Earth Chemistry

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 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

The J5 building extension was completed in 2008. The project involved doubling the length of the extant building and adding a second floor to house offices, a seminar room (The D. H. Green Room), and geochemistry laboratories. Starting in July, SHRIMP II was moved from J3 to its new position in the J5 SHRIMP building and is now operational again. Construction of SHRIMP SI has now recommenced and is proceeding well with expectations of testing in mid 2009. The fit out of the J5 chemistry laboratories is underway with installation of extraction hoods nearly complete. These laboratories will be established under the direction of Dr Yuri Amelin. The completion of the office space upstairs sees a focal point for the Planetary Science Institute at RSES.

Personnel

Dr Stewart Fallon joined Earth Chemistry in 2008. In January 2009, Dr Vickie Bennett will be taking leave of absence from RSES to take up a position at Johnson Space Center, Houston.

The SHRIMP team, comprising Dr John Foster, Dr Peter Holden, Mr Peter Lanc, Mr Ben Jenkins, and Mr Norm Schram, received a Vice Chancellor’s Award for Innovation and Excellence in Service Quality for 2008.

PhD studies were completed by Diane Valente, Courtney Gregory, and Joe Hiess. Congratulations Doctors.

Postgraduate studies were commenced by Ms Heejin Jeon [supervised by Dr Ian Williams], Mr Alexandr Stepanov [Dr Daniela Rubatto], Mr Jung Woo Park [Professor Ian Campbell].
U-Pb ages of angrites

Yuri Amelin1 and Tony Irving2

1Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
2Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA

Angrites form a small but remarkable group of meteorites. These very old differentiated achondrites experienced much less secondary processing than most meteorites, and their peculiar mineralogy and geochemistry facilitates precise dating with several isotopic methods. The group includes a variety of the specimens, ranging from “basaltic” rocks with prominent vesicles that formed rapidly quenched melts, to plutonic igneous rocks with cumulate textures and annealed plutonic rocks. Recent findings of new angrites, mainly in the deserts of northwest Africa and in Antarctica, increased their number from one in 1970’s (Angra dos Reis, or AdoR, originally the prototypical meteorite of this group, which is now considered an anomalous angrite) to 16 in 2008.

Angrites are singularly well suited to serve as benchmarks of the early Solar System chronology. The ages of some of these meteorites were determined in 1970’s to early 90’s, and AdoR has been long known as one of the oldest rocks in our Solar System, but precision and accuracy of these dates are insufficient for constructing a detailed timescale of the early Solar System events. The ages of recently found angrites were not known at all. Recent developments in Pb isotopic analysis of meteorites: using 202Pb-205Pb double spike optimized for isotopic dating, and a new procedure for efficient removal of common Pb, provides a background for revisiting and refining chondrite chronology.

Precise U-Pb ages for seven angrites are determined with double spike (202Pb-205Pb) thermal ionization mass spectrometry. The data for three angrites with well preserved U-Pb isotopic systems are shown in Fig. 1. The implications of these ages are threefold. First, they demonstrate that AdoR and LEW are not coeval, and the group of “slowly cooled” plutonic angrites is genetically diverse. Second, the new age of LEW suggests an upward revision of 53Mn-53Cr “absolute” ages by 0.7 Ma. Third, a precise age of D’Orbigny allows consistent linking of the 56Mn-53Cr and 26Al-26Mg extinct nuclide chronometers to the absolute lime scale.

Furthermore, these data show that the angrite parent body underwent prolonged high temperature igneous (both volcanic and plutonic) activity and metamorphism for at least 7 Ma during a period very early in solar system history. It is difficult to conceive of a thermal mechanism by which this could be accomplished unless the parent body was a relatively large, differentiated planet.
Figure 1. Pb isotopic data for pyroxenes from Angrites AdoR and LEW 86010, and pyroxenes and whole rock fractions from D’Orbigny, plotted in a $^{207}$Pb/$^{206}$Pb vs. $^{204}$Pb/$^{206}$Pb isochron diagram, and the weighted average $^{207}$Pb*/$^{206}$Pb* ages.
Tungsten isotopic compositions of presolar silicon carbide grains: implications for $^{182}$Hf-$^{182}$W and $^{187}$Re-$^{187}$Os chronometers

J. N. Avila, T. R. Ireland, F. Gyngard, S. Amari, E. Zinner

Research School of Earth Sciences and Planetary Science Institute, The Australian National University, Canberra ACT 0200, Australia. Laboratory for Space Sciences and Physics Department, Washington University, St. Louis, MO 63130, USA.

The $s$-process nucleosynthesis in the Hf-Ta-W-Re-Os path has received considerable attention lately (Fig. 01). New neutron capture cross-sections for $^{174,176,177,178,179,180,182}$Hf, $^{184,185}$W and $^{184,186,187,188}$Os have been reported (Sonnabend et al., 2003; Mosconi et al., 2006; Wisshak et al., 2006; Vockenhuber et al., 2007), and small anomalies in W and Os isotopes have been observed in primitive meteorites (Brandon et al., 2005; Yokoyama et al., 2007; Qin et al., 2008). However, as suggested by Vockenhuber et al. (2007) and Sonnabend et al. (2003), model calculations for $s$-process nucleosynthesis appear to underestimate $^{182}$W and overestimate $^{186}$Os, and this may have implications for the $^{182}$Hf-$^{182}$W and $^{187}$Re-$^{187}$Os chronometers. Tungsten isotopes are particularly important because they are affected by several branching points ($^{182}$Ta, $^{184}$Hf, and $^{186}$W), which also affect Re and Os isotopes. Here we report W isotopic measurements in presolar SiC grains in order to provide additional constraints on $s$-process nucleosynthesis.

$^{182,183,184,186,189}$W and $^{180}$Hf were measured with SHRIMP RG at ANU in an aggregate of presolar SiC grains (KJB fraction) extracted from the Murchison meteorite (Amari et al., 1994). Tungsten isotopes were measured as WO$^+$ ions, which have a higher yield than the atomic species (WO$^+$/W$^+$ ~ 3). An O$^+$ primary ion beam of 5 nA was focused to sputter an area of 20 mm in diameter. SHRIMP RG was operated at a mass resolving power of $m/\Delta m$ = 5000 (at 1% peak). At this level, isobaric interferences were well resolved from the WO$^+$ species. NIST silicate glasses and synthetic SiC were used to monitor instrumental mass fractionation and isobaric interferences.

