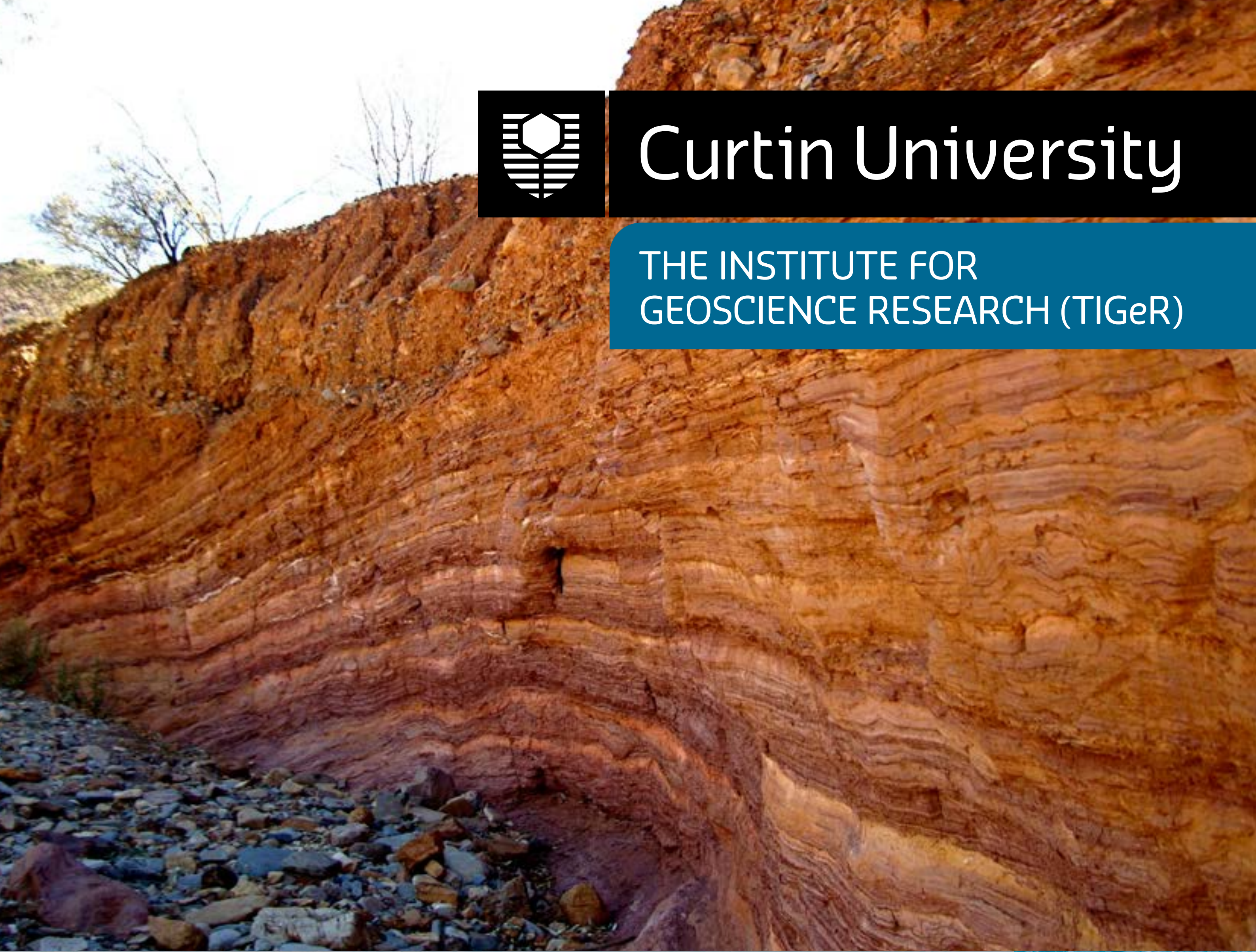

Curtin University

THE INSTITUTE FOR GEOSCIENCE RESEARCH (TIGeR)

TIGeR ANNUAL REPORT 2016

EXPLORING EARTH'S DYNAMIC EVOLUTION

Make tomorrow better.

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TIGeR: The Institute for Geoscience Research

About TIGeR – exploring Earth's dynamic evolution

The Institute for Geoscience Research (TIGeR) brings together active researchers across the spectrum of geosciences within Curtin University with the common goal of understanding the mechanisms and the timescales of the processes that control Earth's dynamic evolution.

TIGeR researchers study processes over a wide range of length scales, from the nanoscale to the macroscale – from reactions operating at grain boundaries in rocks to global tectonics and the origin of the Solar system.

Since the establishment of TIGeR, our researchers have been at the forefront of high-quality, world-leading research in the earth sciences. We produce geochronologic, geotectonic, geodetic and geochemical records, using the latest technology and field and laboratory data, to enhance our knowledge of the Earth's origin within the solar system, its evolution and its current configuration.

Our research forms the basis of understanding the element cycles operating on Earth and their application to the formation of natural resources such as mineral, oil, gas and coal deposits.

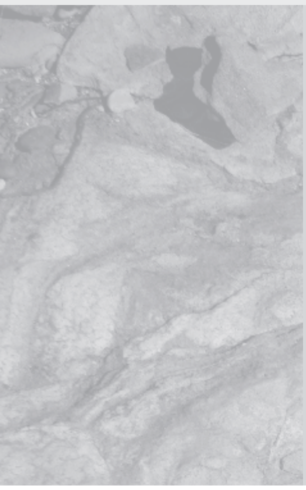
Widespread collaboration

TIGeR is a multidisciplinary group that brings together leading scientists in geology, inorganic and organic geochemistry, geodesy and geophysics with the common goal of advancing new and innovative geoscience research.

Our researchers are drawn from all the geoscience-related departments and centres across Curtin University, including the Department of Applied Geology, the John de Laeter Centre for Isotope Research, the Western Australian Centre for Geodesy, the Western Australian Organic and Isotope Geochemistry Group, the Department of Exploration Geophysics and the Department of Mining Engineering.

We work together with research teams across Australia and internationally and have an excellent track record of obtaining competitive national and international grants, publishing in leading international journals and producing highly-qualified postgraduates.

Contents



Mission statement

To obtain a fundamental understanding of the mechanisms behind complex processes in the Earth.

To establish and maintain a reputation as an international leader in this field.

To enhance our interdisciplinary research by establishing new collaborations and joint ventures.

To actively seek greater involvement with industrial applications of our research.

To find efficient ways of transmitting our basic research to industry, the education sector and the public.

Director's comments

The Institute of Geosciences Research (TIGeR) promotes excellence across the wide spectrum of Earth science related activities at Curtin University. The 2016 Annual Report is the second of a regular series that summarizes the peer-reviewed research publications for each year and serves as both a source of information as well as an archive. The Reports are available on the TIGeR website (tiger.curtin.edu.au).

The articles summarized here are a selection of the 294 reviewed publications by TIGeR members in 2016. This very high level of productivity is also typical of previous years and is why Curtin University continues to be a leader in the "solid earth" disciplines of geology, geochemistry and geophysics. The Excellence in Research for Australia (ERA) results have acknowledged our international reputation with scores of 5 ("well above world standard") in geology and geochemistry and 4 ("above world standard") in geophysics.

A notable new development in 2016 is the continued expansion of TIGeR with the inclusion of Professor Julian Gale's Computational Geochemistry group as TIGeR members. Julian and his colleagues are world leaders in computational methods of modelling properties of minerals and other materials at the atomic level. Their work includes the geochemistry of surface structures of minerals in contact with aqueous solutions and is therefore directly applicable to a better understanding of crystal growth and dissolution, element partitioning and mobility.

Another new aspect of Computational Geoscience on a larger scale has been introduced into TIGeR with the joint appointment between Curtin University and CSIRO of Professor Victor Calo. Victor joins the Department of Applied Geology and will apply his expertise to developing computational tools for high-performance computing applied to problems such as multiphase flow in porous media, reservoir simulations, fracturing and mass transport.

Exciting new results are reported from the Geoscience Atom Probe that is part of a new Advanced Resource Characterisation Facility (ARCF) in partnership with Curtin University, CSIRO and the University of Western Australia, and funded by a grant from the Science and Industry Endowment Fund (SIEF). Funding was also obtained in 2016 for a new Transmission Electron Microscope (TEM) to be housed in the John de Laeter Centre at Curtin. The final commissioning will take place in mid 2017 and I look forward to describing the first results in the next Annual Report. The combined facilities of the Atom Probe and TEM create new opportunities in the field of nanogeoscience that will further establish Curtin geosciences in the top world rankings.

The new palaeomagnetic laboratory in Zheng-Xiang Li's tectonics group opens further research opportunities not only in determining magnetic orientations for continental reconstructions, but also in combination with the TEM and Atom Probe, gives us the possibility to venture into new fields of the origin of magnetic remanence in rocks.

Planetary Sciences and the Fireball Network continue to make news both academically and in public outreach. Two new ARC Discovery grants, one to Phil Bland to continue running the desert fireball network and another to Gretchen Benedix to decode the chronology of Mars, as well as a further ARC LIEF grant to Phil to construct a global Fireball Camera network, have been the main successes through the ARC in 2016. The Fireball Network continues to make meteorite recoveries as a result of tracking, with two finds during 2016, one only 6 days after ground contact. To top all this, for public engagement, "Fireballs in the Sky" won the 2016 Department of Industry, Innovation and Science Eureka Prize for Innovation in Citizen Science category – its second major win in 2016, after being awarded the Chevron Science Engagement Initiative of the Year category at the WA Premier's Science Awards in August.

National and international collaboration is a characteristic of Geosciences research and TIGeR members continue to be active in multidisciplinary research projects as evidenced from the publications and projects reported here. TIGeR members are conspicuous at international conferences such as EGU, AGU and Goldschmidt and it is particularly pleasing to see young researchers and PhD students from Curtin presenting their work at such conferences through the financial help available from the TIGeR Small Grants Scheme.

The Annual TIGeR Conference is a highlight of the year and has already established itself as an international forum for in-depth discussion of specific research issues in Geosciences. In 2016 the Conference theme was "Rock alteration in the upper crust: Element mobility and concentration" and attracted a very impressive list of international and national speakers. As a result of this, new collaborations have been initiated that give Curtin University, through TIGeR, an international visibility and an ever-increasing world-wide reputation of excellence in geosciences research. The Conference programme and abstracts are available for download from the TIGeR website.

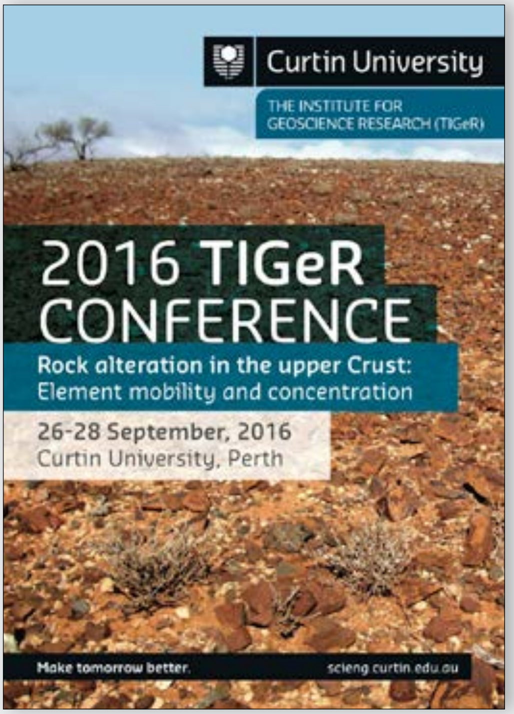
So 2016 was another excellent year!

Andrew Putnis
Director, The Institute for
Geoscience Research (TIGeR)

2016 TIGeR Conference

The second TIGeR Conference was held in September with > 120 international and national participants from Universities and industry.

The details of the 2016 TIGeR Conference programme as well as downloadable abstracts can be found at: **tiger.curtin.edu.au/conference-2016/**



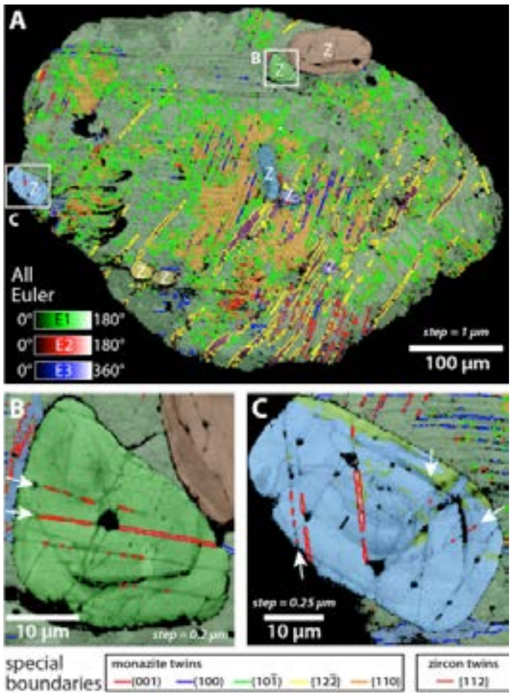
Research reports

MINERAL SYSTEMS, FLUIDS AND ORE DEPOSITS

Shock effects in zircon, monazite and xenotime

Shock microstructures in refractory accessory minerals such as zircon and monazite provide crucial evidence for deciphering impact-related deformation in a wide variety of planetary materials.

Cavosie et al. (2016a,b) describe the first occurrence of shock deformation in xenotime, YPO4, from a shocked quartz–bearing shatter cone in granite at the Santa Fe impact structure (New Mexico) and also shock-induced transformation in zircon from Meteor Crater (Arizona).



Electron backscatter diffraction (EBSD) map of shock deformed monazite with shocked zircon inclusions derived from the Vaal River basin, Republic of South Africa. A. Crystallographic orientation map and grain boundaries of the shocked monazite revealing six shock twin orientations within the grain and eight zircon inclusions. B, C. High-resolution orientation and special boundary maps of the two shocked zircon inclusions showing shock {112} twin lamellae.

Erickson et al. (2016) characterize, for the first time, the shock deformation microstructures in monazite from the Vredefort impact structure in South Africa, indicating shock pressures of 20GPa.

Impact induced effects have also been studied in olivine chondrules from the Allende meteorite by Forman et al. (2016).

Cavosie, A.J., Montalvo, P.E., Timms, N.E., Reddy S.M. (2016). Nanoscale deformation twinning in xenotime, a new shocked mineral, from the Santa Fe impact structure. *Geology*, 44 (10), 803-806.

Cavosie, A.J., Timms, N.E., Erickson, T.M., Hagerty, J.J., Hörz, F. (2016). Transformations to granular zircon revealed: Twinning, reidite, and ZrO2 in shocked zircon from Meteor Crater (Arizona, USA). *Geology*, 44 (9), 703-706.

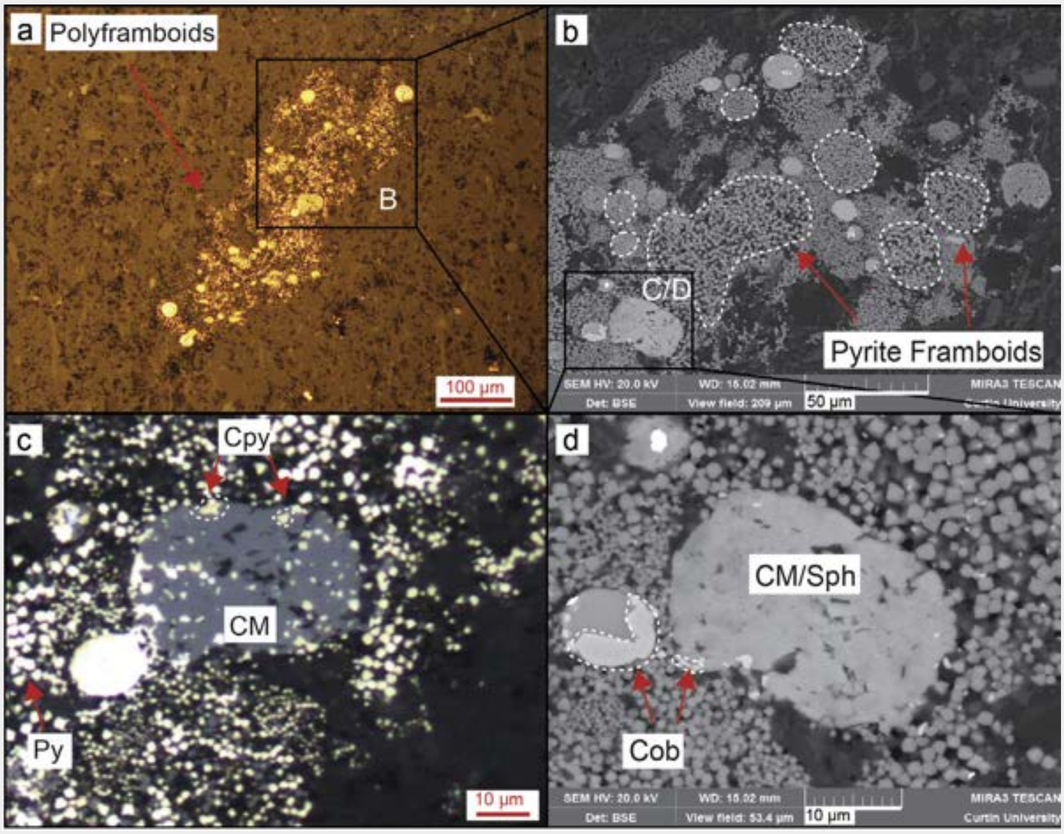
Erickson T.M., Pearce M.A., Taylor R.J., Timms N.E., Clark C., Reddy S.M., Buick I.S. (2016). Deformed monazite yields high temperature tectonic ages: Reply. *Geology*, 44 (1), 378.

Erickson, T.M., Cavosie, A.J., Pearce, M.A., Timms, N.E. and Reddy, S.M. (2016). Empirical constraints on shock features in monazite using shocked zircon inclusions. *Geology*, 44 (8), 635-638.

Orogenic gold deposits – some clues from pyrite polyframboids

Micron scale framboidal pyrite is associated with carbonaceous material and other sulphide minerals in low grade metamorphic rocks of the Otago Schist, New Zealand. Using synchrotron XRF and laser ablation ICP-MS, Hu et al., (2016) have identified a range of trace elements and their associations within the framboids and found that the gold is associated with Zn. The framboids are a likely source of the orogenic Au in the schists, as metamorphism releases the Au into the fluid phase.

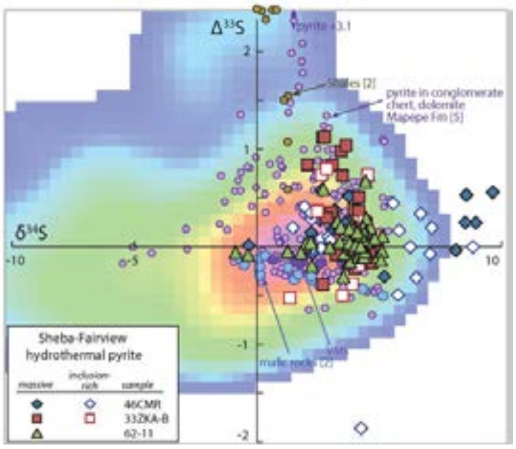
Hu, S.Y., Evans, K.A., Fisher, L., Rempel, K., Craw, D., Evans, N.J., Cumberland, S., Grice, K., Robert, A., (2016). Associations between sulfides, carbonaceous material, gold and other trace elements in polyframboids: implications for the source of orogenic gold deposits, Otago Schist, New Zealand. *Geochimica et Cosmochimica Acta*, 180, 197-213.



