have been undertaken in RSES to investigate the dynamics of global ocean overturning circulation. These waves have been identified as internal gravity waves, and are normally absent in convective flows because the convection tends to keep the fluid well mixed. In contrast, when the ocean surface is heated at low latitudes and cooled at high latitudes, the associated buoyancy forces drive a circulation that maintains both gravitationally stable density stratification and overturning throughout the flow. This form of circulation is known as “horizontal convection”. Our simulations, supported by evidence from laboratory experiments, show that the sinking leg of the circulation, a turbulent plume, excites a spectrum of internal gravity wave modes, and that these are a source of strong variability throughout the domain (figure 1). Further work is required to assess the importance of this phenomenon in the ocean overturning circulation.

Figure 1. Hovmöller plot of the vertical velocity along a horizontal section towards the bottom of the box in a 2-D numerical simulation of horizontal convection. Time increases downwards; blue represents upwelling motion, green approximately no motion, and red downwelling motion. The region of high latitude sinking is located at the left hand end of the horizontal section, and excites strong wave modes that propagate towards the right hand end of the section ("low latitudes"). The waves appear to be responsible for much of the variability in this flow.
Wind forcing of the Southern Ocean

Do small scales alter wind power input?

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Circulation in the Southern Ocean is driven by strong winds which help to force the world’s strongest ocean current, the Antarctic Circumpolar Current (ACC). Recent satellite measurements have indicated small-scale structure to the wind stress field (see Fig. 1). In this study, we investigated the effect of small-scales in the forcing field upon the large-scale circulation.

We use a high-resolution ocean model of the Southern Ocean region, coupled to a dynamic atmospheric mixed layer to evaluate the performance of two different wind stress parameterisation schemes. The first is the standard quadratic drag law used by most climate models, while the second (more exact) formulation is based on the difference between ocean and atmosphere velocities. The two different schemes give very similar magnitudes of stress, but, somewhat curiously, the latter scheme contributes substantially less energy to the ocean circulation. The differences occur because small scale (10-50 km) turbulent eddies act to reduce energy input.

These results have significant implications for the Antarctic Circumpolar Current. In particular, despite the lower power input to the ocean, the relative velocity scheme has a stronger ACC, because there are less turbulent eddies to dissipate the flow.

Pre-print of Hutchinson et al. (2009; In Press)

Figure 1. An image showing the distribution of wind stress over the Southern Ocean. The large spatial scales show stress due to atmospheric motion (e.g. high and low pressure cells, storms) while the smaller scales show the effects due to oceanic eddies.
Thermal erosion of felsic ground by the laminar flow of a basaltic lava

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Thermal erosion of basaltic ground during the laminar flow of a basaltic lava has been observed on the Big Island of Hawaii, where flows about 1 m deep have been observed to erode 5-15 m into the underlying solidified basalt over several months to create deep lava tubes (Figure 1). These observations were first explained fluid dynamically by Kerr (2001).

In Kerr (2001), the lava was assumed to be identical to the ground it was flowing over. However, in many geological situations, the lava will have a composition that is different to that of the underlying ground. For example, in the Cave Basalt on Mt. St. Helens (Figure 2), the basaltic lava flowed over and eroded a dacitic pyroclastic flow, which led to contamination of the basaltic lava. This geophysically and geochemically interesting problem has been recently investigated by Kerr (2009). My analysis predicts that initially a chill layer is grown and then remelted at the base of the lava flow. A steady thermal erosion velocity is then established, which is limited by the buoyant instability of the melted ground or by the effective freezing temperature of the basaltic lava. When my analysis is applied to the longest lava tube system of the Cave Basalt on Mount St. Helens, it is found that about 100 days of flow is sufficient to produce the observed ground erosion.


Model dimension and data uncertainty in non linear inversion : An expanded Bayesian formulation.