The W isotopic compositions are anomalous in comparison to those observed in normal solar system materials. The SiC grains appear to be enriched in $^{182}$W and $^{184}$W relative to $^{183}$W, as expected for $s$-process nucleosynthesis in AGB stars (e.g. Qin et al., 2008). However, an unexpected enrichment in $^{186}$W is observed. The low $^{180}$Hf/$^{186}$W ratios determined here imply a low contribution from radiogenic $^{182}$W after SiC condensation, otherwise the $^{186}$W excesses would be even higher. The enrichment in $^{182}$W appears to be plausible, given the observation that the calculated $r$-process residue of $^{182}$W ($N_r = N_s + N_u$) has a significant positive deviation from the smooth $r$-abundance distribution (Wisshak et al., 2006; Vockenhuber et al., 2007). A lower $r$-process component of solar $^{182}$W would imply a shorter time interval between the last $r$-process contribution to solar $^{182}$Hf and the formation of solid parent bodies (Vockenhuber et al., 2007).

As discussed by Sonnabend et al. (2003), the stellar $s$-process model shows a 20% overproduction of $^{186}$Os, and consequently it underestimates the $s$-process contribution to $^{187}$Re. The enrichment observed in $^{186}$W requires the activation of the $^{186}$W branching point during AGB thermal pulses, when marginal activation of the $^{22}$Ne($\alpha$,n)$^{25}$Mg source produces neutron densities as high as $N_n = 5 \times 10^7$ neutrons cm$^{-3}$ (Lugaro et al., 2003), bypassing $^{186}$Os. This result is in disagreement with $^{96}$Zr depletions in SiC grains, which indicate that the $^{22}$Ne($\alpha$,n)$^{25}$Mg source was weak in their parent stars (Nicolussi et al., 2003). However, the overabundance of $^{186}$Os could also be the result of uncertainties in the nuclear physics data.


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*Figure 1.*
Questions of the antiquity and volumes of Earth’s ancient continental crust have been actively debated for more than 100 years and remain controversial. One view is that massive amounts of continental crust formed very early in Earth’s history and persisted to the present, with new crustal growth balanced by recycling into the mantle. In direct contrast are models calling for progressive growth of the continental mass over geologic time, with small volume early continents. These debates take on added significance when considered in conjunction with potential early life habitats and the timing and mechanisms of formation of Earth’s major chemical domains after the initial stages of planetary accretion.

We have taken a new perspective on Earth’s early history by combining information from two isotopic systems ($^{176}\text{Hf}/^{176}\text{Hf}$ formed from decay of $^{176}\text{Lu}$; half-life=37.1 Gyr) and $^{142}\text{Nd}/^{144}\text{Nd}$ (formed by decay of now extinct $^{146}\text{Sm}$; half life = 103 My), whose signatures are preserved in the oldest rocks. The analysed samples include 3.63−3.87 Ga (billion years old) rare, early crustal relicts from southwest Greenland, Western Australia, and China. Hafnium isotopic data from well-characterised and U-Pb dated zircons extracted from these rocks show that the oldest rocks have initial Hf isotopic compositions that are the same as bulk Earth and primitive meteorite compositions (Hiess et al., in review), indicating that the source of these rocks did not experience early Lu/Hf modification. In contrast the $^{142}\text{Nd}$ isotopic compositions measured from the same rocks as yielded the zircons, are distinct from both modern rocks and from primitive meteorites (Bennett et al., 2007) requiring Hadean Sm/Nd fractionation.

Modelling of the trace element pattern of the Hadean (>4.0 Ga) mantle, as defined from the combined isotopic data, shows that it could not have been generated by extraction of average low Sm/Nd, low Lu/Hf continental crust (Figure 1). This is in contrast to the modern Earth, where the continental crust and the upper mantle have complementary isotopic and trace element characteristics. Thus, continent formation could not have been the primary mechanism of differentiation on the Hadean Earth. Furthermore, owing to the effectiveness of crust formation at changing Lu/Hf ratios, the near-chondritic Hf isotopic data require that the preserved earliest continents were of very limited extent, likely less than 5% of the present day continental mass. The chemistry of the Hadean mantle as recorded by the short and long half-life isotopic systematics of the oldest rocks points towards models of early silicate differentiation in a global terrestrial magma ocean.


Figure 1.

Modern MORB mantle resulting from extraction of complementary low Sm/Nd and low Lu/Hf continental crust.

Sample/primitive mantle

Hadean mantle as required by Hf and Nd isotopic compositions of oldest rocks.

(this study)
Integrating community proteogenomics and lipid biogeochemistry to unravel ancient evolutionary history

Jochen J. Brocks¹ and Jillian Banfield

¹Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
²Dept. of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA

The first appearance of a metabolic pathway that allowed microorganisms to exploit a new and previously untapped energy source, such as methanogenesis, sulfate reduction and photosynthesis, must have had profound effects on the chemical composition of the atmosphere and oceans. It is a captivating goal of geobiology to determine when such physiologies first appeared in Earth history and to correlate these events with the associated chemical and isotopic changes in the rock record. One of the best methodologies to track the first appearances of microorganisms in the geological record is the search for biomarker molecules. Biomarkers can be preserved in billion years old sedimentary rocks and are often the only direct methodology to study ancient microbial ecosystems. If we want to match biomarkers from ancient rocks with the organisms that produced them we rely on information about lipids detected in extant organisms grown in cultivation. However, currently the vast majority of all microorganisms defies isolation, and their lipid biosynthetic capacities, as well as their roles in ecosystems, remain largely obscure. Consequently, our knowledge about the distribution of biomarkers in nature remains highly fragmentary.

Figure 1 shows how environmental genomics and proteomics on natural microbial consortia may help to solve the problem. It summarizes how these methodologies could be combined with lipid biogeochemistry to assemble a phylogenetic tree of the three domains of life where all nodes are (roughly) dated, all branches are annotated with a complete set of lipids that are produced by each lineage, and each lineage is linked to the sequences of the genes required for their biosynthesis. Development and use of phylogenetic trees for lipid genes and their products should provide quantitative data about the frequency of lateral gene transfer and convergent evolution in lipid biosynthetic pathways, and should allow us to determine a level of confidence with which a biomarker from a well-dated ancient rock can be assigned to a particular biological origin.