Optical micrographs of polyframboids showing carbonaceous material (CM), pyrite (Py) and chalcopyrite (Cpy)

The source of sulphur in the structurally-controlled gold mineralisation of the Barberton Greenstone belt

The transport of Au in the carbonated hydrothermal fluids is believed to have involved S complexes, and so tracing the origin of the S might place constraints on the origin of the Au in the greenstone belt. Existing models for orogenic Au deposits suggest either a deep source of the fluids and Au from outside the greenstone belt, or a local source. Agangi et al. (2016) studied the mass-dependent fractionation of S isotopes from ion probe analyses of the pyrite and found that the distribution of analyses in the $\Delta^{33}S$ – $\delta^{34}S$ space matches previously published analyses of pyrite from the entire volcano-sedimentary succession. This suggests that the source of Au should be identified within the greenstone belt. Their findings differ from conclusions of previous studies of other Archaean shear-hosted Au deposits based on mineralogical and isotopic evidence, which suggested a magmatic or mantle source for Au, and imply that there is no single model that can be applied to this type of mineralisation in the Archaean.



S isotope analyses of pyrite from Sheba and Fairview gold mines compared with pyrite and whole-rock analyses from different units of the Barberton Greenstone Belt.

Agangi A., Hofmann A., Eickmann B., Marin-Carbonne J., Reddy S.M. (2016). An atmospheric source of S in Mesoarchaean structurally-controlled gold mineralisation of the Barberton Greenstone Belt. *Precambrian Research*, 285, 10-20.

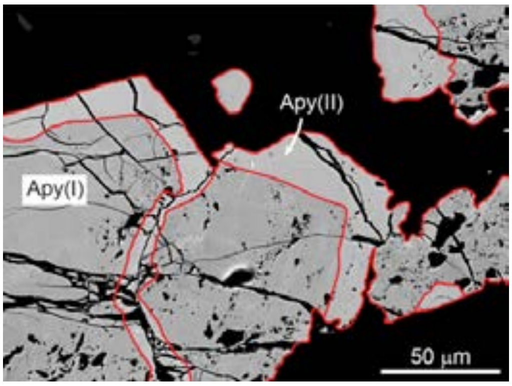
Gold remobilisation by dissolution-precipitation replacement of Au-bearing As-pyrite

How gold is mobilized and transported to form high concentrations in veins is not well-understood, partly because Au is considered to have low solubility in crustal fluids. The Obuasi gold deposit, Ghana, has gold-rich arsenopyrite spatially associated with quartz veins, which have extremely high, localised concentrations of native gold, contained in microcrack networks within the quartz veins.

Fougerouse et al. (2016) studied samples from Obuasi using a combination of quantitative electron backscatter diffraction analysis, ion microprobe imaging, synchrotron XFM mapping and geochemical modeling. They found that the auriferous arsenopyrites have undergone partial replacement (_15%) by Au-poor, nickeliferous arsenopyrite, during localised crystal plastic deformation, intragranular microfracture and metamorphism (340–460 _C, 2 kbars). The arsenopyrite replacement produced strong chemical gradients at crystal-fluid interfaces due to an increase in fS_2 during reaction, which enabled efficient removal of gold to the fluid phase and development of anomalously gold-rich fluid (potentially 10 ppm or more depending on sulphur concentration). Gold re-precipitation occurred over distances of 10 μm to several tens of metres and was likely a result of sulphur activity reduction through precipitation of pyrite and other sulphides.

Fougerouse D., Micklethwaite S., Tomkins A.G., Mei Y., Kilburn M., Guagliardo P., Fisher L.A., Halfpenny A., Gee M., Paterson D. (2016). Gold remobilisation and formation of high grade ore shoots driven by dissolution-reprecipitation replacement and Ni substitution into auriferous arsenopyrite. *Geochimica et Cosmochimica Acta*, 178, 143-159.

Fougerouse D., Micklethwaite S., Halfpenny A., Reddy S.M., Cliff J.B., Martin L.A., Kilburn M., Guagliardo P., Ulrich S. (2016). The golden ark: arsenopyrite crystal plasticity and the retention of gold through high strain and metamorphism. *Terra Nova*, 28(3), 181-187.



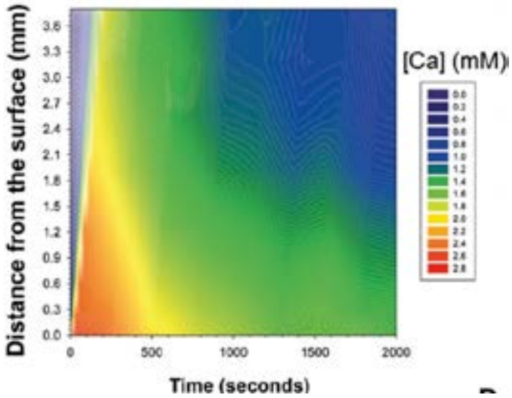
Backscattered electron images showing the replacement of arsenopyrite: Au-bearing Apy(1) by Ni-bearing Apy(II).

Silicate weathering is controlled by dissolution-precipitation and the evolution of local chemical composition at the fluid-mineral interface

Determining the rate of mineral weathering is complicated by the formation of silica-rich surface coatings that may inhibit further dissolution. The mechanism of formation of surface coatings is controversial and hinges on understanding the saturation state of the fluid at the dissolving mineral surface.

Ruiz-Agudo et al (2016) have used interferometry, micro pH and ion-selective electrodes to study the *in situ* evolution of the interfacial fluid composition during dissolution of wollastonite ($CaSiO_3$). Steep concentration gradients develop at the mineral interface as soon as it makes contact with the solution. This interfacial fluid becomes supersaturated with respect to amorphous silica that forms a surface coating, limiting fluid access to the mineral surface and hence affecting the dissolution rate.

The results have implications for understanding the discrepancy between dissolution rates measured in the field and in the laboratory, as well as for predictions of silicate weathering rates and hence climate evolution, as different assumptions on dissolution mechanisms affect calculations on CO_2 drawdown during weathering.



The in situ evolution of free Ca^{2+} composition during experimental dissolution of wollastonite.

Ruiz-Agudo E., King, H.E., Patino-Lopez L.D., Putnis C.V., Geisler T., Rodriguez-Navarro C. and Putnis A. (2016) Control of silicate weathering by interface-coupled dissolution-precipitation processes at the mineral-solution interface. *Geology*, 44, 567-570.

The redox state of fluids released from subducted mantle lithosphere

Magnetite breakdown during subduction of serpentinised ultramafic rocks may produce oxidised fluids that oxidise the deep Earth and/or the sub-arc mantle, either via direct transport of ferric iron, or via redox reactions between ferric iron and other elements, such as sulfur. However, so far, there is no consensus on the oxidation state of fluids released during subduction of ultramafic rocks, or the factors that control this oxidation state.

Evans et al. (2016) have compared subducted samples from a magma-poor rifted margin (Zermatt Saas Zone ophiolite, Western Alps) and a supra-subduction zone geodynamic setting (New Caledonia) to examine evidence of changes in opaque phase assemblage and ferric iron content. The Western Alps samples contain magnetite plus sulfur-rich phases such as pyrite (FeS_2), and are inferred to have equilibrated with hydrogen-poor fluids at oxygen activity greater than FMQ whereas the New Caledonia samples contain awaruite ($FeNi_3$) and equilibrated with hydrogen-bearing fluids at oxygen activity less than the FMQ (fayalite-magnetite-quartz) buffer.

This major difference is independent of differences in subduction pressure-temperature conditions, variation in peridotite protolith composition, or the nature of adjacent units. They propose that the Zermatt Saas Zone samples would have undergone more complete serpentinisation prior to subduction than the supra-subduction zone (SSZ) New Caledonian samples. This difference explains the different fluid compositions, because incompletely serpentinised rocks containing olivine and brucite retain or evolve awaruite-bearing assemblages that buffer fluid compositions to high hydrogen activity.

Evans, K.A., Reddy, S.M., Tomkins, A.G., Crossley, R.J., Frost, B.R. (2016 in press). Effects of geodynamic setting on the redox state of fluids released by subducted mantle lithosphere. *Lithos.*

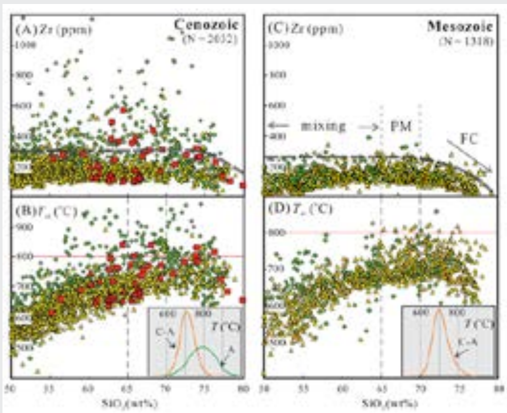
Water-fluxed crustal melting produces Cordilleran batholiths

There was a time, probably over 40 years ago, when most granite petrologists believed that water played an important role in the origin of granite. However, in the 1980s until now the consensus has been that most crustally-derived granites are produced by dehydration melting of the crust by breakdown of hydrous minerals such as biotite or amphibole at temperatures 850ºC. Thus, when Watson and Harrison developed a zircon solubility curve for granitic melts, most workers did not believe it because the temperatures suggested that granitic magmas were far too cool, most <850ºC. The results just did not match the paradigm.

After reading a review by Weinberg and Hasalová (2015), which suggested that aqueous fluids released into the crust under high-temperature conditions could trigger voluminous melting, Collins et al. (2016) asked the question: Can water-fluxed produce Cordilleran batholiths? They used the NAVDAT geochemical database from the US Cordillera and case studies of titanium-in-zircon thermometry T(ti-zirc) to show that Cordilleran plutonic and volcanic rocks of granitic composition (>65wt% SiO_2) are dominantly the products of partial melting, not fractional crystallization, and have the uniformly low temperatures expected by water fluxed melting.

Collins et al. (2016) presented a model suggesting silicic Cordilleran magmas form in magmatic arcs where hydrous basaltic magmas solidify in the arc root, producing mafic underplates which exsolve aqueous fluids that transfer to the crust and promote water-fluxed partial melting at ambient P-T (~750ºC at 8 kbar) conditions. Subsequent rock-buffered melting reactions modulate the water content of arc magmas. The granitic partial melts are water undersaturated, rise adiabatically as increments, but stall in the middle to upper crust, building cool and hydrous, crystal-rich magma chambers (batholiths). However, injections of hotter magmas are required to drive volcanic eruption. In the backarc, granitic magma chambers are intermittently recharged with hotter, drier alkaline magmas, which are produced mostly by decompression melting during lithospheric extension, not hydrous fluxing. This highlights the control of subduction dynamics on water content and consequently magmatic temperatures in silicic magma systems.

Collins, W.J., Huang, H-Q. & Jiang, X. (2016). Water-fluxed crustal melting produces Cordilleran batholiths. *Geology,* 44, 143–146.



Zr concentration and Tzr (zircon saturation) plots vs silica for Cenozoic alkaline and calc-alkaline rocks in the U.S. Cordillera, including Basin and Range (1a, b), based on the modified alkali-lime index (MALI). We divide MALI more simply into "alkaline" (green diamonds), which groups alkalic and alkali-calcic, and "calc-alkaline" (yellow triangles), which groups calc-alkali and calcic. Mesozoic Cordilleran magmatic systems in the U.S. and New Zealand are also shown (1c, d). Mt St Helens (red triangles) and Silver Creek Caldera (red squares) data added. Grey dashed line at 300 ppm Zr to 70% SiO_2 (1a,c) distinguishes >98% of the "calc-alkaline" rocks. 800C isotherm (red line in 1b,d) separates >99% of the "calc-alkaline" rocks for >65% wt% SiO_2. PM = typical partial melt compositions; FC = fractional crystallization. Inserts are probability density plots of temperature (T) that show Tzr values peaking at ~700ºC for calc-alkaline (C-A) and ~800ºC for alkaline (A) systems, for the 65–70wt% SiO_2 interval: only Tzr values within this interval are considered reliable.

Xenoliths in ultrapotassic volcanic rocks in the Lhasa block: direct evidence for crust–mantle mixing and metamorphism in the deep crust

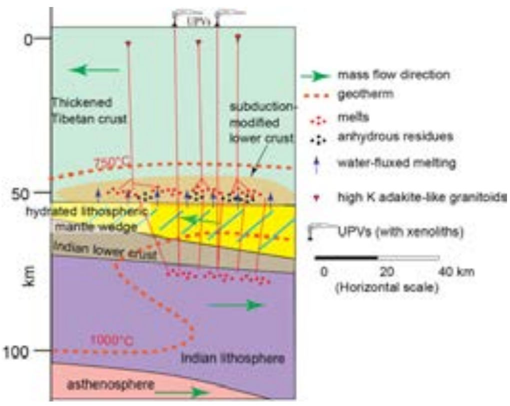
Wang et al. (2016) studied lower crustal granulite-facies xenoliths from a 13 Ma old (Miocene), post-tectonic, ultrapotassic lavas (UPVs) in the Gangdese belt of the Himalayas. They are F-Ti-rich phlogopite and garnet-bearing xenoliths that preserve inherited magmatic and metamorphic zircons. High precision secondary ion mass spectroscopy (SIMS) zircon U-Pb dating combined with systematic zircon Hf-O isotopic and trace element, and garnet O isotopic analyses were used to characterize the origin and evolution of the xenoliths from their early magmatic history, through late metamorphic to low temperature alteration and brecciation.

Felsic granulites are refractory meta-granitoids with garnet and rutile in a near-anhydrous quartzo-feldspathic assemblage. High F-Ti phlogopite occurs as small inclusions in garnet, and high Si phengite in another. The refractory mineralogy suggest that the xenoliths underwent high-T and high-P metamorphism (800–850ºC, >15 kbar).

Zircon populations from the xenoliths indicate that a magmatic component was sourced from Eocene Gangdese arc rocks. 35–20 Ma Miocene ages are derived from zircons with similar Hf-O isotopic composition as the Eocene Gangdese magmatic zircons, and mark a period of early Miocene remelting of the Eocene Gangdese arc. The youngest zircons (13 Ma) have compositional and isotopic characteristics similar to zircons from the host UPV lavas, which formed in equilibrium with garnet. Garnets from the xenoliths show complex compositional isotopic zoning which indicates that separate fractionating magmas were brought together through magma mixing, although a high $\delta 18O$ group formed under high-grade metamorphic conditions during metasomatic exchange. The garnets record complex, open-system magmatic and metamorphic processes in a single rock.

Based on these features, Wang et al. (2016) considered that UPV magmas interacted with juvenile 35–20 Ma old, deep-crust (>50 km) at ~13 Ma to form hybridized Miocene granitoid magmas, leaving a refractory residue. The ~13 Ma zircons retain the original, evolved isotopic character of the UPV magmas, and the garnets record successive stages of the melting and mixing process, along with subsequent high-grade metamorphism followed by low temperature alteration and brecciation during entrainment and ascent in a late UPV dyke. They used the P-T estimates from these are other xenoliths in Tibet, combined with geochronological and isotopic constraints, to reconstruct the geodynamic setting of Tibet in the Miocene.

Wang R., Collins W.J., Weinberg R.F., Li J-X, Li Q-y., He W-y., Richards J.P., Hou Z., Zhou L-m., Stern R.A. (2016) Xenoliths in ultrapotassic volcanic rocks in the Lhasa block: direct evidence for crust–mantle mixing and metamorphism in the deep crust. *Contributions to Mineralogy & Petrology* 171 DOI 10.1007/s00410-016-1272-6



Rock column illustrating the formation of UPVs with lower-crustal xenoliths in the Gangdese belt: subduction mode in the central Tibet, consistent with deep seismic experiments. The UPV melts derived from subducting Indian lithosphere pass through hydrated mantle wedge, and produce hydrous magmas that exsolve an aqueous phase when they underplate the Gangdese lower crust. This lead to water-fluxed partial melting of Gangdese arc root, and the partial melts subsequently mix with UPV melts. Magma segregation leaves anhydrous residues at the base of lower crust. The new UPVs reacted with the refractory residues and carried them as xenoliths to the surface.

Banded iron formations – more clues to their origin

A basic tenet of models for the deposition of banded iron formations (BIFs) is that fine-grained hematite (so-called dusty hematite) represents relict primary ferric oxide/ hydroxide particles. However, a primary origin for dusty hematite has never been conclusively established. Using new high-resolution microscopy of the most extensive and best-preserved BIF (~2.5 billion-year-old Brockman Iron Formation, Hamersley Group, Australia) Rasmussen et al. (2016) have shown *that dusty hematite is formed by replacement of iron-silicate nanoparticles via a process of dissolution and precipitation.* The reason that dusty hematite appears to be primary is that it has directly replaced iron-silicate nanoparticles. The earliest generation of hematite is interpreted to have grown after the 2.2 Ga Ophthalmian Orogeny.

The conflicting environmental conditions implied by BIFs can be reconciled by a hypothesis involving iron-silicate precipitation in the early oceans followed by post-depositional growth of iron oxides. The physicochemical conditions favouring iron-silicate growth suggest that the deposition of BIFs required neither dissolved oxygen nor photosynthetic life, but was an inorganic, chemical process, reflecting anoxic oceans enriched in iron and silica. The paper paves the way toward a new model for the deposition of BIFs, underpinning new insights into ancient ocean chemistry, the cycling of elements and nutrients in the water column, and the role of microbial life in marine processes in the early Earth.

Rasmussen, B., Muhling, J.R., Suvorova, A., Krapez, B. (2016). Dust to Dust: Formation of "Primary" Hematite Dust in Banded Iron Formations via Oxidation of Iron Silicate Nanoparticles. *Precambrian Research*, 284, 49-63.

Hematite mineralized banded iron formation in the Negaunee Iron Formation, Jasper Knob, Ishpeming, Michigan, USA.

Hematite mineralization episodes revealed from U-Pb dating

High-grade hematite ore was first mined in the Marquette region of Lake Superior in 1848 and genetic models developed for their origin have been influential in major iron provinces around the world. However, it has not been possible to test conflicting models due to the lack of absolute dates for mineralization. Rasmussen et al. (2016b) applied in situ SHRIMP U-Pb geochronology of monazite and xenotime to provide the first ages for the formation of iron ore deposits across the Marquette Range, Michigan (or elsewhere in the Lake Superior region).

The results suggest that the hematite ore bodies did not form during a single event but are the products of multiple episodes of fluid flow and iron oxide concentration.

Our results indicate that hematite deposits in the Negaunee Iron Formation formed during the Penokean orogeny (between 1.87-1.85 Ga), and were upgraded at ~1.8 Ga and ~1.77 Ga, coincident with orogeny and accretion along the southern Superior margin. Their findings provide a new model for the formation of this important source of iron, which involves repeated episodes of channelized fluid flow and host-rock alteration coeval with regional tectonic processes.

Rasmussen, B., Zi, J-W., Sheppard, S., Krapez, B., Muhling, J.R. (2016) Multiple episodes of hematite mineralization indicated by U-Pb dating of iron-ore deposits, Marquette Range, Michigan, USA. *Geology*, 44, 547-550.