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In an inverse problem, it is well known that the data fit is improved as more unknowns are added into the problem. If too many unknowns are introduced the data may become over fit and artifacts introduced into the model. In contrast to optimization based approaches to inversion (e.g. a least square minimization), the transdimensional approach uses a sampling based (Bayesian) framework and is able to directly adjust the model dimension in order to fit the data to the degree required by the noise. In this case, the both the degree of freedom in the model and the level to which the data is fit is driven by the data itself rather than imposed subjectively. This property is illustrated when applying the reversible jump scheme to a simple 1D non-linear regression problem. Figure 1 shows solution curves obtained with the same data assuming different values of data noise, \( \sigma_{est} \). The true value of the noise is \( \sigma_{est}=10 \). When assumed too small (\( \sigma_{est}=4 \)) we see the classic feature of over fitting the data. The estimated curve green departs from the true curve (gray) as it tries to fit the data to the required accuracy. When it is too large (\( \sigma_{est}=30 \)) the data are under fit and the model is too smooth. Only when it is correct (\( \sigma_{est}=10 \)) is the recovered model close to the true solution. This shows the importance of knowing the noise in the data in a Bayesian framework. The trans-dimensional inversion approach is the same in all three cases and we see how it has only introduced the number of unknowns (cells) necessary to fit the data adequately. This is an advance over the alternative which is to impose the number of unknowns beforehand. In absence of information about data noise, it would be impossible to give a preference to any of the three solutions in Figure 1.

An expanded Bayesian formulation can take into account the lack of knowledge we have about data errors. Instead of being fixed, the variance of the measurement errors can become an unknown in the problem also and be determined by the data. This methodology is called “Hierarchical Bayes” and results are shown in Figure 2. Without knowledge about the data noise and the complexity of the true model, the algorithm is able to provide a solution model (top panel in Figure 2) with the correct complexity, and that fits the data to the required level. Furthermore, the expected posterior value for the data noise (bottom panel in Figure 2) is close to the true data noise.

Current applications of this approach are to seismic inversion of receiver functions for 1-D earth models and also to palaeoclimate time series data where little is known about data errors. The hierarchical Bayes formulation gives also promising results when used for seismic tomographic imaging.
Figure 2. Results with hierarchical Bayes. Here, the estimated data noise is not a number to be given by the user but an unknown parameter whose posterior probability distribution is to be determined by the Bayesian inversion. Top: solution model. Middle: Posterior probability distribution on the model complexity (the value of the true synthetic model is 9). Bottom: Posterior probability distribution for data noise (the true value of data error is 10).
TerraWulf II: Many hands make light work of data analysis

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In 2008, RSES launched TerraWulf II the latest in a long line of high powered computing facilities, stretching back more than 30 years. As the name suggests, this is the second of its particular species. The first, built in 2003, capitalised on a worldwide trend of combining off the shelf PC computers to form a highly cost effective (BeoWulf) supercomputer. The second, TerraWulf II (or TII as it is known to users) has 10 times the compute power of TI (~1.5 Teraflops) and occupies one quarter of the room space. Its construction was a joint venture between ANU (through RSES) and AuScope Ltd (The Earth Science infrastructure initiative funded through the Federal Government’s National Collaborative Research Infrastructure Strategy program). TII was designed primarily for use in earth imaging and geospatial applications however scientists are constantly finding new and innovative ways to exploit its power and convenience.

A key difference between modern computational clusters like TII and the 1980s machines at RSES is the focus on parallelism. The increase in processing power of each generation of micro-processors has begun to slow down, however computational gains can still be made by combining multiple processors together to perform complex calculations. Hence the rise of parallel based clusters like TI and TII. The initial uses of parallel computers (more than 10 years ago) were largely in areas involving highly advanced simulations of physical phenomena, e.g. weather prediction, ocean modelling, mantle convection and seismic wavefield simulation through complex media. As a consequence, parallel computing facilities gained a reputation for being highly exotic and only for the specialised user. In recent times, this situation has begun to change, as the power of parallel computing has become accessible to a broader range of scientists, even those without the interest in or need for advanced computational methods. A prime driver is the need to analyse data from large spatial arrays of instruments being used to build earth observing datasets, a task which is often particularly suited to parallelism. TII is increasingly being used for this type of 'loosely coupled' calculation.

An example is the geospatial scientist who has to perform the same processing tasks on many separate subsets of data independently (e.g. one analysis for each day of recorded observations). With a cluster of computers, each independent job is performed simultaneously in parallel meaning that the whole task can be achieved in a fraction of the time that it would normally take with single processor workstations. Another example is in the use of Monte Carlo based data inference (inversion) methods where many independent potential solutions to a problem need to be tested against the data, e.g. seismic models of the Earth interior fitting observed travel times or waveforms. TII has been used for both types of calculation, as well as the more traditional simulation of geophysical phenomena using advanced computational techniques. In its short life it has already racked up over seven hundred thousand cpu-core hours of use across applications ranging from earth imaging, geospatial analysis as well as simulation of geophysical processes from the Earth’s surface to its core. In addition it has been used as a test bed to develop a new generation of data inference tools.