Figure 1. With nearly completely reconstructed genomes and the knowledge which genes were expressed at the time when the sample was taken, it should, in principle, be possible to assign each lipid detected in a 'community lipidome' to an organism or group of organisms in the consortium, even if these organisms cannot be isolated and grown in culture: DNA is extracted from a natural sample, fragments are sequenced and sequences assembled to reconstruct (near) complete genomes of all dominant (>5% relative abundance) bacteria and archaea. Genes involved in lipid biosynthesis are identified and primary protein structures predicted based on base sequences. Proteins involved in lipid biosynthesis that were extracted from the same environmental sample can then be identified based on predicted primary protein structures and assigned to individual organisms. Based on enzymes that are part of well-studied lipid biosynthetic pathways and that were detected in the environmental sample, it should be possible to predict major lipid end-products and, thus, to assign actual lipids in the environment to individual organisms or group of organisms. The identification of lipids of organisms that defy isolation may significantly improve our understanding of the sources and environmental significance of fossils lipids in the geological record.
Atmospheric oxygen concentrations in the Earth’s atmosphere rose from negligible levels in the Archaean Era to about 21% at present day. This increase is thought to have occurred in six steps, 2.65, 2.45, 1.8, 0.6, 0.3 and 0.04 billion years ago, with a possible seventh event identified at 1.2 billion years ago. The timing of these steps correlates with the amalgamation of Earth’s landmasses into supercontinents. We suggest that the continent–continent collisions required to form supercontinents produced chains of supermountains. These supermountains eroded quickly and released large amounts of nutrients such as iron and phosphorous into the oceans, leading to an explosion of algae and cyanobacteria, and thus a marked increase in photosynthesis, and the photosynthetic production of O₂.

Enhanced sedimentation during these periods promoted the burial of a high fraction of organic carbon and pyrite, thus preventing their reaction with free oxygen, and leading to sustained increases in atmospheric oxygen.
Hf isotopes in rutile measured in-situ by LA-MC-ICPMS

Tanya Ewing1, Daniela Rubatto1, Jörg Hermann1 and Steve Eggins1

1 Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Hf isotopes are commonly measured in zircon and used to trace input from different mantle reservoirs and crustal components. In contrast, the Hf isotope systematics of rutile (TiO₂), a common accessory mineral in a variety of geological settings, are relatively unexplored.

The recent studies of Choukroun et al. (2005) and Aulbach et al. (2008) have revealed that rutile records a much greater range of ¹⁷⁶Hf/¹⁷⁷Hf ratios than is seen for zircon. These studies have also highlighted the potential for the in-situ measurement of Hf isotopes in rutile using Laser Ablation Multi-Collector Inductively Coupled Mass Spectrometers (MC-LA-ICPMS). However, as yet no detailed study of the accuracy of these in-situ measurements for rutile has been made. As rutile contains very low levels of Hf compared to zircon, proving the reliability of in-situ Hf isotope measurements is a critical first step in exploring the potential of this method to contribute to petrological studies.

We have used a number of approaches to assess the accuracy, precision and limitations of in-situ analysis for Hf isotopes in rutile, as well as refining analytical and data reduction methods for analysis of low levels of Hf. Some novel adaptations have been made, such as the use of synthetic rutiles doped with Hf to monitor change in mass bias over the course of a session and provide an external correction factor where required.

The accuracy of Hf isotope measurements for rutile on our Neptune MC-ICPMS in laser ablation mode is demonstrated by comparison with solution MC-ICPMS values for a rutile containing c.30ppm Hf. The ¹⁷⁶Hf/¹⁷⁷Hf values obtained from the two methods were in excellent agreement. Accuracy is confirmed by the agreement of ¹⁷⁶Hf/¹⁷⁷Hf values for plutonic rutile and zircon – which should record the same Hf isotope signature in an igneous system – from a single trondjhemite sample.

The precision of individual rutile analyses is lower for laser ablation than for solution analyses, but combining populations of 10 to 15 analyses to give a weighted mean significantly improves the precision. This level of precision has proved ample to distinguish between different rutile samples, or between rutile and other minerals that record a different Hf isotope signature.

It is already clear that in-situ Hf isotope measurements for rutile may have exciting applications to petrological problems. An early case study on rutile and zircon from the Duria garnet peridotite has demonstrated that Hf isotope analysis of metamorphic rutile can provide complementary information to isotopic information obtained from zircon. LA-MC-ICPMS analyses of zircon and rutile from the Duria peridotite revealed clearly distinct Hf isotopic ratios for the two minerals: the rutile records a mantle signature, whereas zircon isotopic ratios provide evidence for crustal input. This is in keeping with the metamorphic history of the peridotite as determined by Hermann et al. (2006) based on petrographic analysis and trace element geochemistry. The ability to analyse Hf isotopes in rutile therefore allows us to access isotopic information about parts of the metamorphic history that are not recorded by zircon.


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**Figure 1.** (left) Large thin section of garnet (grt) megacryst including numerous large rutiles (rt). Using LA-MC-ICPMS, Hf isotopes can be measured in-situ for rutiles in this thin section. Areas of interest for analysis have been circled in black pen.

**Figure 2.** (Right) Close-up photo of rutiles (rt) included in garnet (grt) in the thin section shown in Fig. 1.
A simple radiocarbon dating method for determining the age and growth rate of deep-sea sponges

Stewart Fallon¹, Kelly James¹, Rebecca Norman¹, Michelle Kelly² and Michael Ellwood¹

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² National Centre for Aquatic Biodiversity & Biosecurity, National Institute of Water & Atmospheric Research (NIWA) Ltd, Auckland, New Zealand

While radiocarbon-dating is a well established technique in aging marine carbonates, the ability to reliably age siliceous organisms remains largely unexplored. Attempts have been made to carbon date the proteinaceous material bound within fossil diatoms frustules isolated from sediment cores [1,2] and siliceous sponges [3]. The proteinaceous material bound within siliceous spicules is potentially a new and exciting way to age sponges and to date sediments devoid of carbonate material. Indeed the carbon dating of siliceous spicules in the Southern Ocean where carbonates are absent, or not well preserved, could help to validate paleoceanographic and paleoclimatic proxies and further elucidate physical and chemical changes within the oceans interior.

As filter-feeding organisms ubiquitous to the world’s oceans, marine sponges obtain carbon from the food they consume, incorporating low levels (0.05%) into the spicules they produce. The carbon intrinsically incorporated into the spicule matrix from the surrounding water, is protected from contamination and can potentially provide dates in opal rich sediment cores as well as providing information on extension rates in living siliceous organisms. The following is an interpretation of ¹⁴C analysis by accelerator mass spectrometry to constrain currently unknown growth rates of deep-sea sponges.

The Ross Sea sponge (TAN0402/67) was sub-sampled and cleaned using either sequential acid digestion alone, or acid digestion followed by roasting. Samples cleaned using sequential acid digestion alone needed to be placed inside a second quartz tubes to confer sufficient strength for combustion. In certain cases, these samples contained significantly more carbon than anticipated (Figure 1a). Elevated percentage carbon is attributed to insufficient removal of contaminant carbon (sponge tissue) by omitting the pre-roasting step.