Outcrop of quartz-hematite veins in the Palaeoproterozoic Chocolay Group, Wewe Hills south of Marquette, Michigan, USA.

Constraining the origin of ultramafic-mafic bodies in the Archean crust of NW Scotland

The Lewisian Complex of NW Scotland is typical of exposed Archean crust worldwide. Within the granulite facies central region discontinuous belts composed of ultramafic–mafic rocks and structurally overlying garnet–biotite gneiss (brown gneiss) are spatially associated with steeply-inclined amphibolite facies shear zones that have been interpreted as terrane boundaries. The composition of the layered ultramafic–mafic rocks suggests a protolith formed by differentiation of tholeiitic magma, where the ultramafic portions of these bodies represent the metamorphosed cumulates and the mafic portions the metamorphosed fractionated liquids. The brown gneiss most likely represents a metamorphosed sedimentary or volcano-sedimentary sequence.

L to R: Kinny, Brown, Johnson, Clark and White sampling the Lewisian Gneiss Complex on the coast of northwest Scotland. Photo: K.M. Goodenough of the British Geological Survey.

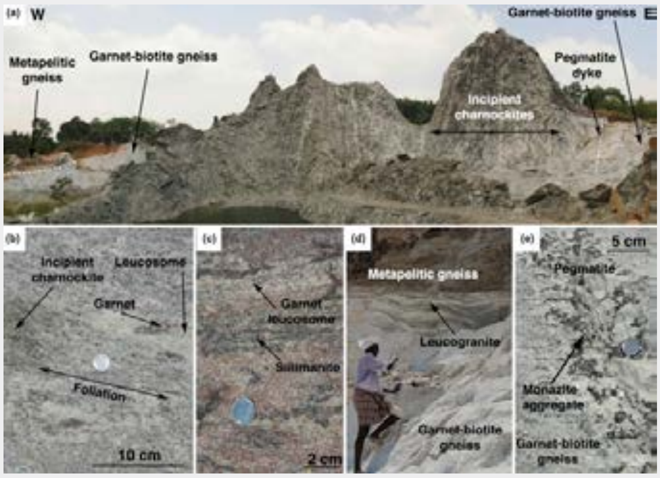
For Archean rocks metamorphosed to granulite facies, the geochemical characteristics used for discrimination of paleotectonic environments are not clearly diagnostic. Many of the rocks have 'arc-like' trace element signatures interpreted to reflect derivation from hydrated enriched mantle and, in the case of the gneisses, partial melting of garnet- and rutile-bearing amphibolite source rocks. However, it is becoming increasingly recognized that in Archean rocks such signatures may not be unique to a subduction environment, but may relate to non-uniformitarian processes such as delamination and dripping. Although a subduction-related origin is possible, Johnson et al. (2016) propose that an intraplate origin is equally plausible, in which the ultramafic–mafic rocks and brown gneisses represent the remnants of intracratonic greenstone belts that sank into the deep crust due to their density contrast with the underlying partially molten TTG gneisses.

Johnson, T.E., Brown, M., Goodenough, K.M., Clark, C., Kinny, P.D. & White, R.W. (2016). Subduction or sagduction? Ambiguity in constraining the origin of ultramafic–mafic bodies in the Archean crust of NW Scotland. *Precambrian Research*, 283, 89–105.

High grade metamorphism, charnockite formation and fluid-rock interaction in the Tivandrum Block, southern India

Incipient charnockites have been widely used as evidence for the infiltration of CO_2-rich fluids driving dehydration of the lower crust. Rocks at Kakkod quarry in the Trivandrum Block of southern India preserve orthopyroxene-bearing charnockite patches in a host garnet–biotite felsic gneiss, but also layers of garnet–sillimanite metapelite gneiss. Blereau et al. (2016) have modeled the phase equilibria for all three bulk compositions and found consistent peak-metamorphic conditions of 830–925ºC and 6–9 kbar with retrograde evolution involving suprasolidus decompression at high temperature.

These models suggest that orthopyroxene was most likely stabilized close to the metamorphic peak as a result of small compositional heterogeneities in the host garnet–biotite gneiss. There is insufficient evidence to determine whether the heterogeneities were inherited from the protolith or introduced during syn-metamorphic fluid flow. U–Pb geochronology of monazite and zircon from all three rock types constrains the peak of metamorphism and orthopyroxene growth to have occurred between the onset of high-grade metamorphism at c. 590 Ma and the onset of melt crystallization at c. 540 Ma. The majority of metamorphic zircon growth occurred during protracted melt crystallization between c. 540 and 510 Ma. Melt crystallization was followed by the influx of aqueous, alkali-rich fluids likely derived from melts crystallizing at depth. This late fluid flow led to retrogression of orthopyroxene, the observed outcrop pattern and to the textural and isotopic modification of monazite grains at c. 525–490 Ma.



Blereau E., Clark C., Taylor R.J.M., Johnson T.E., Fitzsimons I.C.W., Santosh M. (2016). Constraints on the timing and conditions of high-grade metamorphism, charnockite formation and fluid-rock interaction in the Trivandrum Block, southern India. *Journal of Metamorphic Geology*, 34, 527-549.

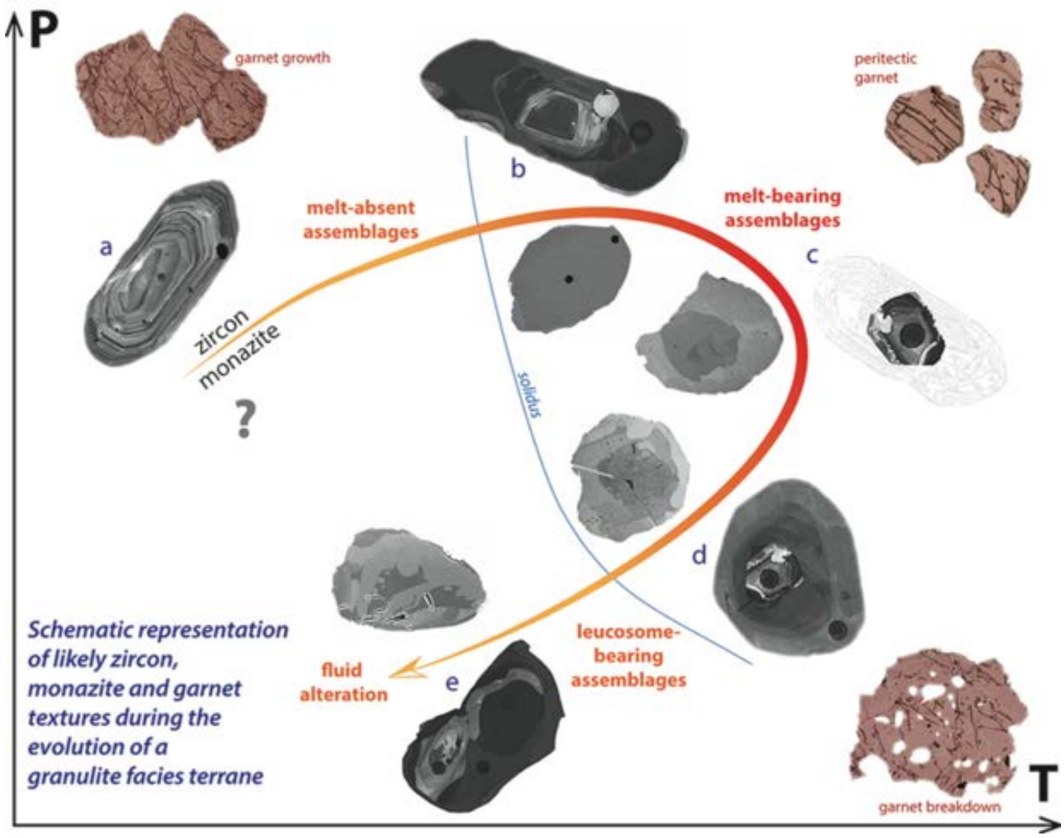
Constraining the timing, duration and conditions of high-temperature metamorphic processes

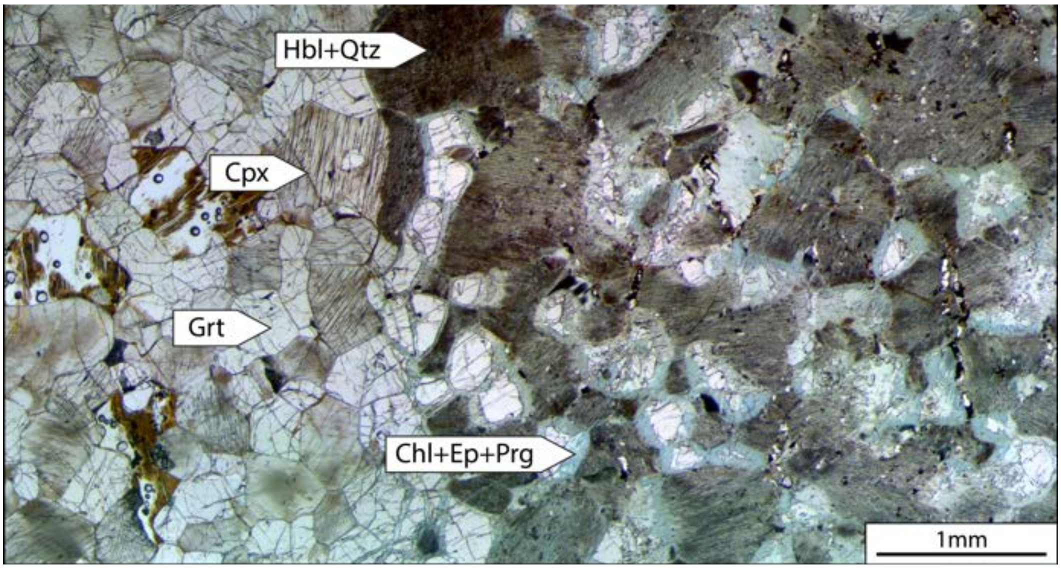
A challenge in the earth sciences is to determine the rates and durations of orogenic processes. Taylor et al. (2016) have reviewed the application of in situ geochemical techniques, focusing on accessory mineral geochronology and thermometry, to understanding orogenic processes in regionally metamorphosed terrains.

High-grade metamorphic terrains provide seemingly ideal settings for the application of these techniques, with high temperatures facilitating elemental diffusion. However the reality of applying these analytical approaches to the granulite facies and the even more extreme conditions of ultra high temperature (UHT) crust is far more complex, with interplay of mineral reactions, elemental and isotopic closure temperatures, and melt-bearing open system behaviour.

High-temperature metapelitic rocks are ideal study materials, containing an abundance of accessory minerals in a variety of bulk compositions. However the heterogeneity of such samples can make dealing with geochronological data difficult. The addition of trace element datasets alongside U–Pb geochronology is capable of providing additional insight when unravelling the complexity that can arise from the study of such rocks.

Taylor R.J.M., Kirkland C.L. Clark C. (2016) Accessories after the facts: Constraining the timing, duration and conditions of high-temperature metamorphic processes. *Lithos*, 264, 239-257.





Photograph of a thin section localized at the boundary between the granulite (left) and the amphibolite (right).

Mass transfer and trace element redistribution during hydration of granulites in the Bergen Arcs, Norway

The Bergen Arcs, located on the western coast of Norway, are characterized by Precambrian granulite facies rocks partially hydrated at amphibolite and eclogite facies conditions. At Hilland Radöy, granulite displays sharp hydration fronts across which the granulite facies assemblage composed of garnet (55%) and clinopyroxene (45%) is replaced by an amphibolite facies mineralogy defined by chlorite, epidote, and amphibole. The replacement of both phases is pseudomorphic and the overall reaction is isovolumetric.

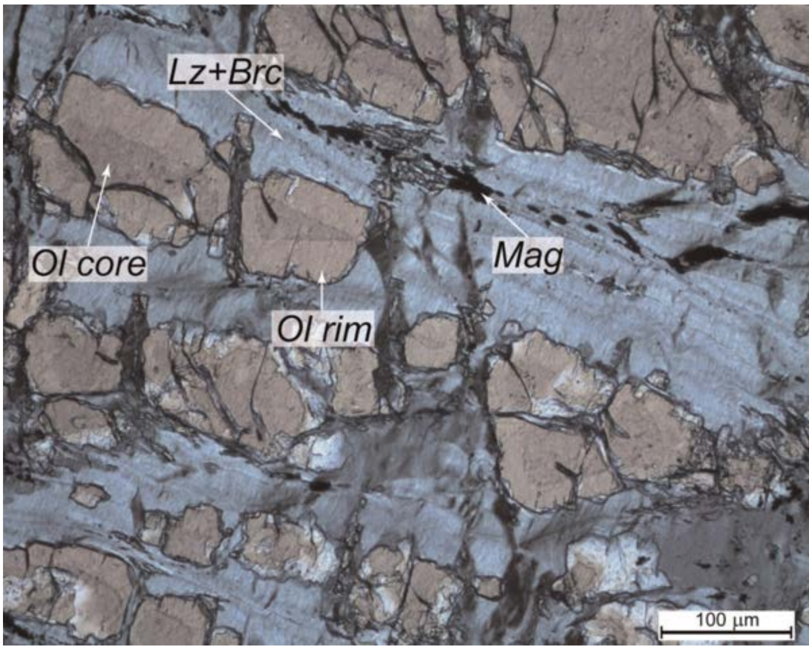
Centrella et al. (2016) used LA-ICP-MS to determine the trace element redistribution during the hydration. Although the bulk concentrations of the trace elements do not change, the LILE, HFSE, and REE losses and gains in replacing the garnet are qualitatively balanced by the opposite gains and losses associated with the replacement of clinopyroxene. From the REE compositions of the parent granulite and the product amphibolite, measured in μg/cm^3, they conclude that the mass of rock lost to the fluid phase during the hydration is approximately 20%. This suggests a mechanism for coupling between the local stress generated by hydration reactions and mass transfer, dependent on the spatial scale over which the system is open.

Centrella S., Austrheim H. and Putnis A. (2016) Mass transfer and trace element distribution during hydration of granulites in the Bergen Arcs, Norway. *Lithos* 262, 1-10.

Formation of Mg-rich Olivine Pseudomorphs in Serpentinized Dunite from the Nuasahi Massif, Eastern India: Insights into the Evolution of Fluid Composition at the Mineral–Fluid Interface

Majumdar et al. (2016) describe unusual textural-chemical features in partially serpentinized dunites from the lower ultramafic unit of the Mesoarchean Nuasahi Massif, eastern India, in which the final stages of a sequence of replacement reactions is the formation of a pseudomorphic rim of Mg-rich olivine (Fo98) directly in contact with the primary olivine (Fo92). The textural–chemical relations, such as sharp but irregular reaction interfaces, propagation of replacement fronts along fractured pathways, allowing transfer of aqueous species towards the center of olivine crystals, and the presence of micro- to nano-porosity within product phases, indicate that each replacement process was governed by an interface-coupled dissolution–precipitation mechanism.

The sequential formation of different pseudomorph phases during progressive hydration of primary olivine reflects a micrometer-scale variation in silica and/or water activity in the precipitating solution across the reaction interface, and may also be associated with a decrease in temperature.



Optical micrograph of partially serpentinised dunite. The original olivine (Ol) core is replaced in the final stages of serpentinisation by a Mg-rich olivine rim. The serpeninised pert contains lizardite (Lz) brucite (Brc) and magnetite (Mag).

Majumdar A.S., Hövelmann J., Vollmer C., Berndt J., Mondal S.K. and Putnis A. (2016) Formation of Mg-rich olivine pseudomorphs in serpentinized dunite from the Mesoarchean Nuasahi Massif, eastern India: Insights into the evolution of fluid composition at the mineral-fluid interface. *Journal of Petrology* 57, 3-26.

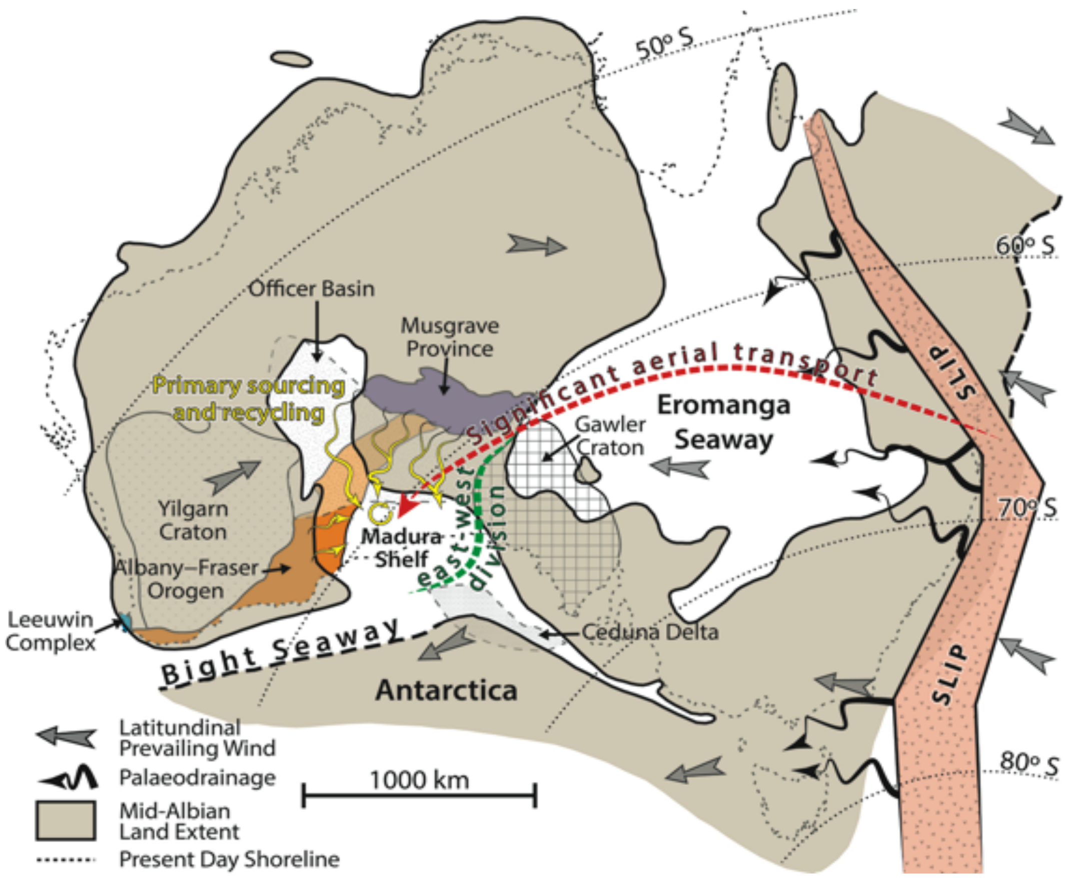
Geochemical fingerprinting demonstrates that super-eruptions on the east coast of Australia more than 100 million years ago could project zircon crystals as far as WA

Barham et al., (2016) studied the geochemistry, grain shape and correlation with matrix sediment age, of zircon crystals found in Western Australia and interpreted these as the products of volcanic airfall from supereruptions on the east coast of Australia, despite the fact that the source volcanoes were 2300km away.

Such distal projection of a unique volcanic mineral population demonstrates that super-eruptions (producing >1000 km^3 of volcanic material) were occurring in eastern Australia approximately 106 million years ago during the break-up of the supercontinent Gondwana and ultimate separation of Zealandia from Australia.