These examples show how cluster-computing facilities like TerraWulf II are becoming an invaluable tool to the geophysicist. Clusters have been proliferating in research institutions, business and industry in recent years and as more applications evolve we can expect demand for such facilities to increase in the future.

http://rses.anu.edu.au/terrawulf/
Figure 1. A Monte Carlo style inversion performed on TII for seismic structure in Australia using ambient noise. (a) Ray path density for 1158 rays in ambient noise dataset of Saygin and Kennett (2009). (b) Shear wave speed model produced by averaging 8000 models generated by the Bayesian Monte Carlo procedure on Terrawulf II, (c) best fit model obtained, (d) number of cells in the model as a function of iteration. Red and blue lines represent results from two of the 200 independent random walks through the model space.
Figure 2. GPS data re-processing of eight years of data performed on TII. On a single CPU it is estimated that this analysis would take approximately 23 years to complete. (a) Map of GPS site locations used in the analysis. The time series of the height estimate of the site at Alice Springs, NT, (b) from the original analysis (upper right) and (c) the refined analysis (lower right). The weighted root-mean-square of the daily height estimates has been reduced from 5.2 to 3.7 mm.
Introduction

The Integrated Ocean Drilling Program (IODP) is the world’s largest geoscience research program. It aims to solve global scientific problems by taking continuous core of rocks and sediments at a great variety of sites in the world’s oceans. IODP carries out deep scientific coring in all the world’s oceans using a variety of platforms, and provides ‘ground truthing’ of scientific theories that are based largely on remote sensing techniques. IODP’s key research areas are:

- Deep biosphere and ocean floor
- Environmental changes, processes and effects
- Solid earth cycles and geodynamics

The Australian IODP Office (AIO) was established at RSES in 2008, and also serves as the Australian and New Zealand IODP Consortium (ANZIC) headquarters (www.iodp.org.au). Australian funding is provided for Australian IODP membership, for running AIO, and for travel for scientists from around Australia involved in IODP activities. Fourteen universities, CSIRO and AIMS all support Australian membership and are involved in scientific activities. New Zealand’s membership is supported by GNS Science in Wellington and three universities.

Neville Exxon is Program Scientist with the Australian IODP Office under a part time professorial contract. His administrative assistant, Sarah Howgogo, was appointed early in the year. The program has a Governing Council and a Science Committee, which meet in person and by video or phone link during the year.

We have representatives on a number of IODP panels which meet around the world, and one panel meeting was held in Melbourne in November. Seven Australian and New Zealand scientists have been placed on six IODP expeditions in ANZIC positions this year. Next year four ANZIC positions have been allocated thus far, with Jody Webster of Sydney University a co-Chief Scientist on the Great Barrier Reef environmental expedition starting in January.

The INVEST Conference was held in Bremen in September, to help design to IODP’s Phase 2, beginning in 2013, and was attended by more than 500 scientists from around the world. An ANZIC white paper was developed and submitted by Stephen Gallagher and others, and is now on www.iiodp.org.au (front page link). AIO sent Brian Kennett, Jody Webster, Stephen Gallagher, Richard Arculus and Chris Yeats to INVEST; Chris Hollis was funded by GNS Science NZ; Australian younger scientists Helen McGregor and Liz Abbey attended at IODP-MI expense. A committee of fourteen has been appointed to draft the new science plan, and this includes Richard Arculus of ANU and Peter Barrett of Victoria University, Wellington.

There are two important but smaller IODP review committees in action at present. One includes Chris Yeats of CSIRO, and the other Geoff Garrett, the former head of CSIRO. It is very apparent that ANZIC, a small member of IODP, is highly regarded for its scientific and organisational expertise. It also tends to represent Southern Hemisphere science in a broad sense.