The results for the percentage of carbon extracted and Δ¹⁴C for samples where pretreatment included incremental increases in roasting temperatures is presented in Figure 2b. These results indicate that the optimal roasting is >400 °C. Above this temperature all the external carbon is removed yielding low but consistent results for both percentage carbon recovered and the radiocarbon Δ¹⁴C results for proteinaceous material bound within the siliceous matrix (Figure 1b). The age results for sponge TAN0402/67 collected from the Ross Sea are presented in Figure 1c. A linear increase in age versus length was obtained for this sponge, although there is a significant water reservoir affect on the radiocarbon results.

The estimate Δ¹⁴C value for organic carbon consumed by the sponge is about –150‰ based on modern organic carbon sedimentation in the Ross Sea. Our Δ¹⁴C results for the outer part of the sponge, at about –140‰, are close to the modern organic carbon sedimentation value thereby confirming that the sponge faithfully records the Δ¹⁴C signature of the organic carbon it consumes. After correcting for the reservoir age of the water, the extension rate for this sponge is around 2.9 mm yr⁻¹. Using this extension rate and a length 15 cm along the axis of growth, we estimate that sponge TAN0402/67 is around 440 years old. This novel technique for elucidating extension
rates in sponges and more broadly for dating siliceous organisms is testament to the broad applications of $^{14}C/^{12}C$ ratios by accelerator mass spectrometry as both a paleo- and modern oceanographic tool.


**Figure 1.** A) Percentage carbon versus length for samples oxidised with sequential acid digestion (acid digested) and acid digested followed by combustion at 450 °C for 12 hours (Roasted). B) Percentage carbon and $\Delta^{14}C$ versus roasting temperature. Sample points are the mean of two replicates while the error bars indicate the range.

**Figure 2.** Radiocarbon age versus length along the axis of growth for samples removed from sponge TAN0402/67. The red square indicates a sample that was not included in the calculation of sponge extension rate.
Argon enters the retentive zone: 
Reassessment of diffusion parameters for K-feldspar

Marnie Forster¹ and Gordon Lister¹

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

“Ar/Ar apparent age spectra have been measured for unusually retentive potassium feldspars from the South Cyclades Shear Zone, Ios, Greece. The data obtained helped constrain the age and duration of the operation of this crustal-scale shear zone. We investigated traditional methods used to analyse Arrhenius plots by simulating the effect of step-heating experiments on argon loss. Fractals were used to define theoretical distributions of diffusion domain size and volume, allowing recognition of a Fundamental Asymmetry Principle (FAP) which is required if line fitting is to be consistent with the multi-domain diffusion hypothesis. The FAP means that a fitted line must divide the population by rank order. Points from data obtained earlier in the sequence of step heating experiments must lie on the fitted line, or to the right of it. Points from data obtained later in the sequence must lie on the fitted line, or to the left of it. Applying the FAP has lead to the estimation of higher activation energies.

To understand whether these results are limited, for example, to the K-feldspars from this study, data from previously published papers was examined (Fig. 1a), including data from the UCLA archive. The results obtained, using multi-domain diffusion modelling (Lovera et al. 1997) led us to an in depth look at the method and the fundamentals behind these methods. Analysis of Arrhenius data should take account of the Fundamental Asymmetry Principle since this is an inherent part of any multi-domain diffusion model. Results showed that if the Fundamental Asymmetry Principle is not applied (Fig. 1a b), numerical analysis will invariably underestimate the value of activation energy used in simulating the effect of step-heating experiments on fractal volume-size distributions (Fig. 1c d).

It was found that the application of the Fundamental Asymmetry Principle, determined from modeling using eAr software makes a considerable difference in respect to the magnitude of the activation energies estimated. The average of activation energy for K-feldspar is significantly higher than previously reported. These results imply that the Argon Partial Retention Zone for the most retentive domains in K-feldspar can expand into the ductile regime (i.e. with temperatures ~400-450°C), as recorded for the South Cyclades Shear Zone (Fig 1e). This means that K-feldspar can routinely be used as a geochronometer to estimate the timing and duration of events in complexly deformed terranes.


Figure 1. Arrhenius plots where (a) activation is calculated at 46.5 kcal/mol (Baldwin & Lister 1998). The fundamental asymmetry principle (FAP) has not been followed in this calculation and the activation energy is incorrect; (b) when the FAP is applied to this same plot the calculated activation energy is much higher, 60.2 kcal/mol; (c) mathematical calculation using the fractal cube and Menger sponge (d) [http://members.cox.net/fathauerrecent/FractalCrystal.html](http://members.cox.net/fathauerrecent/FractalCrystal.html) (http://en.wikipedia.org/wiki/Menger_sponge) used in the mathematical representation of the Arrhenius plot; (e) A Temperature / Time plot show the region where the shear zone is at rest and where the shear zone operated, temperature calculated from mineral paragenesis.
Behaviour of allanite during incipient partial melting in the Southern Central Alps

Courtney Gregory1, Daniela Rubatto1, Jöerg Hermann1 and Alfons Berger2

1 Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
2 Institute of Geological Sciences, University of Bern, CH-3012 Bern, Switzerland

The chemical and U-Th-Pb isotopic behaviour of accessory allanite during incipient partial melting was investigated in a field-based study of upper-amphibolite facies migmatites in the southern Central Alps (Switzerland). Orthogneiss and leucosome sampled from the core of the migmatite zone (peak T of ~680–720°C) to its limit (T ~650°C), contained both zircon and allanite, which permitted a comparison of U-Th-Pb systematics in these phases.

Allanite found in orthogneiss showed complex internal zoning (see backscatter electron or BSE image in Fig. 1), suggestive of multi-stage growth. Bright BSE cores with high La/Lu and Th/U and low Eu/Eu* chemical signatures yielded Permian ages and thus were inherited from the pre-Alpine magmatic protolith. In contrast, chemically distinct overgrowths and single grains gave age populations between 30 ± 1 Ma and 23 ± 1 Ma in line with an Alpine metamorphic origin. Textural and inclusion relationships with major melt-formed minerals and their LREE-depletion supports the interpretation that allanite was an anatectic phase. Further evidence is provided by comparing magmatic and metamorphic mineral Eu compositions (Fig. 1).

Plagioclase did not impose a negative Eu anomaly on co-existing metamorphic phases because 80-90 % of the bulk-rock Eu was actually hosted in metamorphic allanite and titanite. To account for this, it is suggested that metamorphic allanite and titanite formed during feldspar breakdown, which would have occurred above the wet solidus for this system (i.e. at T > 650°C).