The arrangement of landmasses and atmospheric circulation at the time indicates that the recorded eruptions occurred during the southern hemisphere winter, when strong winds from the east would have pushed volcanic ejecta towards the west. These results are significant in terms of demonstrating integrated methods to improve our understanding of ancient super-eruptive episodes.

Barham, M., Kirkland, C.L., Reynolds, S., O'Leary, M.J., Evans, N.J., Allen, H., Haines, P. Hocking, R., McDonald, B.J., Belousova, E., Goodall, J. (2016). The answers are blowin' in the wind: ultra-distal ashfall zircons, indicators of Cretaceous super-eruptions in eastern Gondwana. *Geology,* 44 (8), 643-646.



Origin of the Nizhny Tagil clinopyroxenite-dunite massif of the Uralian Platinum Belt, Russia

Clinopyroxenite-dunite Uralian-Alaskan type complexes of the Uralian Platinum Belt are the source of economic platinum placer deposits. One of the striking features of Uralian-Alaskan type complexes is a pronounced Pt anomaly which clearly distinguishes them from cumulate series of ophiolite massifs elsewhere, but there is still uncertainty regarding the nature of platinum enrichment and related geodynamic setting.

Tessalina et al. (2016) have studied the PGE and Os isotope systematics of platinum-group minerals, chromitites and other ultramafic rocks from the Nizhny Tagil massif. The Os model age is *ca*. 400 Ma older than the melt depletion event corresponding to the Tagil island arc development, and can be ascribed to a Neoproterozoic mantle melting event under an influence of either a pre-Uralian subduction zone, or a superplume, overprinted by younger processes.

The striking similarities (P-T-fO_2 and type of parental magma, high Pt/Pd ratio etc) with other zoned clinopyroxenite-dunite massifs such as Kondyor, situated within the stable Archean shield zone, led them to conclude that this type of massif is not exclusive to the subduction zone setting, but may reflect a specific depleted, fluid-metasomatised type of relatively shallow mantle in the Palaeozoic. Moreover, the systematic Pt/Pd ratio increase in Nizhny Tagil rocks toward the chromite mineralized zone suggests that Pt-Pd fractionation may be related to the preferential retention of Pt in chromitites as Pt-Fe alloys.

Tessalina S.G., Malitch K.N., Auge T., Puchkov V.N., Belousova E. and McInnes B.I.A. (2016). Origin of the Nizhny Tagil clinopyroxenite-dunite massif (Uralian Platinum Belt, Russia): insights from PGE and Os isotope systematics. *Journal of Petrology*, 56(12), 2297-2318.

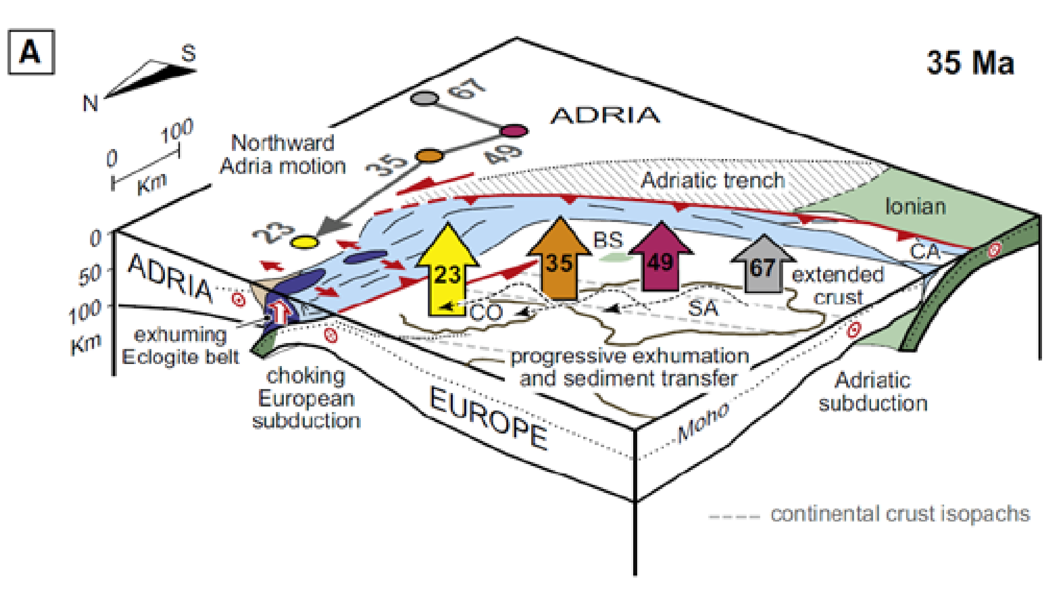
Panoramic view of the dunite open pit, Nizhny Tagil clinopyroxenite-dunite massif, Urals, Russia.

Using low-temperature thermochronometry to track the Adriatic-slab travel beneath the Tethyan margin of Corsica–Sardinia

Malusà et al. (2016) used a new multi-thermochronological dataset from Corsica–Sardinia to constrain the Meso-Cenozoic evolution of the Western Mediterranean area and the problematic transition in space and time between the opposite-dipping Alpine (European) and Apenninic (Adriatic) subductions.

Zircon and apatite fission track and apatite (U–Th)/He data covers the whole Meso-Cenozoic time interval, and fits the theoretical age pattern that is expected in distal passive margins after continental break-up. This demonstrates that Corsica–Sardinia represents a fragment of the northern Tethyan margin still preserving the thermochronological fingerprint acquired during Middle Jurassic rifting. Mesozoic apatite (U–Th)/He ages from crustal sections located close to the Tethyan rift axis (i.e., central and eastern Sardinia) show that no European continental subduction took place south of Corsica since the Mesozoic. Along the Sardinia transect, post-Jurassic Adria–Europe convergence was possibly accommodated by Adriatic subduction, consistent with the onset of orogenic magmatism. In middle Eocene–Oligocene times, the northward translation of the Adriatic slab beneath the former Tethyan margin induced a coeval northward migration of erosional pulses at the surface, constrained by a trend of progressively decreasing fission track ages from southern Sardinia to NW Corsica. The Adriatic slab reached the Alpine wedge of Corsica by the end of the Oligocene without any breakoff of the European slab, and started retreating in Neogene times triggering the long-recognized basin opening in the backarc region.

Malusà M.G., Danišík M., Kuhlemann J. (2016). Tracking the Adriatic-slab travel beneath the Tethyan margin of Corsica–Sardinia by low-temperature thermochronometry. *Gondwana Research*, 31, 135-149.



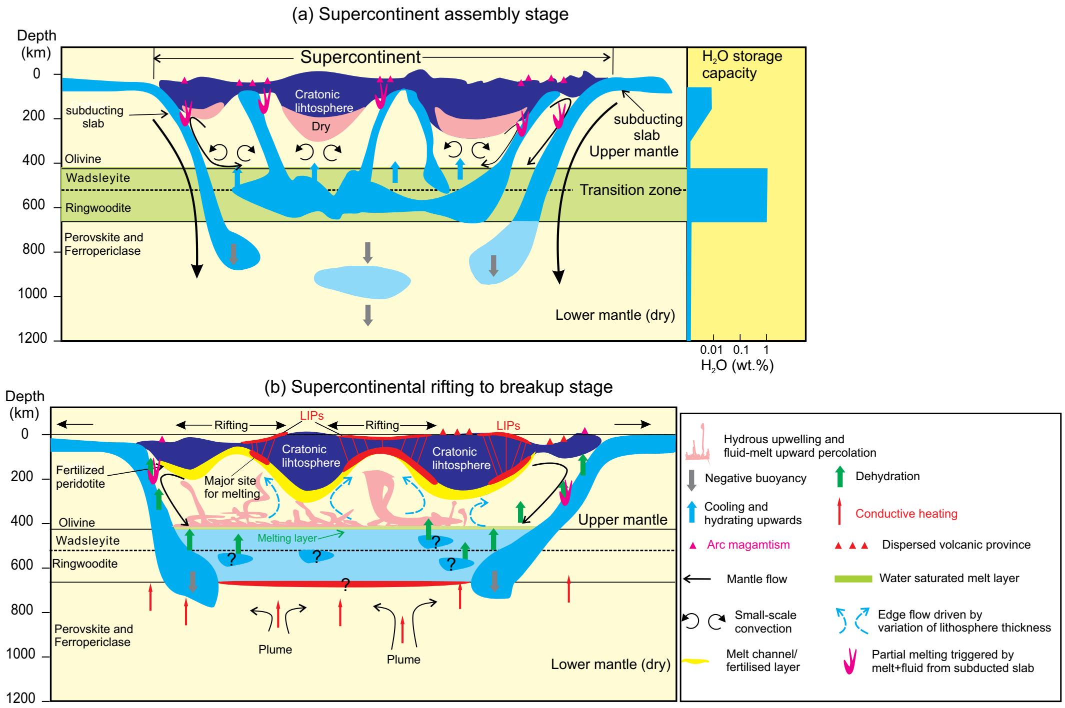
Deep-Earth volatile cycling, mantle dynamics, and surface feedback

Wang et al. (2016) analysed global data sets to address the question why continental basalts generally display geochemical signatures similar to those that evolved in the subduction environment, but different from oceanic intraplate counterparts. Continental flood basalts (CFBs) from six large igneous provinces and the Basin and Range basalts are characterized by high magma water contents and high primary melt water contents. They proposed that water flux melting played an important role in the generation of many intra-continental igneous provinces.

They proposed a mantle transition zone (MTZ) water-filtering model that links deep-Earth fluid cycling, supercontinent cycling, mantle dynamics, and surface feedback:

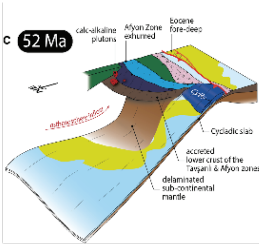
Assembly of supercontinents potentially leads to accumulation of a large volume of hydrated oceanic slabs within the MTZ and may change the mode of mantle convection. The metastable slabs within the MTZ eventually penetrate into the lower mantle or partially return to the shallow upper mantle to melt. This would generate large-scale wet upwellings that hydrate the sub-continental lithosphere, resulting in instability of the lowest part of the continental lithosphere. Plate- and slab avalanche-driven upwelling originating from the MTZ may have played an important role in the breakup of supercontinents and the circulation of water (possibly include other volatiles) between Earth's surface and its interior.

Wang, X.-C., Wilde, S.A., Xu, B., Pang, C.-J. (2016). Origin of arc-like continental basalts: Implications for deep-Earth fluid cycling and tectonic discrimination. *Lithos*, 261, 5-45.



The mantle transition zone water-filtering model that links deep-Earth fluid cycling, large-scale intra-continental magmatism and supercontinent cycles into a self-organised system. (a) Supercontinent assembly stage and (b) Supercontinent rifting to breakup stage.

Neotethyan closure history of the Eastern Mediterranean



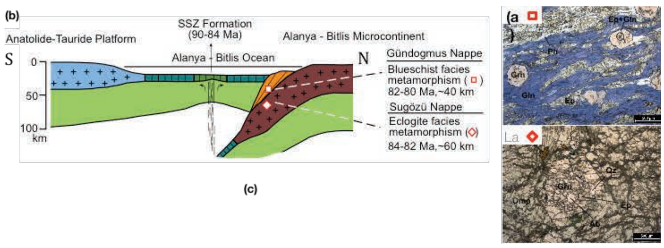
Snapshot of the tectonic evolution of the Aegean–West Anatolian convergence zone at 52 Ma (Pourteau et al., 2016).

Within the Mediterranean realm, and how it relates to the closure of the Neotethys ocean during the Cenozoic, Anatolia has long remained little studied. In contrast to the adjacent Aegean domain, and despite great progress over the last 15 years, the tectonic evolution of Anatolia remains variously interpreted. Whereas continuous northward subduction of a unique lithospheric slab since the earliest Cenozoic at least is the broadly accepted view for the Aegean, three types of lithosphere-scale subduction–collision models have been envisaged for Anatolia. They involve Aegean-type protracted subduction, episodic subduction with intermittent slab break-off, or multiple, coeval subduction zones. Pourteau et al. (2016) presented a review and comparison of these various models and identify key debated aspects that can be re-evaluated in the light of multidisciplinary constraints from the literature. The authors thus addressed the timing of subduction initiation outboard of the then subducted passive margin, the existence hypothetical oceanic basins, the number of intervening subduction zones, the palaeogeographic origin of tectonic units, and the possibility for slab break-off, alleged in the Campanian or Early Eocene. A favoured tectonic model was proposed to reconcile the Neotethyan closure histories of Western Anatolia and the Aegean domain.

Scheffler et al. (2016) reported calcite pseudomorphs after metamorphic aragonite and evaporitic gypsum from multiple localities of low-grade high-pressure metamorphosed Triassic, and mid-Cretaceous limestone throughout Anatolia. A detailed stratigraphic analysis of one mid-Cretaceous locality in SW Anatolia provides insights into the depositional environment of this unique rock. This so-called Rosetta Marble were derived from giant gypsum deposits, formed both during Triassic continental rifting and the opening of the Neotethys, and sometime in the mid-Cretaceous in a hemi-pelagic environment possibly comparable to the Messinian Mediterranean basin.

Rosetta Marble displays intact selenite structures in SW Anatolia (Scheffler et al., 2016). Gypsum was first replaced by aragonite during early tectonic burial, and transformed into calcite during exhumation (preserving its fibrous habit and high Sr content).

In southern Anatolia, a metamorphic nappe complex comprising a blueschist- to eclogite-facies unit has long been overlooked in tectonic reconstructions of the Eastern Mediterranean. Çetinkaplan et al. (2016) provided detailed geological maps, new petrological observations and analyses, and geochronological data that constrain the structural and metamorphic evolution of this complex between 85–70 Ma. This high-pressure metamorphic domain represents the western end of the peri-Arabian subduction zone that connects SE Anatolia to Oman through the Zagros fold-and-thrust belt.



Late Cretaceous tectonic setting at the southern margin of Anatolia (a) as inferred from the study of blueschist (b) and eclogite (c) of the Alanya Massif (Çetinkaplan et al., 2016).

Pourteau A., Oberhänsli R., Candan O., Barrier E., Vrielynck B. (2016). Neotethyan Closure History of Western Anatolia—A Geodynamic Discussion. *International Journal of Earth Sciences*, 105, 1, 203–224

Scheffler F., Oberhänsli R., Pourteau A., Candan O., Immenhauser A. (2016). Sedimentologic to metamorphic processes recorded in the high-pressure/low-temperature Mesozoic Rosetta Marble of Anatolia. *International Journal of Earth Sciences*, 105, 1, 225–246

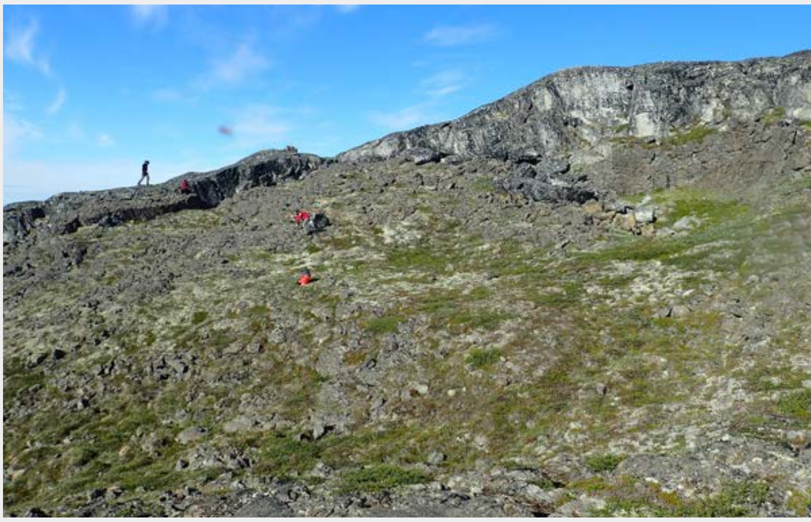
Çetinkaplan M., Pourteau A., Candan O., Koralay O. E., Oberhänsli R., Okay A., Chen F. (2016). P–T–t evolution of Eclogite/Blueschist Facies Metamorphism in Alanya Massif: Time and Space Relations with HP Event in Bitlis Massif, Turkey. *International Journal of Earth Sciences*, 105, 1, 247–281

The Centre for Exploration Targeting (Cet) – Curtin Node

The Centre for Exploration Targeting - Curtin University Node aims to reduce exploration risk through enhanced geological understanding, specifically using geochronology and isotope geology to date mineralization and track fertile lithotectonic domains in the crust. This node has projects with various geological surveys including an encompassing Lu–Hf interpretation program based on previously dated zircon samples from the Geological Survey of Western Australia.

The Lu-Hf project is in collaboration with the Core to Crust Fluids ARC centre of excellence. More than 10580 zircons, from 668 samples, have been analyzed during the life of the project, including 56 samples and 1535 zircons in 2016. The project has addressed questions on the affinity of crustal blocks, helped map major lithospheric structures, and elucidated the timing of mantle input into the crust. The isotopic datasets produced have provided a powerful tool to understand fundamental components of mineral systems.

Recent results of note include the first major Hf dataset from the East Pilbara, with a unique focus on the magmatic evolution of a single granite dome. The East Pilbara Terrane is the archetypal granite-greenstone belt, and studies of East Pilbara have informed many ideas regarding early Earth geodynamic processes. Using a new Hf dataset, important interpretations regarding: (a) the geodynamic operating model of pre 3.2 Ga Earth, (b) the existence of a ca. 3.7 Ga sialic protocrust in East Pilbara, and (c) the change in geodynamic style post 3.2 Ga can be made.



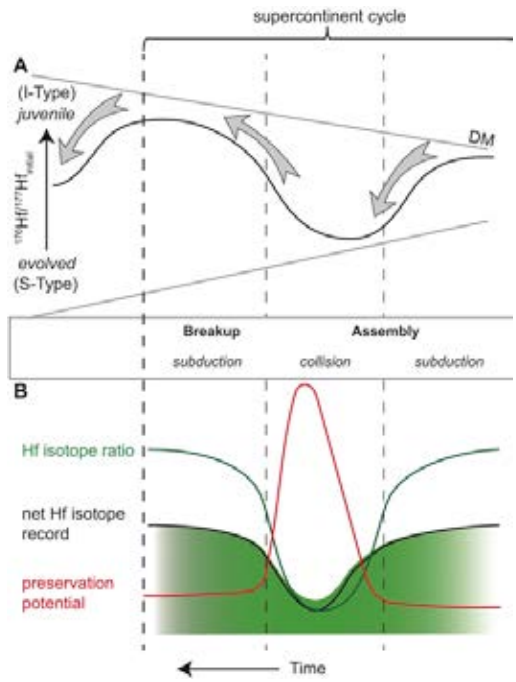
Fieldwork in western Greenland by members of TiGER; sampling mafic intrusives that cut Tonalite-Trondhjemite-Granodiorite. These mafic intrusives have a spatial relationship to kimberlite bodies which the CET-Curtin node and the Greenland Ministry of Mines are researching to assist the minerals industry in Greenland.