A major Australian IODP Office activity this year was putting together a bid for additional ARC LIEF funding, which succeeded. Twelve partners each agreed to put in an additional $5000 p.a. for 2009–2012. In the end ARC decided to make a simple variation of the existing Arculus LIEF grant, increasing their funding to $1,550,000 p.a. This puts us on a much firmer financial footing in paying $US1,400,000 p.a. as the Australian IODP membership fee. The total annual budget is now $2,180,000 through to 2012, $410,000 p.a. more than it was previously. We can also spend up to $20,000 per head on post-cruise funding for 5 university scientists, a total of $100,000 p.a. This latter development is invaluable in enabling those with access to no other source of funding in the immediate post-cruise period to make a start on their work.
PRISE

Introduction

PRISE continued to operate as an externally funded research group within the Research School of Earth Sciences, providing access to the Research School’s specialised equipment and expertise in areas of geochronology, geochemistry and petrology. PRISE scientists also undertake their own research projects as supported by competitive grant applications. They supervise postgraduate students, both within the Research School and internationally.

During 2009, Dr Greg Yaxley was awarded an ARC Future Fellowship. Drs Richard Armstrong and Marc Norman have been successful in ARC Discovery Projects and as part of a LIEF grant to purchase a new thermal ionisation mass spectrometer.

All PRISE staff members are actively involved in wide-ranging collaborative research projects with academic colleagues throughout the world, as well as providing research and analytical skills to industry and Government agencies on a commercial basis. During 2009 PRISE hosted twenty-nine local and international visitors, most of whom undertook collaborative projects using the SHRIMP, Laser ablation- and solution ICPMS, electron microprobe and TIMS analytical facilities. PRISE staff also participated in a number of field-orientated studies in Australia, Africa, North and South America and Europe.

Some areas of current research include:

- Investigations of the origins of pyroxenite bodies in peridotite massifs of the Western Gneiss Region, Norway (PhD student A. Rosenthal)
- High pressure experimental investigations of kimberlite and carbonatite petrogenesis (PhD student K. Kiseeva)
- Impactor fluxes in the inner solar system from the ages and compositions of lunar glasses (PhD student S. Hui)
- Bioarchaeology in early Cambodian populations and in situ oxygen and strontium analysis of human teeth
- Multi-isotopic and trace element zircon studies to constrain magmatic evolution of plate margins and continental reconstructions; combined U-Th-Pb, Lu-Hf, Ti geothermometry, trace and REE chemistry, and oxygen isotope studies.
- Development of in situ sulphur isotope analytical protocols for the SHRIMP
- Use of sulphur isotopes to aid in understanding the origin and conditions of formation of metal sulphides
- Chronology of the Archaean-Proterozoic transition and the rise of oxygen in the atmosphere
- Geological Connection between West Antarctica and Patagonia since the late Paleozoic: Tectonism, Paleogeography, Biogeography and Paleoclimate
- Placing realistic constraints on the timing of world-wide Neoproterozoic glacial events: a critical examination of the “Snowball Earth” hypothesis
- Ages of granites and related mineralisation in NSW
- Origin and evolution of plume magmas and Hawaiian volcanoes
- Hydrochemistry of groundwater resources in the Sydney basin and Murrumbidgee Irrigation area of NSW
Imbrium Provenance for the Apollo 16 Descartes Terrain: Argon Ages and Geochemistry of Lunar Breccias

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The primary geological objective of the Apollo 16 mission to the Moon was to investigate and sample two physiographic units identified by pre-mission planning: the “Descartes Mountains” and the “Cayley Plains”. Both units were found to be impact-related deposits, distinguished by differences in lithology and bulk composition as well as morphology, but the provenance and genetic relationship of these units to specific basins or craters is not well established. The Descartes breccias are of particular interest because they are often considered to be primary ejecta from the Nectaris basin. Existing constraints on the source of the Descartes breccias are, however, permissive and subject to interpretation. Arguments for an origin as Nectaris ejecta are based mainly on analogues with the Orientale basin, the youngest and best-preserved multi-ring basin on the Moon, and predictions from cratering models. Alternatively, geological relationships observed from lunar orbit suggest that the Descartes and Cayley units both could be distal ejecta from the Imbrium basin.

As Nectaris ejecta, the emplacement age of these breccias would have significant implications for lunar stratigraphy and the hypothesis that the Moon experienced a late heavy bombardment of impacting planetesimals at about 4 Ga. Nectaris is the one of oldest nearside basins and together with Imbrium stratigraphically brackets 12 other lunar basins. The often-quoted ages of 3.92 Ga for Nectaris and 3.85 Ga for Imbrium tend to favor a late heavy bombardment, whereas an older age of Nectaris would weaken the case for a late cataclysm. Geochemical characteristics of the Descartes breccias are similar to those of the Feldspathic Highlands Terrane, so a better understanding of these breccias may provide insights into the origin and evolution of major crustal provinces on the Moon as well as the early impact history of the inner solar system.