The inheritance of Permian cores provides first hand evidence for minimal Pb diffusion in allanite during Alpine partial melting (i.e. ~7 million years above 650°C). Importantly, in samples where co-existing zircon had rare or limited metamorphic overgrowths (i.e. at T < 700°C), allanite was the only accessory mineral chronometer that recorded the Alpine event. The U-Th-Pb system in allanite therefore presents a solid, complementary approach for the geochronology of low-temperature (~650-700°C) partial melt processes in the crust.

Accepting allanite as a melt-product, the youngest U-Th-Pb age obtained from a discordant leucosome indicates that the Alpine melting regime lasted over several million years (until 23 Ma) and later than previously accepted. Combined with previous constraints, the prolonged high temperature evolution down to 23 Ma requires a subsequent period of fast cooling (~100 ± 20°C/Ma) for the studied samples.
Figure 1
An inclusion suite of “granitic” phases within 3.81 Ga tonalite zircons: Restrictions for studying Hadean crustal evolution with detrital zircons

Joe Hiess¹ and Allen P. Nutman²

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Institute of Geology, Chinese Academy of Geological Sciences, 26 Baiwanzhuang Road, Beijing 100037, PR China

Petrogenetic interpretation of Hadean detrital zircons is problematic, because their source rocks are no longer preserved. Tonalites represent the dominant component of Eoarchaean (3500–4000 Ma) crustal rocks and therefore form an important reference point for the interpretation of Hadean detrital zircons, and Earth’s earliest crustal evolution.

We conducted an electron microprobe survey of inclusions contained within igneous zircons from the best-preserved ca. 3810 Ma meta-tonalite sample G97-18 from West Greenland. Crystalline inclusions were K-feldspar, plagioclase, quartz, hornblende, biotite, ilmenite and apatite. Additionally, one globular polymineralic inclusion interpreted as crystallised melt occurs at the surface of a polished grain mount (Fig. 1). This consists of plagioclase + quartz + K-feldspar around a biotite lath. Other similar, but rare globular inclusions were seen buried within other zircons below the polished surface. These phases, particularly the presence of K-feldspar and plagioclase in broadly equal amounts, suggest the zircons crystallised from a residual granitic (sensu-stricto) melt, as opposed to a tonalitic melt. SHRIMP U-Pb dating of zircons with inclusions indicates that they grew at ca. 3810 Ma, the accepted igneous age of the rock.

This inclusion suite is compatible with the low Ti-in-zircon temperatures for G97-18 igneous zircon (Hiess et al., 2008). Therefore, low Ti-in-zircon temperatures and “granitic” inclusions reported for Hadean detrital zircons do not necessitate crystallisation from low temperature granites. Such features could also be found within Hadean zircons that crystallised late from a higher temperature zircon-undersaturated melt of tonalitic composition.


Figure 1. Cathodoluminescence (CL) and transmitted light (T) images for a single globular polymineralic inclusion exposed at the mount surface (at least one more appears to be present at depth in other grains), interpreted as a crystallised melt inclusion. Shown to the right is an enlarged back-scattered electron image of the globular inclusion. Note that the lower edge of the biotite is altered to chlorite. Errors on SHRIMP 207Pb/207Pb ages (Ma) are 2.
The processes that mobilise gold through the Earth's crust and concentrate it in ore deposits have been widely debated. Most workers emphasise the importance of CO₂-H₂O fluids and phase separation or wall-rock reaction as depositional mechanisms. However, the possible importance of mantle components and the significance of CH₄-dominated fluid inclusions have been subject to speculation. The Yilgarn Terrane of Western Australia is richly endowed with gold-only ore deposits that have a low concentration of base metals, and are associated with quartz ±carbonate veins in regionally-significant, mid-crustal (3-15 km), shear zones that formed in an arc or back arc setting. Recent mapping of mineral alteration assemblages in the world class St Ives Gold Camp, in Western Australia, has shown high grade gold occurs preferentially at the intersection of 'oxidised' pyrite-magnetite-hematite-anhydrite bearing veins that are dominated by H₂O-CO₂ fluid inclusions; and 'reduced' pyrrhotite-pyrite bearing quartz veins that are dominated by CH₄ fluid inclusions.

H₂O- and CO₂-dominated fluid inclusion assemblages have maximum [Ar/Ar] values of ~21,000 (Fig. x-a) and ppb 36Ar concentrations, consistent with the involvement of magmatic fluids. Based on the fluid inclusion abundances, this suggests Cl must be present as HCl in CH₄ as well as NaCl in rare H₂O fluid inclusions. Provided Cl has a lower abundance in CH₄ than in the H₂O-CO₂ fluid inclusions, this measurement also suggests CH₄ has the lowest 36Ar concentration. As wall-rock reaction increases the 36Ar concentration of the volatile phase, this inference precludes a CH₄ source by localised reduction of CO₂. Instead, the high [Ar/Ar] value favours an abiogenic CH₄ origin in the deep-crust or mantle. The Ne isotope data reveal a mantle component in pre- to early-gold pyrites, but the quartz-hosted H₂O and CO₂ fluid inclusions are dominated by atmospheric and crustal Ne (Fig. x-b). If all these fluids had a magmatic origin, this pattern is consistent with the changing style of regional magmatism from bimodal (mafic-felsic) prior to mineralisation to dominantly Ca-poor granite during the main-stage of gold deposition. The maximum [Ne/Ne] value of 0.55 determined for CH₄-dominated fluid inclusions corresponds to the maximum [Ar/Ar] value of ~50,000. The highest [Ne/Ne] values require a source in which U is hosted by a mineral with an O/F value of greater than the upper-crustal average for U minerals. If CH₄ was generated by serpentinisation of deep-crustal mafic intrusions, the Ne data would be consistent with precursor H₂O-CO₂ fluids derived from lower-crustal rocks in which zircon or pitchblende were important U hosts.