Specifically, results from the East Pilbara indicate reworking of existing tonalite-trondhjemite-granodiorite crust dominated late Paleoarchean magmatism which supports a vertical tectonic geodynamic regime >3.2 Ga for the Pilbara. Other projects of note for the research group include an extensive U-Pb geochronology program for the Greenland Ministry of Mines, which thus far has helped to define cooling paths for the Karrat Group in the southernmost Rae Craton within the 1.88 Ga Rinkian Fold Belt. The group has also used detrital zircon geochronology to help fingerprint the straigraphy of rocks on the southern margin of the McArthur Basin, Northern Territory in collaboration with Bowgan Minerals Ltd. This work is helping to track the stratigraphic location of unconformity related uranium mineralization.

The juvenile hafnium isotope signal as a record of supercontinent cycles

Hf isotope ratios measured in igneous zircon are controlled by magmatic source, which may be linked to tectonic setting. Over the 200–500 Myr periodicity of the supercontinent cycle - the principal geological phenomenon controlling prevailing global tectonic style - juvenile Hf signals, i.e. most radiogenic, are typically measured in zircon from granites formed in arc settings (crustal growth), and evolved zircon Hf signals in granites formed in continent-collision settings (crustal reworking). Interrogations of Hf datasets for excursions related to Earth events commonly use the median value, however this may be equivocal due to magma mixing. The most juvenile part of the Hf signal is less influenced by crustal in-mixing, and arguably a more sensitive archive of Earth's geodynamic state. Gardiner et al. (2016) analyzed the global Hf dataset for this juvenile signal, statistically correlating supercontinent amalgamation intervals with evolved Hf episodes, and breakup leading to re-assembly with juvenile Hf episodes. The juvenile Hf signal is more sensitive to Pangaea and Rodinia assembly, its amplitude increasing with successive cycles to a maximum with Gondwana assembly which may reflect enhanced subduction-erosion. They demonstrated that the juvenile Hf signal carries important information on prevailing global magmatic style, and thus tectonic processes.

Gardiner, N.J., Kirkland, C.L., Van Kranendonk, M.J. (2016) The Juvenile Hafnium Isotope Signal as a Record of Supercontinent Cycles. *Scientific Reports* 6, 38503.

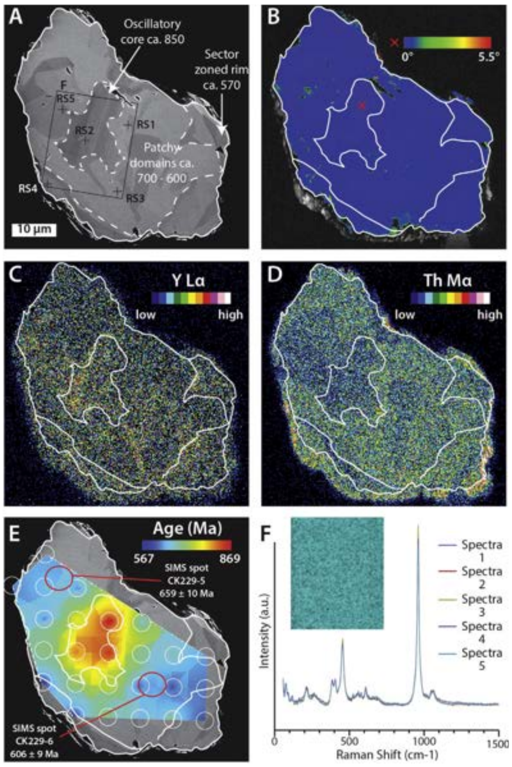


(A) Schematic showing the conceptual evolution of initial 176Hf/177Hf ratios with respect to the stages of supercontinent assembly and breakup. During initial assembly, subduction processes prevail, with the generation of predominantly juvenile magmatism leading to a more radiogenic Hf signature. As the supercontinent amalgamates, crustal thickening becomes increasingly dominant, with crustal reworking processes leading to more evolved magmatism during final assembly, driving global Hf towards more evolved ratios. Breakup and rifting processes leading to subduction give rise to more juvenile Hf signatures. (B) Diagram showing the proposed effect of preservation bias on the Hf signal during a supercontinent cycle.

The origin of complex age spectra in monazite single crystals

Monazite from a granite that has intruded the Kalak Nappe Complex (Norway) shows U-Th-Pb ages that scatter for ~300Ma along the Concordia. The spread of ages can be related to different textures seen in BSE SEM, but it is unclear whether these are due to prolonged growth or the influence of a variety of radiogenic- Pb mobility processes.

Kirkland et al. (2016) have used detailed chemical, EBSD, and Raman imaging in combination with U–Pb analyses, to resolve the primary mechanism for this protracted age spread. They find that the spread of monazite ages is not due to (i) deformation-induced radiogenic Pb loss, nor (ii) the result of thermally induced radiogenic Pb mobility nor (iii) the result of metamictization.
The age distribution is attributed to fluid-mediated element mass transfer driven by coupled substitution in the altered parts of monazite, consistent with the geochemical signatures in these domains. These results indicate that even a single monazite grain can record several tectonothermal events and potentially chart much of an orogens history.



SEM photomicrographs, LA-ICPMS age map and laser Raman data from a typical monazite from the Nordneset Granite.

Kirkland, C. L., Erickson, T. M., Johnson, T. E., Danišík, M., Evans, N. J., Bourdet, J. & McDonald, B. J. (2016). Discriminating prolonged, episodic or disturbed monazite age spectra: An example from the Kalak Nappe Complex, Arctic Norway. *Chemical Geology*, 424, 96–110.

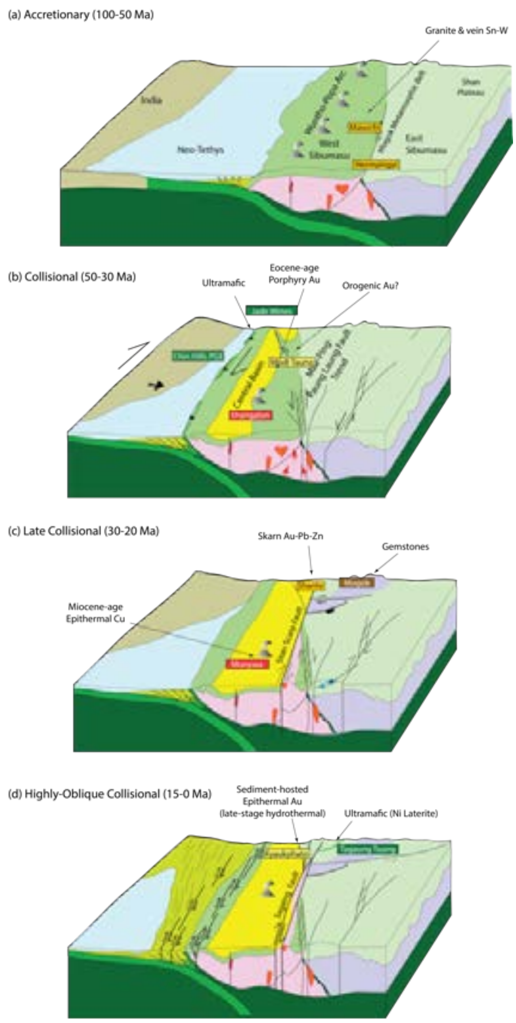
The tectonic framework of Myanmar and its mineralization

Myanmar is perhaps one of the world's most prospective but least explored minerals jurisdictions, containing important known deposits of tin, tungsten, copper, gold, zinc, lead, nickel, silver, jade and gemstones. A scarcity of recent geological mapping available in published form, coupled with an unfavourable political climate, has resulted in the fact that, although characterized by several world-class deposits, the nation's mineral resource sector is underdeveloped. Myanmar lies at a crucial geologic juncture, immediately south of the Eastern Himalayan Syntaxis, however it remains geologically enigmatic. Its Mesozoic-Recent geological history is dominated by several orogenic events representing the closing of the Tethys Ocean.

Gardiner et al. (2016) present new zircon U-Pb age data related to several styles of mineralization within Myanmar and outline a tectonic model for Myanmar from the Late Cretaceous onwards, documenting nine major mineralization styles representing a range of commodities found within the country.

They propose a metallogenetic model that places the genesis of many of these metallotects within the framework of the subduction and suturing of Neo-Tethys and the subsequent Himalayan Orogeny. The genesis of much of Myanmar's mineral deposits, represents a single, evolving, mineral system: the subduction and suturing of Neo-Tethys.

Gardiner N.J., Robb L.J., Morley C.K., Searle M.P., Cawood P.A., Whitehouse M.J., Kirkland C.L., Roberts N.M.W., Tin Aung Myint (2016). The Tectonic and Metallogenic Framework of Myanmar: A Tethyan Mineral System. *Ore Geology Reviews* 79, 26-45



Schematic tectonic evolution of Myanmar, detailing interpreted metallogenesis related to each major stage and location of major mines.

The ARGUS VI noble gas mass spectrometer.

THE WESTERN AUSTRALIAN ^{40}AR/^{39}AR ISOTOPE FACILITY (WAAIF)

The ^{40}Ar/^{39}Ar dating method is used to measure the age and timing of a large variety of geological processes, from meteorite samples as old as the Earth (4.5 billion years) to the age of historical events such as the Vesuvius eruption (79 AD). The Ar technique can be applied to any rocks and minerals that contain K (e.g. hornblende, sanidine, plagioclase and basalts) is also used to date a myriad of other geological events such as volcanism, tectonic plate movements, mountain building rates, sediment formation, weathering and erosion, hydrothermal fluid movements, and alteration and diagenesis of minerals. The Western Australian Argon Isotope Facility includes two noble gas mass spectrometer (MAP 215-50 and the ultra-precise ARGUS VI) and is equipped with two laser systems and a furnace and is operated by A/ Prof. Fred Jourdan.

Ancient volcanic activity at Bunbury caused by mega-continent breakup

This research has shed light on why so many ancient volcanic eruptions – some now submerged in the Indian Ocean – occurred along the west coast of Australia where no volcano activity is expected to be found. The research found the volcanic eruptions were a direct consequence of the breakup of the ancient supercontinent Gondwana nearly 140 million years ago, when India separated from Australia. The results fit well with the researchers' earlier findings which showed that large volumes of lava erupted on the Wallaby Plateau off the northwest coast of WA about 125 million years ago. These results show that lava flows erupted at different times and places as Gondwana slowly tore apart along what is now the west coast of Australia.

Olierook H.K.H., Jourdan F., Merle R.E., Timms N.E., Kusznir N., Muhling J.R. (2016). Bunbury Basalt: Gondwana breakup products or earliest vestiges of the Kerguelen mantle plume? *Earth and Planetary Science Letters*, 440, 20-32.

Basaltic lavas flows from the Greater Kerguelen province, Bunbury, Western Australia. (F. Jourdan).

CO_2-sequestration by carbonate mineralization – the Hellisheidi project

The strategy for sequestration of the green-house gas CO_2 generally involves the injection of the gas into porous rocks that may also be associated with oil and natural gas recovery. The aim is to contain the CO_2 in the rocks and isolate it from the Earth's surface by utilizing the same cap-rocks that captured the hydrocarbons.

An alternative strategy and potentially a longer-term storage method is to inject a CO_2-bearing solution into Ca- and/or Mg-bearing silicate rocks to enhance the dissolution of the silicate, release the Ca and Mg which then reacts with the CO_2 to precipitate Ca and Mg carbonates. While theoretically feasible, there are many practical problems that have to be solved before such a process becomes practical on a large scale. Among them is how to enhance the permeability and porosity of the host rock, whether the carbonate precipitation would destroy any existing or generated permeability, whether any trace elements released from the host rock after dissolution might contaminate ground water and critically, whether the kinetics of the carbonate formation is fast enough to make the method practical.

The Hellisheidi project in Iceland is arguably the most advanced and successful attempt to realize the potential of this strategy of sequestration through mineralisation. The Hellisheidi geothermal power plant operated by Reykjavik Energy produces CO_2 gas as well as steam, and the aim of the project is to dissolve the CO_2 in water and pump it back into the basaltic rock to react with the rock and precipitate carbonate. As would be expected, this is a large project and involves researchers from many countries.

The Hellisheidi Geothermal Power Plant.

TIGeR's involvement in the Hellisheidi project is through Dr. Domenik Wolff-Boenisch who was the laboratory manager and set up the original experimental pilot plant in Iceland. Since taking up a position in the Department of Applied Geology, he continues to be involved in both the experimental and practical aspects of the Hellisheidi project.

Matter et al. (2016) report in the journal Science on the results of a field trial using Reykjavik Energy's injection and monitoring wells. 248 tonnes of CO_2 were injected in two separate phases into basalt rocks around 550m underground. Through observations and tracer studies at the monitoring well, we found that over 95% of the injected CO_2 (around 235 tonnes) was converted to carbonate minerals in less than two years. While the initial amount of injected CO_2 was small, the Icelandic field trial clearly shows that mineralisation of CO_2 is feasible and more importantly, fast.

CO_2 injection bore at Hellisheidi.

Rendel P.M., Gavrieli I., Wolff-Boenisch D., Ganor J. (2016). Gypsum solubility under pressure conditions relevant to CO_2 geological storage. *International Journal of Greenhouse Gas Control*, 55, 15-22.

Wolff-Boenisch D., Galeczka I.M., Mesfin K.G., Gislason S.R. (2016). A foray into false positive results in mineral dissolution and precipitation studies. *Applied Geochemistry*, 71, 9-19.

Matter J.M., Stute M., Snæbjörnsdottir S., Oelkers E.H., Gislason S.R., Aradottir E.S., Sigfusson B., Gunnarsson I., Sigurdardottir H., Gunnlaugsson E., Axelsson G., Alfredsson H.A., Wolff-Boenisch, D. et al. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, 352, 1312-1314.

Research reports

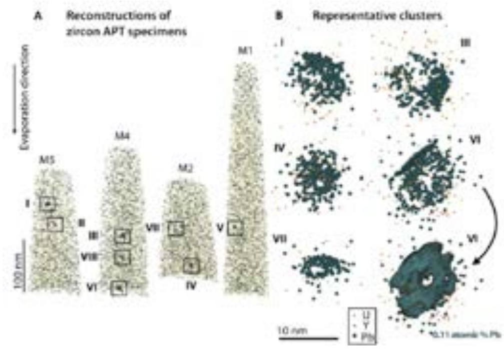
GEOSCIENCE ATOM PROBE FACILITY

Geoscience Atom Probe facility

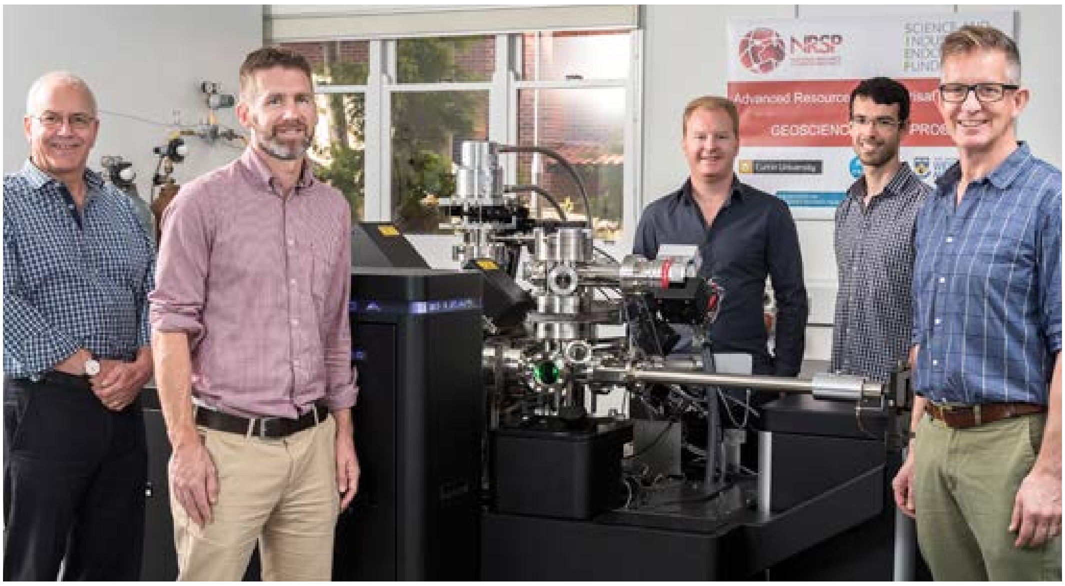
The Geoscience Atom Probe (GAP) facility is the only atom probe laboratory in the world with a focus on geoscience applications. The past year has seen several developments in this exciting field, and the GAP facility (in its first full year of operation) has been at the forefront of these advances in nanoscale geochemical characterisation. Outputs from the facility include: 22 conference and workshop presentations; three high-impact journal publications presenting new insights into nanoscale geochemistry; and involvement in three workshops dedicated to the application of atom probe methods to geoscience, as invited speakers or organisers.

The atom probe method is unique in providing atomic-scale (geo)chemical and isotopic information in three-dimensions with sub-nm spatial resolution. Much of its potential within the geosciences resides in its ability to distinguish isotopic differences at unprecedented length scales. This is a field that is only beginning to develop and is expected to see widespread application in the coming years.

The Geoscience Atom Probe.



APM reconstructions from discordant zircon. (A) Atom map showing clustered distributions of Pb (green) atoms. Each reconstructed dataset measures between 200 and 500 nm in length. (B) Highlighted clusters from within the reconstructed data showing detected Pb, U and Y atoms. Cluster VI is also shown with an isoconcentration surface defined at 0.11 at. % Pb, illustrating a toroidal morphology related to a dislocation loop defect.



An example of the potential for such studies is found in the work on 'nanogeochronology', published in the journal, Science Advances (Peterman et al. 2016). This study, performed within the GAP facility, demonstrated that geologically significant ages could be extracted from Pb reservoir features as small as 10 nm within a discordant zircon (see figure). Individual 206Pb and 207Pb atoms were identified within these nanoscale features and used to calculate a model age consistent with the known age of crystallization.

This research represents a fundamental advance in the development of nanogeochronology by atom probe. It is significant in providing a mechanism for trapping and retaining radiogenic Pb within zircon during metamorphism. It also suggests that isotopic discordance may be caused by discrete nanoscale reservoirs of Pb that record different isotopic compositions and are related to discrete geologic events.

Peterman, E.M., Reddy, S.M., Saxey, D.W., Snoeyenbos, D.R., Rickard, W.D.A., Fougerouse, D., Kylander-Clark, A.R.C. (2016). Nanogeochronology of discordant zircon measured by atom probe microscopy of Pb-enriched dislocation loops. Science Advances 2, e1601318.

Tescan Lyra FIB-SEM with ToF-SIMS

The Tescan Lyra focused ion beam scanning electron microscope (FIB-SEM) facility is part of the Advanced Resource Characterisation Facility and is located within the John de Laeter Centre at Curtin University. It is used extensively to support research involving the Geoscience Atom Probe as well as for high spatial resolution time of flight secondary ion mass spectrometry (ToF-SIMS).

In 2016, the first full year of the instrument's operation, the Lyra was used in a range of studies including the nanoscale distribution of Pb in zircon (Peterman), mechanisms driving Au distribution in arsenopyrite (Fougerouse), Pt-enriched pyroxenites (Barnes) and the trace element migration in shocked zircons (Reddy).

In addition to geoscience work the Lyra was also used for studies on nanoscale chemical interfaces (Liu) and abrasion in stainless steel (Stachowiak). The Lyra was involved in a number of research projects with industry. In particular the ToF-SIMS capability was utilised to map the spatial distribution of lithium in various micas providing valuable information to the industry partner. The Tescan Lyra was used to produce 9 journal articles and 6 conference papers that were published in 2016.