The goal of this study was to improve constraints on the provenance and emplacement age of the Descartes breccias based on \(^{40}\text{Ar}-^{39}\text{Ar}\) incremental heating ages, major element, and trace element compositions of clasts extracted from two feldspathic fragmental breccias that represent the Descartes terrain (67016, 67455). Anorthositic clasts with well-behaved \(^{40}\text{Ar}-^{39}\text{Ar}\) spectra define ages that are identical with the currently accepted age of the Imbrium basin, and trace element compositions suggest a provenance in the Procellarum-KREEP Terrane. We conclude that these characteristics points toward emplacement of the Descartes breccias as Imbrium ejecta, rather than from Nectaris.

This conclusion pulls the pin on the Late Cataclysm hypothesis. Mass flux curves showing a late cataclysm depend critically on an assumed age of ~3.9 Ga for Nectaris to create a sharp rise in the accretion rate at this time. In addition, crater density populations on the large lunar basin deposits and dynamical evolution models tend to favor a late increase in mass flux if Nectaris is ≤4 Ga, but provide little support for a late cataclysm if Nectaris is as old as ~4.1-4.2 Ga. However, the age of Nectaris now appears to be unconstrained by the lunar sample data, in contrast to previous conclusions. A robust test of the late cataclysm hypothesis will require an accurate absolute age for one or more of the older lunar basins. Obtaining these ages will be a high priority goal in the next phase of lunar exploration.

This research was published as:


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Experimental phase and melting relations of metapelitic rocks in the upper mantle – implications for the petrogenesis of intraplate magmas

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The return of extensive volumes of crustal material to the mantle is an inevitable consequence of long-lived plate tectonics on Earth. Accordingly, previously subducted materials may collectively represent a significant proportion of the mantle and may strongly influence its geochemical inventory and the production of mantle-derived magmas. Some distinctive enriched components detected in primitive oceanic basalts have been attributed to the presence in the basalts’ upper mantle source of recycled pelitic sedimentary material, recycled back into the convecting upper mantle via subduction zones.

To examine the melting behaviour and phase relations of sedimentary rocks at upper mantle conditions, we performed a series of piston-cylinder experiments on a synthetic pelite starting material over a pressure and temperature range of 3.0 to 5.0 GPa and 1100 to 1600 °C. The anhydrous pelite solidus is between 1150 and 1200 °C at 3.0 GPa and close to 1250 °C at 5.0 GPa, whereas the liquidus is likely to be at 1600 °C or higher at all investigated pressures, giving a large melting interval of over 400 °C. The subsolidus paragenesis consists of quartz/coesite, feldspar, garnet, kyanite, rutile, ±clinopyroxene ±apatite. Feldspar, rutile and apatite are rapidly melted out above the solidus, whereas garnet and kyanite are stable to high melt fractions (>70%).

Our results indicate that sedimentary protoliths entrained in upwelling heterogeneous mantle domains may undergo melting at greater depths than mafic lithologies to produce ultrapotassic dacitic melts. Such melts are expected to react with, and metasomatise, the surrounding peridotite, which may subsequently undergo melting at shallower levels to produce compositionally distinct magma types. This scenario may account for many of the distinctive geochemical characteristics of EM-type ocean island magma suites.
Tracking Formation and Transport of Apollo 16 Lunar Impact Glasses through Chemistry and Dating

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Lunar impact spherules are micron to centimetre sized glass particles formed during impact events where shock induced melting of the lunar regolith and impactor produce melt splashes that can be deposited locally or be ejected far beyond the point of impact. These particles can be found within the lunar soil and in microbreccias and are a medium from which we can study lunar chemistry and impact history.