These Ar and Ne data suggest CO₂-H₂O was derived from a lower crustal magmatic source and conclusively demonstrate that CH₄ had an independent ‘abiogenic’ origin. As CH₄ fluid inclusions or graphite are found in many gold-only ore deposits, we suggest that oxidation of abiogenic CH₄, possibly sourced from as deep as the Earth’s mantle, has been a critical and overlooked control on the formation of many of the planets largest gold deposits.
Figure 1. Fluid inclusion noble gas data for pre- to syn-gold minerals of the St Ives Gold Camp, Western Australia: a) Cl/36Ar versus 40Ar/36Ar; b) 21Ne/22Ne versus 20Ne/22Ne. The high Cl/36Ar values determined for CH₄ fluid inclusions suggest Cl is present as HCl and imply a parts per trillion 36Ar concentration. CO₂-H₂O fluid inclusions have higher 36Ar concentrations. The convergence of mixing trends and increase in 36Ar concentration is interpreted to result from fluid interaction with mafic host-rocks rich in seawater-derived noble gases. Note that few of the deeply-derived fluids have Ne isotope compositions within the light grey envelope that could be explained by mixing atmospheric or mantle Ne with ‘average-crustal’ Ne. This suggests Ne-isotope heterogeneity in the lower crust; assuming an atmospheric intercept, the best fit slope for CH₄ indicates a source region in which U-minerals have an O/F value of close to the average crustal O/F value of 752.
Contamination-free biomarker analysis of shales using oxidative microwave digestion

Janet Hope and Jochen J. Brocks

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Surficial contamination of drill core and outcrop samples with anthropogenic hydrocarbons is a common phenomenon and can compromise the analyses of molecular fossils, particularly of lean and very ancient samples. A survey studying the molecular content of the exterior and interior portions of 26 rock samples from a wide range of drill cores and outcrops, found that all samples were surficially contaminated with petroleum products [1]. For compact and impermeable rock samples, surficial contaminants can be removed by trimming of surfaces [1]. However, we demonstrated that this is not possible for fissile and fractured samples where contaminants may have entered fissures and cracks. We tested whether contaminant hydrocarbons can be removed with solvents by extracting intact pieces of diesel stained shale with dichloromethane using an Automated Solvent Extractor (ASE). After 3 extraction cycles only ~40% of the diesel was removed, demonstrating that solvent rinsing does not efficiently eliminate surficial petroleum products. In a second experiment, we subjected diesel stained shale with hot concentrated nitric acid in a microwave digestion oven. This treatment successfully removed 98.5 to 100% of the contaminant hydrocarbons from the shale.

We further tested the microwave digestion technique on a Precambrian shale. Figure 1 shows the hydrocarbons of this sample after heating of the rock in concentrated nitric acid at 180°C for 30 minutes. The treatment successfully removed nearly 100% of all contaminants while the indigenous diamondoid and polyaromatic hydrocarbons were retained. The experiments demonstrate that our oxidative microwave digestion technique is highly efficient for the removal of surficial hydrocarbons and other contaminants.

Figure 1. Mass chromatograms of the hydrocarbons of a 1.6 billion year old sample from the McArthur Basin in northern Australia. (A) Untreated sample showing a mixture of contaminants and indigenous biomarkers. (B) Predominantly indigenous hydrocarbons after treatment of the rock sample with hot nitric acid. BAOC = 5,5-diethylalkanes (branched alkanes with quaternary carbon); BHT-CHO = 3,5-di-tert-butyl-4-hydroxybenzaldehyde; Fl = fluorene; DBT = dibenzothiophene; DMP = dimethylphenanthrenes; MeFl = methylfluorenes; Me2Fl = dimethylfluorenes; MP = methylphenanthrenes; MPyr = methylpyrenes; P = phenanthrene; Phth = phthalates; Pyr = pyrene; Std = standard; • = alkyl diadamantanes; ● = alkylcyclopentanes; ◆ = n-alkanes.
We have previously reported an isotopically heavy component (5% enriched in $^{17}$O and $^{18}$O) in the lunar soil that is preserved in the top few hundred nanometers of lunar metal grains. The location of this component appears consistent with the site expected for solar wind oxygen. However, McKeegan and colleagues reported at the Lunar and Planetary Science Conference this year that solar wind appears enriched in $^{16}$O. We have carried out measurements on a larger number of grains from a variety of soils in an attempt to elucidate this discrepancy. Many more grains have been discovered with $^{17}$O, $^{18}$O enrichments with surprisingly few having $^{16}$O-rich compositions, and none around the 6% enriched composition reported by McKeegan et al. (2008). Further analyses by Hashizume and Chaussidon (2008) also reveal $^{17}$O, $^{18}$O-rich compositions in modern lunar soils, while $^{16}$O rich compositions in ancient soils are typically mass-dependently fractionated. The question then arises, what happened to the solar wind oxygen on the surface of the Moon.

We have measured Ne isotopic compositions in olivine grains from the lunar soils and these are consistent with solar wind implantation. It should therefore be expected that solar wind oxygen should be present in the surfaces of these grains. We cannot measure olivine grains for implanted solar-wind oxygen because of the high intrinsic concentration of oxygen in olivine. The issue is either the high density of the lunar metals biasing metal grains from exposure to the solar wind, or an issue of preservation. To address this, we will attempt to measure Ne in these metal grains to ascertain their exposure history. The solar wind exposure takes place at lunar surface temperatures of around 100°C. At such temperatures, oxygen diffusion is probably a major issue in retention in the lunar grains, particularly with the high flux of hydrogen carried by the solar wind. These issues will be examined with experiments on oxygen diffusion in metals under appropriate physical conditions.

While solar wind appears poorly represented in the metal grains, the component enriched in $^{17}$O and $^{18}$O is quite widespread. This component may be carried in cometary water, which is expected to have an isotopically heavy composition. The preservation of this component may be related to subsurface reaction of water with Fe metal.
Lachlan and New England fold belts are major tectonic components of eastern Australia. Because the boundary between them is totally covered by the huge Sydney basin, their tectonic relationship is unclear. However, the Carboniferous granites in the north-eastern Lachlan Fold Belt show similarities in age and composition with granites (Chappell et al., 1988) and volcanics (Shaw and Flood, 1993) in the New England Fold Belt. Based on these data, we could infer that the two fold belts might share the same basement and lower crustal structure. Therefore, our purpose is to trace the geologic history and decipher their relationship under the crust through the signature recorded in similar aged granites (Carboniferous to Permian) across the boundary between the Lachlan and New England fold belts. The combination of in situ U/Pb - O - Hf isotopic data for zircon will be a key for this study (e.g., Kemp et al., 2007).

Although a large amount of isotopic work on the granites of the Lachlan Fold Belt has been done over 30 years, there is little published work for the Carboniferous granites. Zircon from the Oberon, Bathurst and Gulgong batholiths has been dated. The ages of the granites dated so far range from ~340 to ~330 Ma. There is no simple age trend north to south, but the granites immediately west of Lithgow do appear to become younger from west to east.