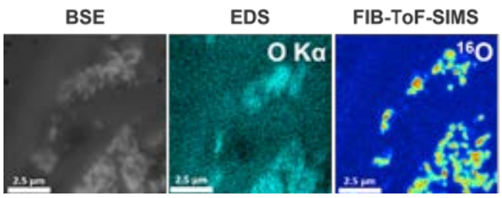


Figure 1. Backscattered (BSE) image with corresponding energy dispersive x-ray spectroscopy (EDS) and FIB-ToF-SIMS elemental maps for oxygen from a coal sample. The high spatial resolution of the ToF-SIMS maps allows for more accurate APM specimen targeting than can be achieved with EDS analyses (Rickard et al 2016).

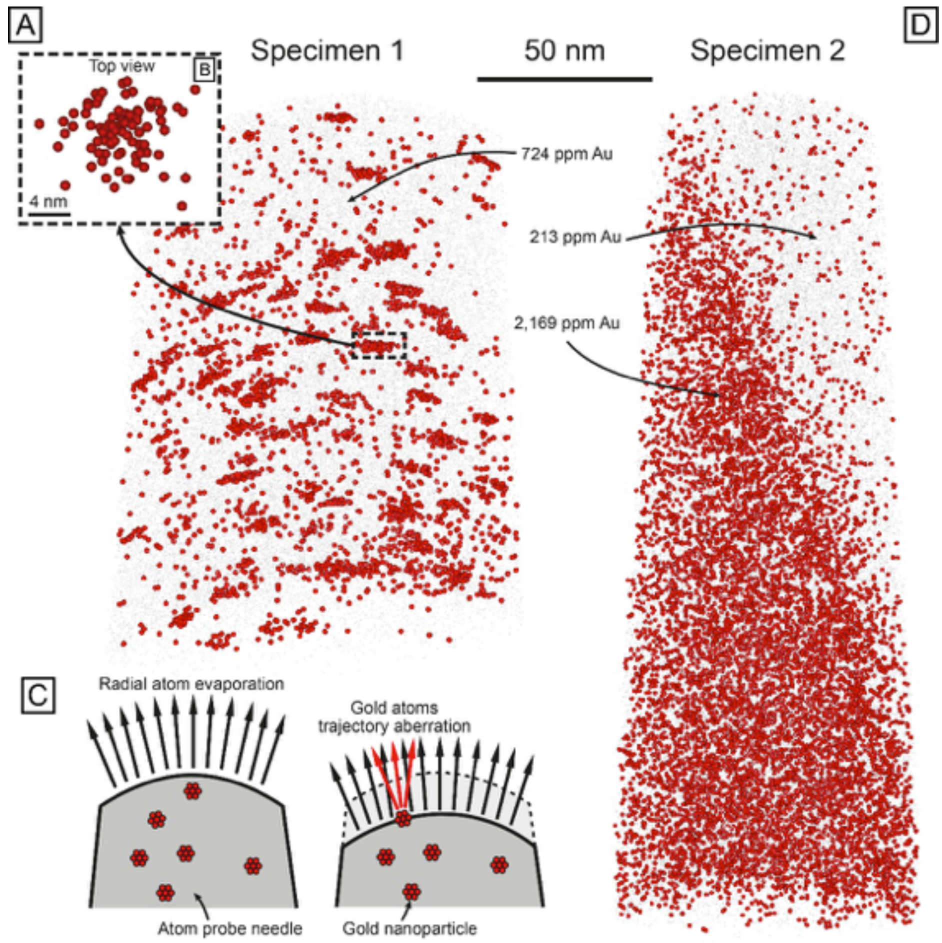
The Tescan Lyra.

Barnes, S.J., L.A. Fisher, B. Godel, M.A. Pearce, W.D. Maier, D. Paterson, D.L. Howard, C.G. Ryan, and J.S. Laird (2016). Primary cumulus platinum minerals in the Monts de Cristal Complex, Gabon: magmatic microenvironments inferred from high-definition X-ray fluorescence microscopy. *Contributions to Mineralogy and Petrology*, 171(3): 23.

Nanoscale gold clusters in arsenopyrite

Auriferous sulfides, most notably pyrite (FeS_2) and arsenopyrite (FeAsS), are among the most important economic minerals on Earth because they can host large quantities of gold in many of the world's major gold deposits. Fougerouse et al. (2016) presented the first atom probe study of gold distribution in arsenopyrite to characterize the three-dimensional (3D) distribution of gold at the nanoscale and provide data to discriminate among competing models for gold incorporation in refractory ores. In contrast to models that link gold distribution to gold concentration, gold incorporation in arsenopyrite is shown to be controlled by the rate of crystal growth, with slow growth rate promoting the formation of gold clusters and rapid growth rate leading to homogeneous gold distribution. This study yields new information on the controls of gold distribution and incorporation in sulfides that has important implications for ore deposit formation. More broadly this study reveals new information about crystal-fluid interface dynamics that determine trace element incorporation into growing mineral phases.

Fougerouse D., Reddy S.M., Saxey D.W., Rickard W.D., Van Riessen A., and Micklethwaite S. (2016). Nanoscale gold clusters in arsenopyrite controlled by growth rate not concentration: Evidence from atom probe microscopy. *American Mineralogist*, 101, 1916-1919.



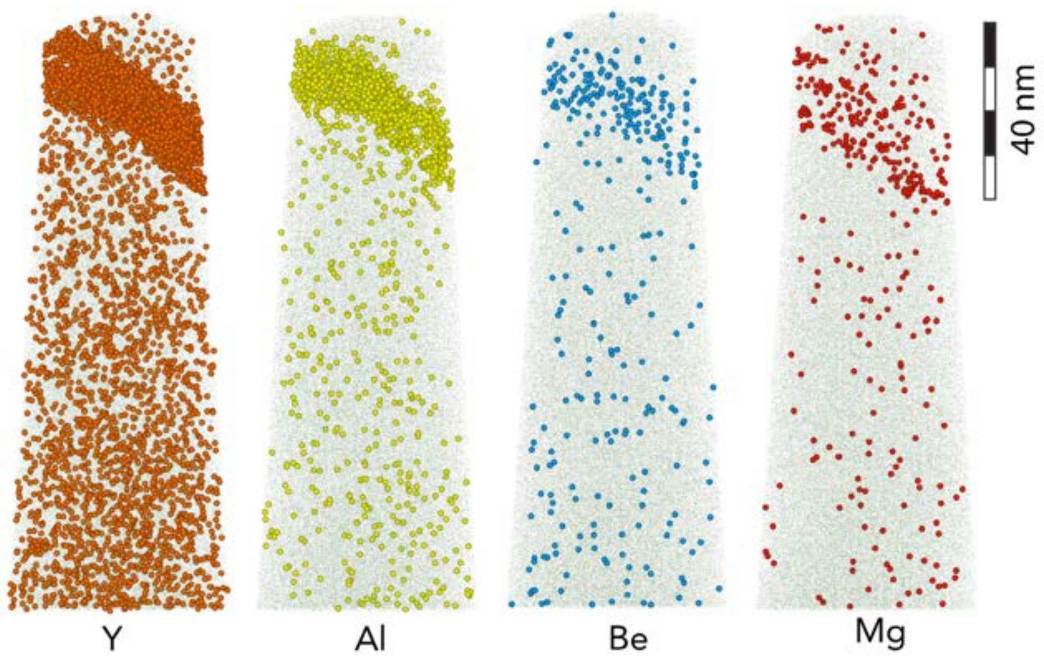
Deformation and element migration in zircon

Deformation during tectonic and impact related strain is known to modify zircon trace element compositions, but the mechanisms by which this occurs remain unresolved. Reddy et al. (2016) combined electron backscatter diffraction, transmission Kikuchi diffraction and atom probe microscopy to investigate trace element migration associated with a ~20 nm wide, 2º low-angle subgrain boundary formed in zircon during a single, high-strain rate, deformation associated with a bolide impact.

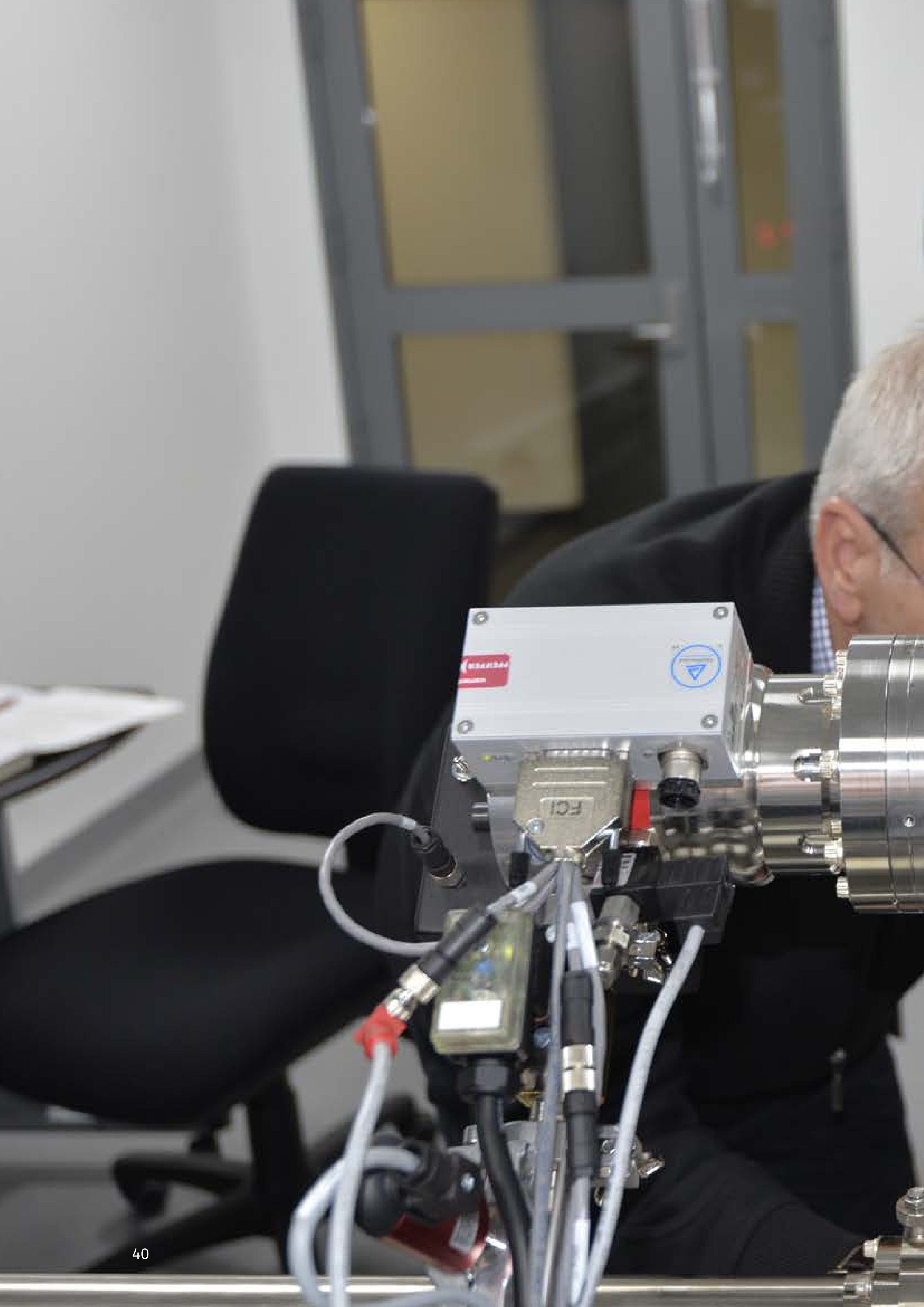
The low-angle boundary shows elevated concentrations of both substitutional (Y) and interstitial (Al, Mg and Be) ions. The observed compositional variations reflect a dynamic process associated with the recovery of shock-induced vacancies and dislocations into lower energy low-angle boundaries. Y segregation is linked to the migration and localisation of oxygen vacancies, whilst the interstitial ions migrate in association with dislocations.

These data represent the direct nanoscale observation of geologically-instantaneous, trace element migration associated with crystal plasticity of zircon and provide a framework for further understanding mass transfer processes in zircon.

Reddy, S.M., van Riessen, A., Saxey, D.W., Johnson, T.E., Rickard, W.D.A., Fougerouse, D., Fischer, S., Prosa, T.J., Rice, K.P., Reinhard, D.A., Chen, Y., Olson, D. (2016). Mechanisms of deformation-induced trace element migration in zircon resolved by atom probe and correlative microscopy. *Geochimica et Cosmochimica Acta,* 195, 158–170.



Reconstruction of atom probe data showing trace element variations for Y, Al, Be and Mg. The coloured spheres represent the positions of the illustrated elements. The band showing increased concentration of trace elements corresponds to the position of a low-angle sub-grain boundary.


FCI

Research reports

ORGANIC AND ISOTOPE GEOCHEMISTRY

(Paleo)climate, Oceans, Continents, Life & Our Resources

The molecular, genetic and stable isotopic composition of organic matter is determined by its source. The elements – hydrogen, carbon, sulfur and nitrogen are basic constituents of organic matter and play key roles in biochemistry, ecology, climate change, hydrologic and atmospheric processes. Therefore stable isotopic compositions preserved in organic matter can provide powerful insights into these processes.

Compound specific isotope analysis – CSIA is important for determining the stable isotopic compositions of individual organic components in complex mixtures (e.g., petroleum, natural gases, sediments, soils, groundwater, potable waters and extracts from plants and other media). The WA Organic & Isotope Geochemistry (WA-OIG) led by Professor Kliti Grice are applying the CSIA technique (carbon, hydrogen & nitrogen) and molecular geochemical and (paleo)genomic techniques to infer relationships between components so that their origins and formation pathways can be established.

Research Themes

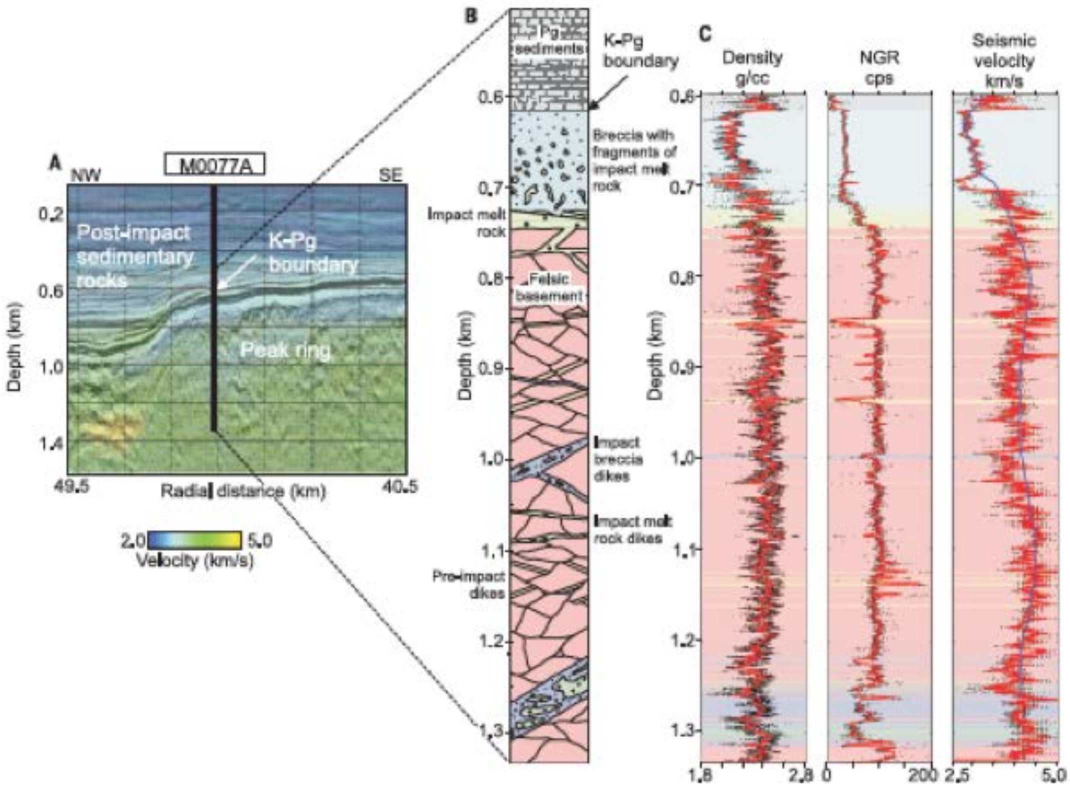
The research themes investigated within WA-OIG using compound specific isotopes, lipid biomarker geochemistry and (paleo) genomics are:

1. Natural Resources (Petroleum & Minerals)
2. Microbial Communities
3. Biochemical Pathways
4. Integrated Ocean Drilling Projects (IODP) & Petroleum
5. Mass Extinctions
6. Climate & Paleoclimate
7. Environment
8. Medical Geochemistry

The formation of the peak ring of the recently cored Chicxulub Impact crater, Yucatan, Mexico

Large impacts provide a mechanism for resurfacing planets through mixing near-surface rocks with deeper material. Central peaks are formed from the dynamic uplift of rocks during crater formation. As crater size increases, central peaks transition to peak rings. Without samples, debate surrounds the mechanics of peak-ring formation and their depth of origin. Chicxulub is the only known impact structure on Earth with an unequivocal peak ring, but it is buried and only accessible through drilling. Integrated Ocean Drilling Program (IODP) Expedition 364 sampled the Chicxulub peak ring, which we found was formed from uplifted, fractured, shocked, felsic basement rocks. The peak-ring rocks are cross-cut by dikes and shear zones and have an unusually low density and seismic velocity. Large impacts therefore generate vertical fluxes and increase porosity in planetary crust.

Morgan J.V., Gulick S.P.S., Bralower T., Chenot E., Christeson G., Claeys P., Cockell C., Collins G.S., Coolen M.J.L., Ferrière L., Gebhardt C., Goto K., Jones H., Kring D.A., Le Ber E., Lofi J., Long X., Lowery C., Mellett C., Ocampo-Torres R., Osinski G.R., Perez-Cruz L., Pickersgill A., Poelchau M., Rae A., Rasmussen C., Rebolledo-Vieyra M., Riller U., Sato H., Schmitt D.R., Smit J., Tikoo S., Tomioka N., Urrutia-Fucugauchi J., Whalen M., Wittmann A., Yamaguchi K.E., Zylberman W. (2016). The formation of peak rings in large impact craters. *Science*, 354, 878-882.



IODP/ICDP Expedition 364. (A) Location of Site M0077A (B) Lithology encountered at SiteM0077A from 600m to total depth. (C) Corresponding petrophysical properties: gamma density [grams per cubic centimeter (g/cc)] and NGR [counts per second (cps)] measured on the cores using a MSCL, and seismic P wave velocity (km/s) obtained from sonic (red) and VSP (blue) wireline logging data.

An organic and inorganic geochemical appraisal of a Toarcian fossil-bearing carbonate concretion

Carbonate concretions are widespread within the geological record. However, the lack of recent known analogues creates a need for novel approaches to unravel the major microbial players involved in concretion formation and establish their suitability as palaeoenvironmental recorders. Plet et al. (2016) used a combination of geochemical and geological techniques to study two pyritiferous calcite concretions and compared the results with their host sediment (Toarcian "Posidonia Shale", 183 Ma, SW-Germany). The 13C-depleted nature of the concretion bodies, with average values of $\delta 13C_{carb}$ (−14.8‰), $\delta 13C_{org}$ (−32.4‰), and $\delta 13C_{n\text{-}alkanes}$ (−34.9‰), indicates that sulfate-reducing bacteria (SRB), played a major role in the concretion growth and preservation of the nucleus via the rapid decomposition of organic matter (OM). However, Rock-Eval analyses from both concretions revealed elevated hydrogen indices (HI) in the body and low HI values at the rim.