We have separated over 900 lunar spherules from the Apollo 16 fines, 66031. Using new mounting and analysis techniques we have obtained major and trace element compositions while preserving the maximum volume of sample for $^{39}$Ar/$^{40}$Ar dating on single particles. Petrographic descriptions and dimensions were obtained for 272 lunar glasses greater than 75µm in diameter along with major element compositions. Trace element compositions were obtained for a total of 164 lunar impact spherules. Thirty of these spherules were further selected for radioisotopic dating using the $^{40}$Ar/$^{39}$Ar method. Twenty-two of the dated spherules gave statistically acceptable $^{40}$Ar/$^{39}$Ar isochrons and plateaus, allowing us to develop the first impact flux for local impact spherules at the Apollo 16 site (See Figure 1.) complementing previous work at Apollo 12 (Levine et al., 2005) and 14 (Culler et al., 2000). This is the first time such an integrated dataset has been collected for lunar impact spherules. This additional resolution allows us to determine contributions to the impact flux from local and exotic events and identify groups of impact spherules that may have been formed from a single impact. Our results show that 13-17 unique impact events may have produced the twenty-two spherules that were dated at our site, depending on how the groups are identified. Our approach has shown that there is potential to suppress apparent peaks on the impact age distribution, as seen by lunar impact spherules, and increase the apparent contribution of spherules from exotic sites.

Results of this study were presented at the 9th Australian Space Science Conference, Sydney, Australia, 28th September – 30th September 2009.


Figure 1. Fig 1. Bombardment history as shown by ideograms created using the lunar impact spherule flux from Apollo 12 (Levine et al., 2005), Apollo 14 (Culler et al., 2000) and Apollo 16 (this study). The shaded regions in the Apollo 16 histogram indicate the presence of exotic impact spherules.
Visiting Fellows

Geological exploration of Australia in the early 19th century
An account of the Baudin expedition

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Following the establishment of the first European settlement in New South Wales, geological investigations were carried out by interested amateurs including naval officers and educated citizens. The first university trained geologists to visit Australia were members of the French expedition commanded by Nicolas Baudin in 1801-1803. My research into the scientific work of this expedition has involved the study of manuscripts and early publications in archives, museums and libraries in both Australia and France and visits to the localities around Australia’s coastline where the French naturalists carried out their investigations.

The Baudin expedition’s scientific investigations in Australia provided the first insights into the geological constitution of this hitherto unexplored landmass and contributed to a better understanding and appreciation, among European scientists, of the global extent of some geological processes and the formation of major rock formations.

The science of geology was, at that time, still in its infancy. The identification of minerals was imprecise and the classification of rocks was disputed. The expedition’s geologist, Louis Depuch and Charles Bailly, followed a four-fold scheme of rock classification taught by the famous French geologist Déodat de Dolomieu. This recognised primary rocks, such as granite; secondary rocks, such as stratified sandstone and limestone; alluvium; and volcanic rocks, such as basalts. The French geologists’ recording of these four categories of rocks in Australia confirmed their world-wide distribution. Together with the zoologist François Péron, who also carried out geological investigations, the French travellers were the first to establish the presence of a chain of highlands along the eastern coast of the Australian continent, they noted evidence of past sea level changes and the presence of living molluscs, long extinct in Europe. While many of their discoveries in Australia confirmed that the explanation and interpretation of geological features in Europe could be applied on a global scale, their findings suggested that some long-held European views about the universality of geological processes might need to be changed.
Planetary Crusts: Their Composition, Origin and and Evolution

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Planetary Crusts is the first book to explain how and why planets and satellites develop crusts. It presents a geochemical and geological survey of the crusts of the Moon, Mercury, Venus, the Earth and Mars as well as the distinct crusts of the asteroid Vesta and the major satellites of the giant planets. Spanning a much wider compass than mere description of the diverse crusts encountered in the solar system, the book begins with a discussion of the nature of solar system bodies and their formation. The authors then adopt a comparative approach to investigate the many controversies surrounding the development and evolution of planetary crusts. The authors conclude that stochastic processes dominate crustal development and the book ends with a discussion of the likelihood of Earth-like planets and plate tectonics existing elsewhere in the cosmos. The following comments are from a review by W. Bruce Banerdt (Jet Propulsion Laboratory) in Nature Geoscience Vol 2, 237 April 2009: "The authors ultimate conclusion is a cautionary tale for advocates of comparative planetology. They argue that planetary formation and evolution is governed by essentially random processes. The implications of the book’s conclusions for the search for ‘Earth-like’ planets are profound. It is not enough for a planet to be of the correct size and to orbit a star at the right distance. Even a composition similar to Earth’s will not guarantee an Earth-like environment. We now know that the details of crustal formation are a key to many of the attributes of our planet that make it so agreeable, and if Taylor and McLennan are correct, the evolutionary preconditions for the environment that exists on the Earth’s surface appear to be absurdly improbable. When it comes to forming planets and their crusts, it seems that God does indeed play dice."