Zircon has also been studied from the Banalasta (~290 Ma) and Inlet (~250 Ma) granites of the Bundarra and Moombi supersuites, respectively, in the New England Fold Belt. Zircons of Banalasta show Carboniferous cores around 330 Ma old, while those of Inlet have no old cores at all. These preliminary results are not enough to conclude, but a beautiful story would be envisaged soon because O and Hf isotopic analyses for dated zircon grains are in progress now.
Figure 1. Typical feature of Bathurst and Gulgong batholiths that contain big pink feldspar crystals.
Evolution of the Angrite Parent Body and Concordancy of Isotope Chronometers in Angrite Meteorites

Seann J. McKibbin¹, Trevor R. Ireland¹, Yuri Amelin¹, Hugh St. C. O’Neill¹

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The small achondrite meteorite clan classified as angrites have unique mineralogy, chemistry and oxygen isotopic compositions that strongly suggest they share a single parent body. They come in two broad petrologic groups: quenched ‘volcanics’ such as D’Orbigny and Sahara 99555, and ‘plutonics/metamorphics’ like LEW 86010. They are particularly suited to isotopic dating using the Pb-Pb chronometer and the short-lived (extinct) Mn-Cr system ($^{53}$Mn → $^{53}$Cr, $t_{1/2} = 3.74$ My) from which age differences between meteorites can be obtained. The angrites have yielded ages in these systems spanning a period of Solar System history critical to understanding of protoplanet formation (~4564.5 to ~4557.5 Ma from Pb-Pb).

However, concordancy between the two decay systems has been poor, with Pb-Pb isotopes recording up to 7 My of evolution between early volcanic and later plutonic varieties, while the Mn–Cr ages preserve a difference in ages of only ~5.5 My for the same meteorites [1]. To investigate this discrepancy, the Mn–Cr systematics of D’Orbigny and Sahara 99555 have been reinvestigated using the SHRIMP-RG ion-probe. Results support an early Mn–Cr age for both meteorites, and reinforce the discordancy between D’Orbigny and LEW 86010 in the Mn–Cr/Pb–Pb systems. However, the new result for Sahara 99555, along with improved agreement in the community over its Pb–Pb crystallisation age, suggests that this meteorite is concordant when compared with the younger LEW 86010 (Figure 1). This means that the two meteorites sample a common isotopic reservoir evolving in time, with no complications from diffusive closure occurring in different minerals at different times, and no later disturbance.

The emerging consensus is that angrite basalts crystallised from lava flows or a magma ocean around 4564.5 Ma, and magmatism and thermal activity continued until at least 4557.5 Ma as the protoplanet cooled. Further work will centre on angrites NWA 4590 and NWA 4801, which have not yet been dated using the Mn–Cr system.

Figure 1.
Copper concentrations in silicate mineral phases of the Boggy plain zoned intrusion

Jung Woo Park1 and Ian H. Campbell1

1 Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Understanding copper geochemistry in an evolving magmatic system is important because it may give the information about the relationship between copper mineralization and the magma and the variation of physical and geochemical condition, e.g. oxidation state and sulfur and water contents, of the magma.

Copper is a distinctively chalcophile element and therefore it strongly partitions into sulfide melts if the magma is S-saturated. However, depending on the physical and chemical condition of magma, dissolved copper in the magma as Cu+1 or Cu+2 can be trapped in a silicate mineral as an intrinsic element. Cu+2 is likely to be substituted for Fe+2 or Mn+2 in Fe-Mg silicates and Cu+1 for Na+1 in feldspar or hornblende because of their similar charge and radius (Stanton, 1994). Ewart et al. (1973) obtained 11-53 ppm copper in pyroxenes and 0-27 ppm in plagioclases of the Tonga-Kermadec volcanic island chain and found the copper levels in the plagioclases have positive correlation with whole-rock copper concentration. Wedepohl (1974) lists mean copper contents of 9.4-18, 9-17 and 2-45 ppm in amphibole, biotite and plagioclase of granitic rocks respectively.

Copper concentrations in silicate minerals were analyzed by LA-ICPMS in order to document variations in copper contents in the selected minerals during differentiation of the Boggy Plain magma, and their relationship with whole rock copper concentration.

Copper concentration in plagioclase are slightly higher in the mafic rocks of FeO+MgO>14.5 per cent, and copper contents of the northern gabbro which contains the highest whole rock copper concentration is distinctively enriched in copper compared with the felsic rocks of Boggy Plain zoned pluton (Figure 1). Except for several anomalously high copper values, the majority of them of plagioclases from outer/inner granodiorite and adamellite (FeO+MgO<14.5 %) are lower in order of 2-5 than them of mafic rocks. The mean copper contents of intermediate-felsic rocks range from 0.2 to 1 ppm showing a flat trend along with further magma differentiation. The Average values of copper concentration in plagioclase of Boggy Plain zoned pluton (0.18-2.2 ppm) is significantly less than that of the El Abra-Pajonal suite intrusion (0.4-69.1 ppm; Dianne 2008). This difference between the two suites can be partly explained by higher whole rock copper contents (12.5-5493 ppm) of the El Abra-Pajonal suite intrusion.

In order to estimate the amount of copper hosted by silicates phase, copper concentrations in other major silicate minerals are measured and mass balanced. This analysis yields silicate selective copper abundances ranging from 0.5 to 7.3 percent of whole-rock copper abundance. It indicates that the subtraction of copper by silicate crystallization is insufficient for the observed decrease of whole-rock copper in Boggy Plain rocks of FeO+MgO<14.5 per cent and the additional mechanism is required, e.g. the formation of Cu-bearing sulfide or Cu loss in vapor phase.


Figure 1. Copper concentration in plagioclase of the Boggy Plain zoned pluton. Values below detection limits are on the x-axis and numbers in the brackets are number of analysis points of them.
Dating the allanite-monazite metamorphic reaction
Daniela Rubatto¹, Courtney Gregory, Emilie Janots and Ioan Gabudianu-Radulescu

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Institute of Geological Sciences, University of Bern, Bern, Switzerland
³ Institute for Geography and Geology, Copenhagen, Denmark

U-Pb geochronology is one of the most widely used methods for the investigation of the timing of crustal processes. One main limitation of the application of U-Pb geochronology to metamorphism is the lack of direct links between the age measured and the conditions at which the dated minerals formed. In this respect, dating metamorphic reactions that can be placed in pressure-temperature space is particularly appealing.

One metamorphic reaction between U-Pb minerals that has been widely reported is the mutual replacement of allanite and monazite (figure 1 and 2). With the recent set-up of a protocol for accurate dating of allanite by SHRIMP ion microprobe (Gregory et al. 2007) it has become possible to date this reaction in-situ. We applied this method to the two geological settings where allanite-monazite reactions are most commonly documented.