These values suggest that most of the microbial activity did not occur in the concretion body but rather at the rim and at the surface of the nuclei, which generally supports the exceptional preservation of OM in carbonate concretions. Furthermore, enrichment in euhedral pyrite in the concretion rims suggests they were formed through increased activities of iron reducing (FeR) bacteria coupled to a decrease of SRB activity leading towards conditions more favourable to the direct precipitation of pyrite. Despite low δ13C values, the known lipid biomarkers such as acyclic extended isoprenoids or 3β-methyl-hopanes did not reveal evidence of an active methane cycling.

The present study emphasises the crucial role of carbonate concretion in OM preservation and highlights their great potential as palaeoenvironmental recorders.

Plet C., Grice K., Pages A., Coolen M.J.L., Schwark L. (2016). Microbially-mediated fossil-bearing carbonate concretions and their significance for palaeoenvironmental reconstructions: A multi-proxy organic and inorganic geochemical appraisal. *Chemical Geology*, 426, 95-108.

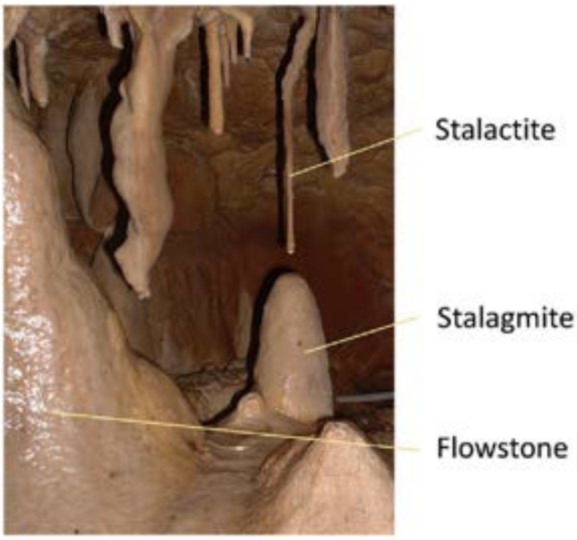
Organic proxies in speleothems

Blyth et al. (2016) and Baker et al. (2016) focus on how organic matter is transported and preserved in cave deposits. Baker et al. (2016) demonstrated that molecules derived from archea that are used in reconstructing temperature are not being transported from the overlying soil, but are generated in the cave. This provides a new basis for considering the future calibration of this palaeothermometer.

Blyth et al. (2016) is an invited review paper summarising the current state of the art in the analysis of organic matter in speleothems, focusing on how material is transported to the cave, to what degree it is generated in situ, and the advantages and limitations of different forms of organic proxy record. The paper shows that analysis of organic matter in calcite deposits is a growing field, which offers considerable potential in the reconstruction of past environments.

Blyth A.J., Hartland A., Baker A. (2016). Organic proxies in speleothems - New developments, advantages and limitations. *Quaternary Science Reviews*, 149, 1-17.

Baker A., Jex H., Rutlidge H., Woltering M., Blyth A.J., Andersen M., Cuthbert M., Marjo C., Markowska C., Rau G. (2016). An irrigation experiment to compare soil, water and speleotherm tetraether membrane lipid distributions. *Organic Geochemisty*, 94, 12-20.



Linking sequences to environments through text mining

Understanding the distribution of taxa and associated traits across different environments is one of the central questions in microbial ecology. High-throughput sequencing (HTS) studies are presently generating huge volumes of data to address this biogeographical topic. However, these studies are often focused on specific environment types or processes leading to the production of individual, unconnected datasets. The large amounts of legacy sequence data with associated metadata that exist can be harnessed to better place the genetic information found in these surveys into a wider environmental context. Here we introduce a software program, seqenv, to carry out precisely such a task. It automatically performs similarity searches of short sequences against the "nt" nucleotide database provided by NCBI and, out of every hit, extracts–if it is available–the textual metadata field. After collecting all the isolation sources from all the search results, we run a text mining algorithm to identify and parse words that are associated with the Environmental Ontology (EnvO) controlled vocabulary. This, in turn, enables us to determine both in which environments individual sequences or taxa have previously been observed and, by weighted summation of those results, to summarize complete samples. We present two demonstrative applications of seqenv to a survey of ammonia oxidizing archaea as well as to a plankton paleome dataset from the Black Sea. These demonstrate the ability of the tool to reveal novel patterns in HTS and its utility in the fields of environmental source tracking, paleontology, and studies of microbial biogeography.

Sinclair L., Ijaz U.Z., Jensen L., Coolen M.J., Gubry-Rangin C., Chroňáková A., Oulas A., Pavloudi C., Schnetzer J., Weimann A., Ijaz A., Eiler A., Quince C., Pafilis E. (2016). Seqenv: linking sequences to environments through text mining. *PeerJ*, 4, e2690.

Hydrocarbons and the environmental legacy of shipwrecks

Like all vessels sunk during service, the HMAS *Sydney (II)* and HSK *Kormoran* had fuel oil and other hydrocarbons on board when they sank. This project's science program provided a unique opportunity to investigate and estimate the rate of deterioration, and the pollution potential of any hydrocarbons that had leaked from the two vessels. The types of oils and fuel on both vessels are known from the historical record. To check if any hydrocarbons had leaked into the surrounding water and sediments, it was decided to collect both sediment and water samples from sites close to both the HMAS *Sydney (II)* and HSK *Kormoran* and at an 'upstream' reference site some distance away from the wrecks.

This variety of samples allowed Harvey et al. (2016) to determine two potential environmental effects. The first was to determine if it is possible to measure hydrocarbon concentrations in the water column and in sediment samples. The second was to determine if microbes with the capacity to degrade hydrocarbons are present in the sediments and/or the water column around the wreck sites.

Analyses of degraded organic hydrocarbons in the sediments by two dimensional gas chromatography × gas chromatography time-of-flight mass spectrometry (GC×GC TOF MS) revealed a high amount of unusual (microbially-formed) components, in addition to waxes from fresh coastal vegetation (dry climate grasses). Paired high throughput sequencing of sedimentary chloroplast DNA confirmed that the waxes were derived from dry climate grasses in the distant coastal vegetation.

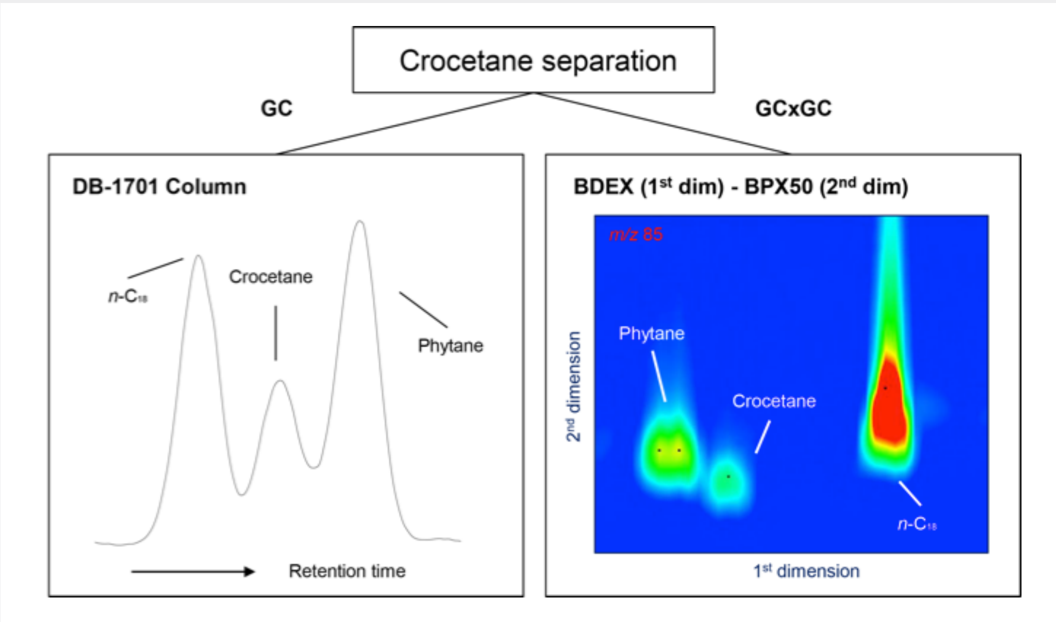
Moreover the sequencing of environmental DNA revealed a possible candidate bacterium that could be *involved in the degradation of complex hydrocarbons in the sediments based on its high genetic similarity to bacteria associated with the Gulf of Mexico deep horizon oil spill*. Based on this finding, in the event of a future oil spill in this region there may be naturally-occurring microbes in these sea floor sediments that would be capable of degrading the oil.

Harvey E. S., Bunce M., Stat M., Saunders B.J., Kinsella B.J., Machuca L., Lepkova K., Grice K., Coolen M., Williams A., et al. 2016. "Science and the Sydney." In From Great Depths The Wrecks of HMAS Sydney [II] and HSK Kormoran, 279-303. Australia: UWA Publishing and The Western Australian Museum.

Separating crocetane and phytane using GC-MS and GC´GC-TOFMS

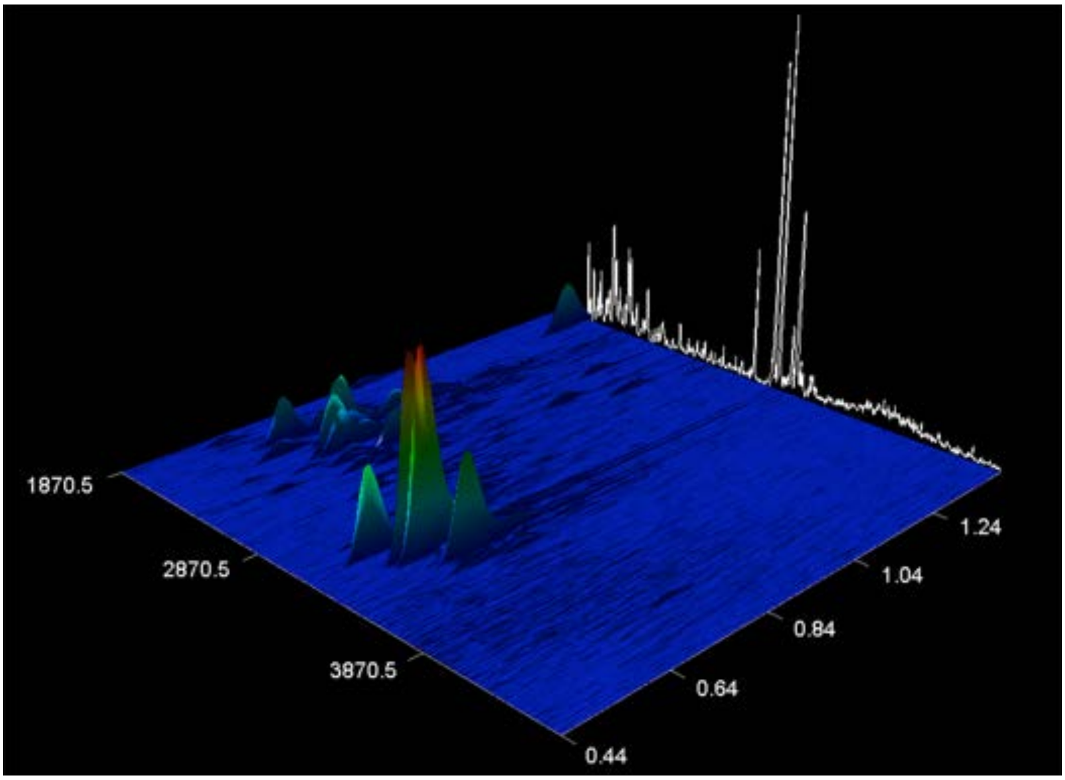
Crocetane and phytane are diagnostic biomarkers routinely used as proxies in organic geochemical studies. However, due to their structural similarity is it analytically challenging to separate these two compounds. Spaak et al. (2016) explored different chromatographic methods to separate crocetane and phytane. This resulted in improved separation on both GC-MS and GC×GC–TOFMS systems. Baseline separation was achieved using a chiral primary and BPX50 secondary column on the GC×GC–TOFMS. GC×GC–TOFMS method allows minimal sample preparation.

Spaak G., Nelson R.K., Reddy C.M., Scarlett A.G., Chidlow G., Grice K. (2016). Advances on the separation of crocetane and phytane using GC-MS and GC´GC-TOFMS. *Organic Geochemistry*, 98, 176-182.



Using biomarkers to characterise crude oils and their source rocks

Over the past few decades the characterisation of crude oils and their source rocks using hydrocarbon biomarkers has expanded and improved enormously. These biomarkers, sometimes referred to as molecular fossils, have proved useful across a range of applications particularly for oil-source rock correlations and for pollution identification studies. However, for highly weathered and/or biodegraded samples the number of biomarkers available for characterisation becomes increasingly limited. More recently, the polar constituents of crude oil, such as carboxylic acids, have come under scrutiny. This has been particularly important for characterising waste water from the oil sands industry of Alberta Canada where the acid fraction of extracted bitumen has become concentrated into a supercomplex mixture of so-called 'naphthenic acids' – a broad oil industry term for a range of mainly alicyclic carboxylic acids but estrogenic aromatic acids can represent a large fraction of the compounds in the process-affected waters. There has been only limited success at structural identification of the acids present in these waters or indeed in crude oils generally. However, even without complete structural identification, the use two-dimensional gas chromatography with time-of-flight mass spectrometry (GC×GC-TOFMS) has proved powerful enough to resolve the peaks in the supercomplex mixture sufficiently to enable comparisons between waste water storage ponds from different industries and river water. For example compounds hypothesised



'Mountain view' 3-D GC×GC-TOFMS chromatogram of an aromatic acid fraction (as methyl esters) of a light crude oil using an ionic liquid primary capillary column.

to be monoaromatic tricylic acids were successfully used by Frank et al (2016) to discriminate between spatial and temporal samples from multiple tailings ponds containing process-affected waters.

Characterisation of crude oils (and potential source rocks) using acids is currently being applied by WAOIGC. To better understand what acids are present in crude oils, different methods of extracting the acids are being trialled and the fractions analysed by a range of techniques including GC×GC-TOFMS. In addition, new chromatographic column configurations for GC×GC have been developed to optimise the separation of aromatic acids as methyl esters. The results of this novel configuration, utilising an extremely polar ionic liquid capillary primary column, was presented at the recent Australian Organic Geochemistry Conference in Fremantle.

Scarlett A.G., West C.E., Peru K.M., Hewitt L.M. (2016). Assessing spatial and temporal variability of acid-extractable organics in oil sands process-affected waters. *Chemosphere*, 160, 303-313.

Dissanayake A., Scarlett A.G., Jha A.N. (2016). Diamondoid naphthenic acids cause in vivo genetic damage in gills and haemocytes of marine mussels. *Environmental Science and Pollution Research*, 23, 7060-7066.

Jonker M.A., Candido C., Vrabie C., Scarlett A., Rowland S. (2016). Synergistic androgenic effect of a petroleum product caused by the joint action of at least three different types of compounds. *Chemosphere*, 144, 1142-1147.

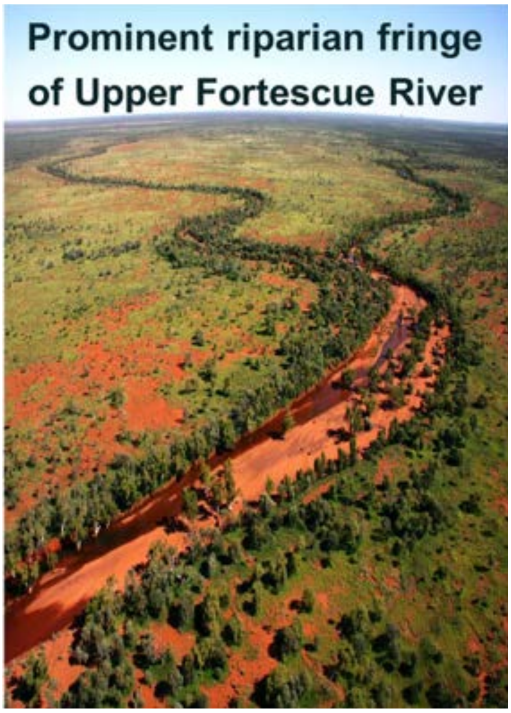
Scherr K., Backes D., Scarlett A., Lantschbauer W., Nahold M. (2016). Biogeochemical gradients above a coal tar DNAPL. *Science of the Total Environment*, 563, 741-754.

Evidence for extreme floods in arid subtropical northwest Australia during the Little Ice Age chronozone

Rouillard et al. (2016) conducted an organic geochemical study of a multi-dated (^{210}Pb, ^{137}Cs and ^{14}C) late Holocene sedimentary core from the Fortescue Marsh (Pilbara, NW Australia) to evaluate the potential of using the hydrocarbon products and $\delta^{13}C$ values of plant waxes detected in these sediments for reconstructing catchment vegetation and hydroclimatic histories of this arid environment. The low total carbon (TC) content (<1.4%) of the core – consistent with the low OM contents of modern Pilbara soils and typical of both oligotrophic aquatic systems and dry stream-bed sediments - challenged the sensitivity of these analyses. Notwithstanding, three separate period sections of the core - P1 (*CE 1990 – 2012*); P2 (*CE 1600 – 1990*); and P3 (*CE 700-1600*) - each revealed a wide distribution of aliphatic hydrocarbons.

The relative contribution of C3 and C4 plant sources in P1-P3 were estimated by a mixing model developed using the mean $d^{13}C$ values of n-alkanes from C3 or C4 sources from a literature survey of arid zone studies. Their model suggests C4 plants make 41–50% median contribution towards the n-alkanes detected. Interestingly, this was notably lower than the current 64% (aboveground biomass) landscape dominance of grasses. The large riparian fringe of the Fortescue Marsh may contribute to this discrepancy. Riparian vegetation can produce slightly ^{13}C depleted n-alkanes compared to most other C3 plant sources.

These results show that it is possible to extract organic molecular fossil distributions and $\delta^{13}C$ of n-alkanes from lake sediments of low OM content in tropical arid ecosystems.



Rouillard A., Skrzypek G., Turney C., Dogramaci S., Hua Q., Zawadzki A., Reeves J., Greenwood P.F., O'Donnell A.J.,Grierson P.F. (2016). Evidence for extreme floods in arid subtropical northwest Australia during the Little Ice Age chronozone (CE 1400–1850). *Quaternary Science Reviews*, 144, 107-122.

Climate oscillations reflected in the Arabian Sea subseafloor microbiome

Marine sediment contains a vast microbial biosphere that influences global biogeochemical cycles over geological timescales. However, the environmental factors controlling the stratigraphy of subseafloor microbial communities are poorly understood.