1) Monazite replacing allanite is observed in prograde greenschist to amphibolite facies metamorphism of metapelites in the Central Alps (Fig. 1). Petrographic observations and thermobarometric calculations allow placing the reaction at T = 560-580°C, whereas initial allanite formation occurred at T = 430-450°C. In-situ SHRIMP U-Th-Pb dating of allanite (31.5 ± 1.3 and 29.2 ± 1.0 Ma) and monazite (18.0 ± 0.3 and 19.1 ± 0.3 Ma) constrains the time elapsed between 430-450°C and 560-580°C, which implies an average heating rate of 15-8 °C/My (Janots et al., in press).

2) During subduction-related metamorphism, the replacement of monazite by allanite is associated to increasing pressure. This is observed in the silvery micaschists of the Gran Paradiso Massif, Western Alps where microstructural relationships among major and accessory minerals indicate the following prograde sequence of U-Th bearing accessory minerals: florencite -> monazite -> allanite (Fig. 2). Thermobarometric calculations indicate that the allanite-bearing peak assemblage was stable at P = 2.3 ± 0.4 GPa and T = 570 ±30 °C, while monazite formed earlier at pressures over 2.0 GPa. SHRIMP dating of allanite yielded 34.5 ± 0.8 Ma, interpreted as the age of the high-pressure metamorphic peak. Prograde monazite yielded an age of 37.5 ± 0.9 Ma, implying a minimum duration of ~3 Ma for the Alpine subduction event (Gabudianu Radulescu et al., in press).


Figure 1.

Figure 2:
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 and Cambrian halite-bearing evaporites were investigated for their lipid biomarker content. This time frame encompasses tremendous environmental and biotic changes (e.g., major glaciations, oxygenation of the deep ocean, evolution and radiation of microorganisms, and the first appearance of animals). While previous work identified potential halophiles in the Cambrian and Precambrian, we aim to present a more detailed investigation of biotic evolution over a significant period of geologic time.

In order to assess changes in microbial ecosystems over geologic time, it is important to focus on a variety of different environmental settings. Dissimilar environments offer different ecological niches which organisms can exploit. Such niches may respond differently to environmental changes over time.

Thus far, the results look very promising and has led to the discovery of lipid biomarkers that are over 1 billion years old. I am also trying to investigate rock samples from that period that originated in shallow water, particularly hypersaline facies. So far, most investigations concentrated on deep water facies. I have collected rock samples from drill cores (Figure 1) held at Australian drill core repositories. These rocks are from shallow water facies and contain numerous evaporate (salt-bearing) sequences.

A major theme in any chemical work dealing with ancient life is the interpretation of molecules as original contemporaneous components of a rock sample or as more recent additions in the form of contamination. Therefore, I investigated techniques aimed at removing potential contaminants from rock samples. Thus far, the techniques have worked very well and helped determine which biomarkers were likely derived from the Precambrian-Cambrian interval and which samples are contaminants (e.g. from the use of drilling fluids, fingerprints etc).

![Figure 1.](image-url)
In situ oxygen isotopic analyses of zircon from granites of the Bega Batholith, south-eastern Australia

Ian S. Williams1 and Bruce W. Chappell2

1 Research School of Earth Sciences, Australian National University, Canberra, ACT 0200
2 School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522

The oxygen isotopic composition of granites is a sensitive indicator of both their source materials and the low-temperature processes that occurred as or after the magma cooled. Oxygen isotopes have been used extensively, particularly in the USA, for studies of granite genesis. Granite O isotopic compositions are normally measured on whole rocks or major minerals, but these are susceptible to late alteration. A major recent advance in the study of granite O isotopes has been the recognition that the O isotopic composition of zircon accurately reflects the O composition of the melt from which it precipitated (e.g. Monani & Valley, 2001). Because zircon grains are commonly strongly zoned and in many cases contain older cores, the ideal method of measuring the isotopic composition of the melt-precipitated components is in situ analysis by secondary ion mass spectrometry.

Over the past few years, the SHRIMP II ion microprobe has been progressively upgraded for the high precision isotopic analysis of light elements, including O. In addition, sample mounting procedures have been modified and analytical protocols developed to minimise variations in instrumental mass fractionation (Ickert et al., 2008). The resulting ability to measure the O isotopic composition of single 25 μm spots on a crystal with a precision and accuracy of better than 0.4‰ has opened up a range of new opportunities for the study of granite petrogenesis in Australia.

The Bega Batholith, SE of Canberra, consists of ~130 plutons of I-type granite covering ~8900 km². These have been grouped into a series of suites that show remarkably systematic regional changes in chemical and isotopic composition. East to west, across the elongation of the suites and the batholith as a whole, in granites of any given general bulk composition there is, for example, a systematic decrease in Na, Sr, (Al, P) and increase in Ca, Sc, (Rb, V). East to west, the granites become more isotopically evolved, initial $^{87}$Sr/$^{86}$Sr rising from 0.704 to 0.709 and eNd falling from +4.3 to -8.7 (Chappell et al., 1990). It is generally agreed that these changes are due to a westerly increasing sediment component in the magmas, but whether that originates in the lower or upper crust or mantle, and whether the magmas also contain a juvenile mantle component, are matters of vigorous debate.

The early O isotopic work done on eastern Australian granites by O'Neil and Chappell (1977) and O'Neil et al. (1977) showed a clear distinction between the whole-rock O isotopic compositions of the I- and S-type granites, consistent with the proposed contrasts in their source materials. Later Chappell et al. (1990) reported mean whole rock d$^{18}$O values for seven supersuites from the Bega Batholith ranging from 8.2 to 10.0‰. The range in individual granite compositions exceeded 6‰, some values reflecting the effects of late magmatic and/or post emplacement interaction with meteoric water.

A major study of the age and O isotopic composition of selected granites from the Bega Batholith is now nearing completion. Analyses of over 600 zircons from 30 plutons representing a range of bulk chemical compositions, mainly from the eastern and western sides of the batholith, has shown that there is a broad trend for the granites to be younger in the east than in the west. Contrary to expectations, however, with a few notable exceptions, the mean isotopic composition of the O in the granite zircons shows no clear regional trend. The range of mean O isotopic
compositions of the zircons is much smaller than the range of whole rock compositions, consistent with the expectation that the zircon isotopes are much more resistant to alteration than those in the whole rock, thereby more closely reflecting the original O isotopic compositions of the magmas. The radiogenic and stable isotopic systems in the granites appear to be for the most part decoupled.

The next stage of this project will be to measure the Hf isotopic compositions of the same spots on the same grains as have been analysed for O. In combination with the O isotopes, this is expected to give a clearer indication of the relative contribution of bulk juvenile and crustal components to the magmas.