Orsi et al. (2016) studied a sediment core directly underlying the Arabian Sea oxygen minimum zone (OMZ), which exhibits organic carbon rich sapropelic laminae deposited under low oxygen conditions. Consistent with several other cores from the same location, age dating revealed the sapropelic layers coincide with warm North Atlantic millennial-scale Dansgaard-Oeschger events, indicating a direct link between the strength of the OMZ and paleoclimate. A total of 214 samples spanning 13 m and 52 Kyr of deposition were selected for geochemical analyses and paleoclimate proxy measurements, as well as high-throughput metagenomic DNA sequencing of bacteria and archaea. A novel DNA extraction protocol was developed that allowed for direct (unamplified) metagenomic sequencing of DNA from each sample. This dataset represents the highest resolved sedimentary metagenomic sampling profile to date. Analysis of these data together with multiple paleoceanographic proxies show that millennial-scale paleoenvironmental conditions correlate with the metabolism and diversity of bacteria and archaea over the last glacial-interglacial cycle in the Arabian Sea. The metabolic potential for bacterial denitrification correlates with climate-driven OMZ strength and concomitant nitrogen stable isotope fractionation, whereas catabolic potential reflects changing marine organic matter sources across the Last Glacial Maximum.

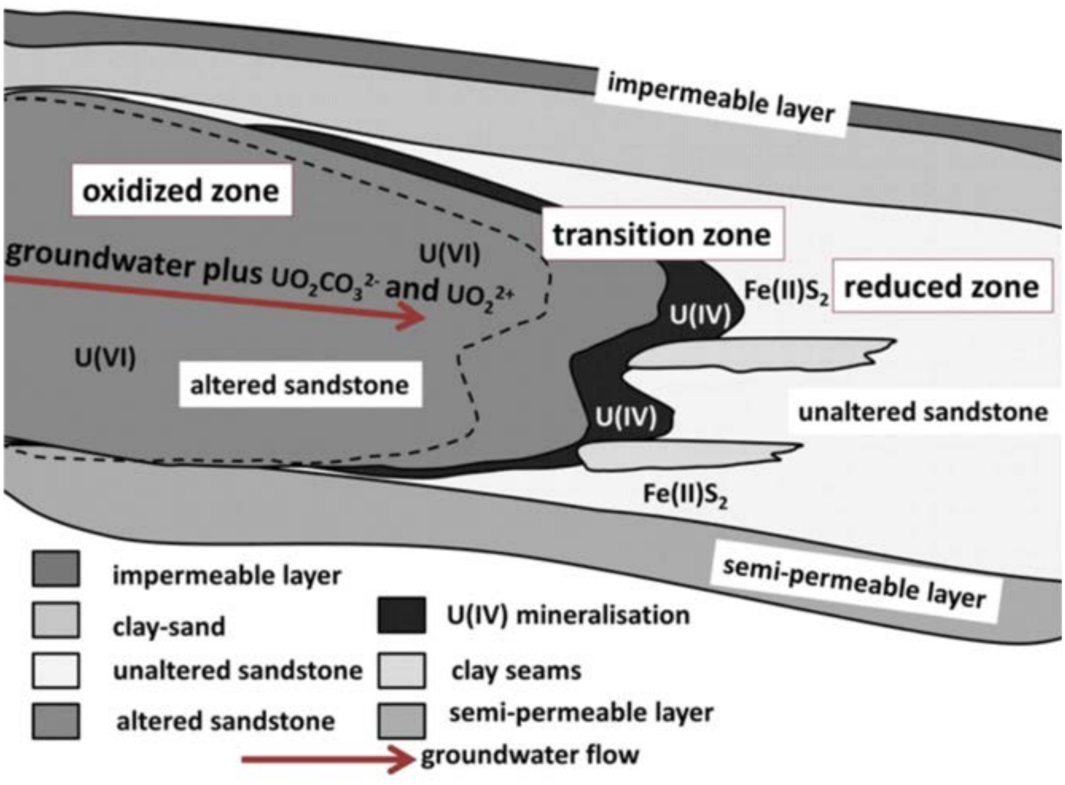
These results indicate that the subsisting microbial communities had been stratified to a large extent by paleoceanographic conditions at the time of deposition. Paleoenvironmental conditions should thus be considered as a mechanism that can help explain microbiome stratigraphy in marine sediment.

Orsi, W.D., Coolen, M.J.L., He, L., Wuchter, C., Irigoien, X., Chust, G., Johnson, C., Hemingway, J., Lee, M., Galy, V., Giosan, L., Climate oscillations reflected in the Arabian Sea subseafloor microbiome. EGU General Assembly 2016, p.4912

Uranium mobility in organic matter-rich sediments

Uranium (U) is of enormous global importance because of its use in energy generation, albeit with potential environmental legacies. While naturally occurring U is widespread in the Earth's crust at concentrations of ~1 to 3 ppm, higher concentrations can be found, including within organic matter (OM)-rich sediments, leading to economic extraction opportunities. The primary determinants of U behaviour in ore systems are of U(VI)) will also influence the mobility of U. In addition, the presence of OM can influence U mobility and fate by the degree of OM sorption to mineral surfaces (e.g. Fe- and Si- oxides and hydroxides). Within solid-phase OM, microbes can influence U oxidation state and U stability readily susceptible to reoxidation and therefore more likely remobilised over longer time periods. Thus several areas of uncertainty remain with respect to factors contributing to U accumulation, stability and/or (re)mobilisation. To address these uncertainties, Cumberland et al. (2016) review U dynamics at both geological and molecular scales.

Cumberland S.A., Douglas G., Grice K., and Moreau J. (2016). Uranium mobility in organic matter-rich sediments: a review of geological and geochemical processes. *Earth Science Reviews*, 159, 160-185.

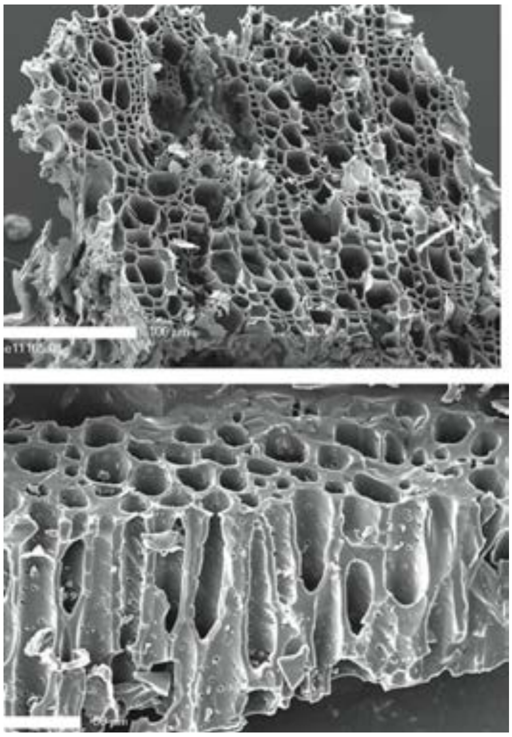


Conceptual diagram of a uranium roll-front deposit in cross-section. Oxidised groundwater moves from left to right. The roll front associated interface moves in the same direction. Mineralised U(IV) precipitates along the transition zone as shown in black.

Cretaceous fire in Australia: a review with new geochemical evidence, and relevance to the rise of the angiosperms

Much of the Australian flora has high flammability. It is therefore of interest whether burning was a feature in the Cretaceous, the geological period in which angiosperms rose to dominance. Determining the extent of fire in the Australian Cretaceous is limited by a paucity of surface exposures of strata, and of published reports of definite charcoal from exploration cores. Nevertheless, charcoalified tissues occur much more widely than is currently reported in the international literature, and there are also numerous references to inertinite macerals in Australian Cretaceous coals. Combustion-related hydrocarbons can also be detected in ancient sediments using organic geochemical methods, and Carpenter et al. (2016) demonstrate the potential of this approach here.

Overall, the available evidence is in concert with that from elsewhere on Earth: fire was apparently widespread in the Australian Cretaceous, and can reasonably be invoked as a force that influenced the evolution of modern Australian environments. Just as in extant open, nutrient-limited regions, proteaceous lineages seem to have been important in burnt, open habitats in the Late Cretaceous, perhaps retaining dominance of such niches for >70 million years. However, there is so far no fossil evidence for the Cretaceous presence of *Eucalyptus*, the principal tree genus of modern Australian fire-prone vegetation.



Scanning electron images of charcoalified plant tissues from the Huckitta 11 borehole, Central Australia.

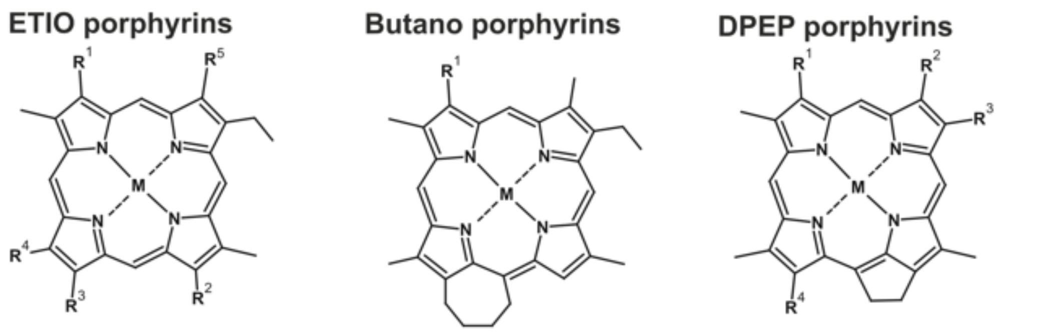
Carpenter R., **Holman A.**, Abell A., **Grice K.** (2016). Cretaceous fire in Australia: a review with new geochemical evidence, and relevance to the rise of the angiosperms. *Australian Journal of Botany*, 64, 564-578.

Simultaneous quantitative analysis of Ni, VO, Cu, Zn and Mn geoporphyrins by liquid chromatography-high resolution multistage mass spectrometry: Method development and validation

Woltering et al. (2016) describe a method for the identification and quantification of Cu, Ni, VO, Zn and Mn metalloporphyrins in geological samples using a high performance liquid chromatography (HPLC) system coupled to a high resolution Thermo Orbitrap XL mass spectrometer (MS) and verified the suitability of the methodology for the quantification of these compounds.

The method was validated by the analysis of complex porphyrin distributions in geological sample isolates from the Australian Toolebuc Formation and Bight Basin. The methodology described in the paper provides a new high resolution tool for routine analysis of complex metalloporphyrin distributions in geological sample extracts, enabling the simultaneous quantitative analysis of Cu, Ni, VO, Zn and Mn porphyrins without the need of prior demetalation or further fractionation of the porphyrin extract.

Woltering M., Tulipani S., Walshe J., Schwark L., Boreham C.J., Grice K. (2016). Simultaneous quantitative analysis of Ni, VO, Cu, Zn and Mn geoporphyrins by liquid chromatography – high resolution multistage mass spectrometry: Method development and validation. *Chemical Geology*, 441, 81-91.

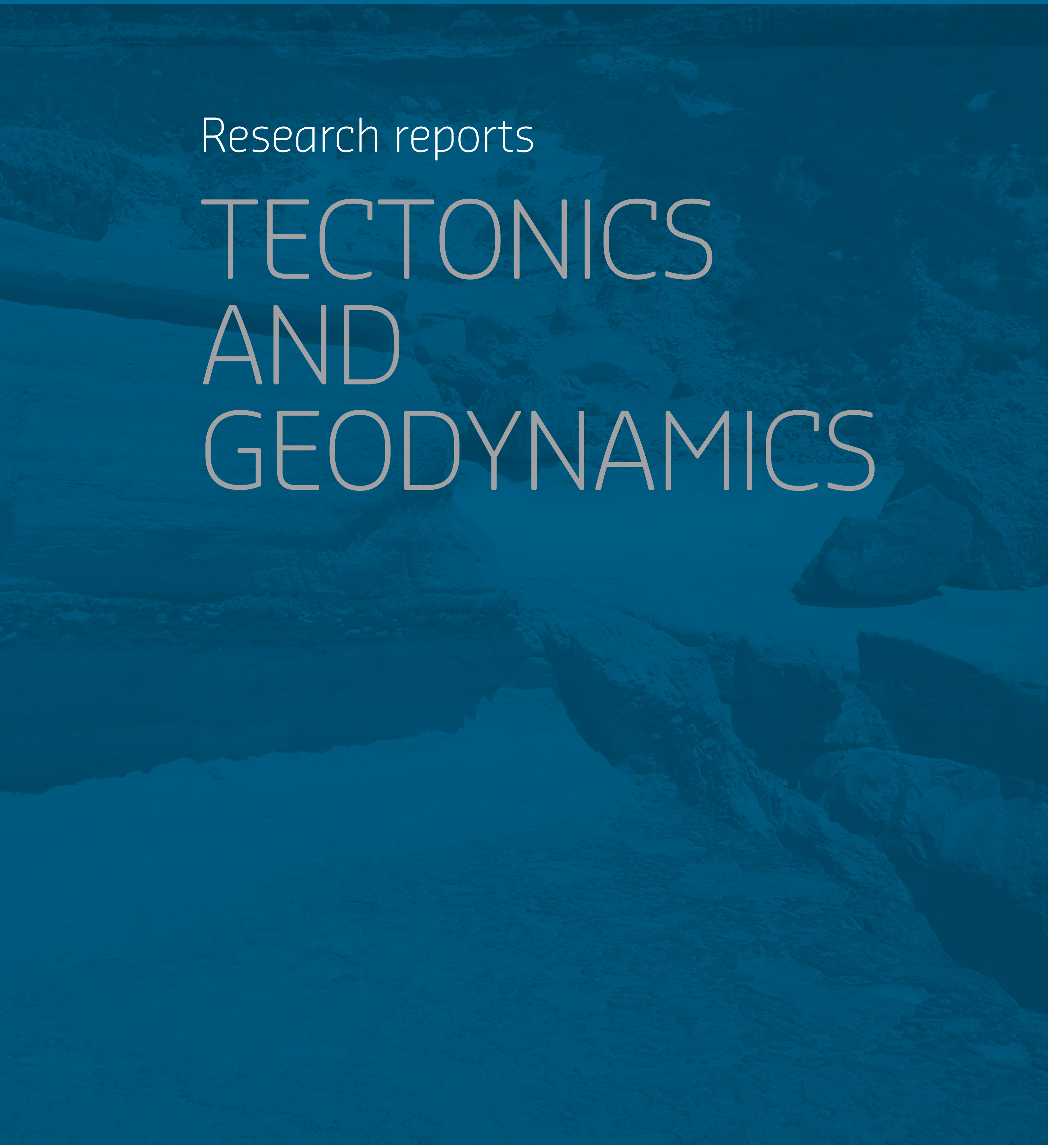


3a: M=Ni; $R^{1,2}$=H, R^3=Et, R^4=Me, R^5=H (C_{28})

4a: M=Ni; R^1=H (C_{30})
4b: M=Ni; R^1=Me (C_{31})
4c: M=Ni; R^1=Et (C_{32})

5a: M=Ni; R^1=H, R^2=Me, $R^{3,4}$=Et C_{30}
5b: M=Ni; $R^{1,2}$=Me, $R^{3,4}$=Et (C_{31})
5d: M=Ni; $R^{1,3,4}$Et, R^2=Me (C_{32})

Structure of some selected porphyrins.



Research reports

TECTONICS AND GEODYNAMICS

Tectonics and geodynamics

Tectonics and geodynamics involve the understanding of processes related to the motion of tectonic plates through time such as mountain building, basin formation and cyclic evolution of supercontinents, and the interaction of tectonic plates with the Earth's deep interior. Such knowledge is essential for understanding life evolution, environmental changes, and the exploration of mineral and energy resources.

The Earth Dynamics Research Group

Supercontinent Cycles and Global Geodynamics — How the Earth Engine Works, is mainly funded by an ARC Laureate Fellowship grant to Zheng-Xiang Li, a flagship research project funded by the ARC Center of Excellence for Core to Crust Fluid Systems and Curtin University matching funds.

We study the dynamic distribution and evolution of tectonic plates on Earth through time, geodynamic driving mechanisms and tectonic processes, and their relevance to Earth resources and environments. We have a particular focus on supercontinent cycles, global plume records, and 4D geodynamic modelling.

Our research involves palaeomagnetism, all aspects of field-based studies, geochemical, petrological, and geochronological analyses, data-mining, numerical modelling, and regional to global syntheses.

The Earth Dynamics Research Group.

IGCP648 Group.

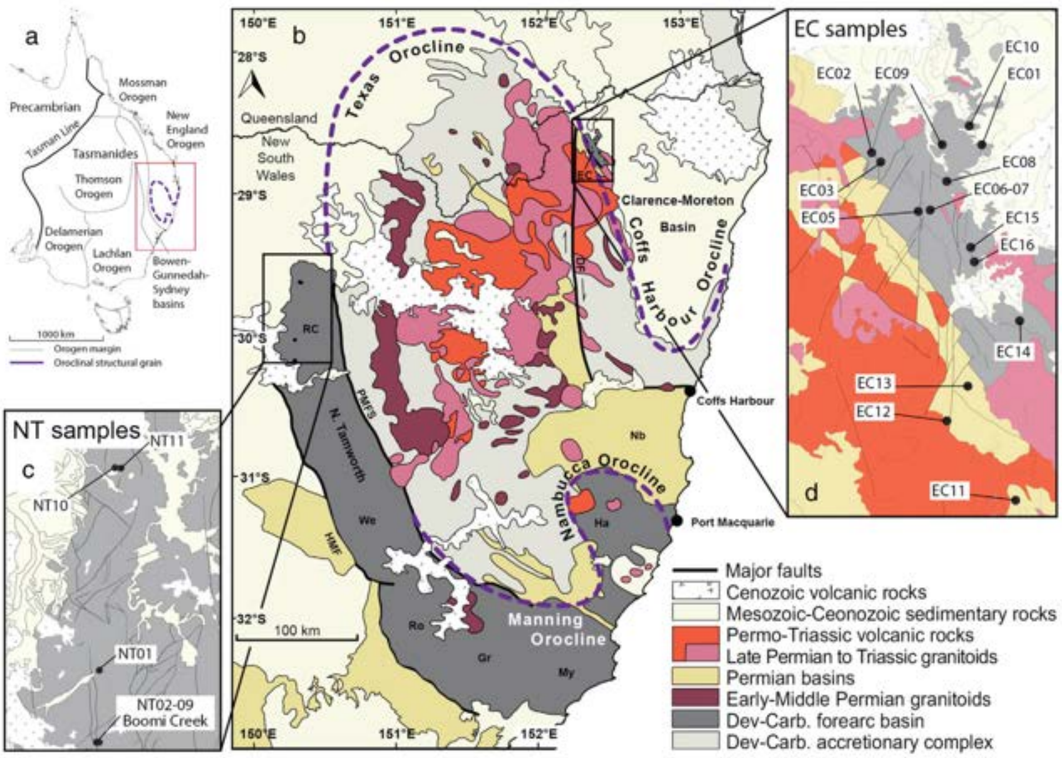
Our field regions cover all major cratons of Australia, and many other parts of the world. In 2016 we kick started a major field-based program to investigate northeastern Australia's record of the assembly and breakup of the supercontinent Nuna, and continued to work on geochronological, palaeomagnetic, geochemical, and basin record or supercontinent cycles in field regions ranging from Australia, Antarctica, China, Russia, South America, and other parts of the world. Out team, consisting mostly ECRs and PhD students, presented many preliminary findings at the Australian Earth Science Convention in Adelaide in June 2016, and many exciting new science findings will be published in the coming year.

Our research program goes hand-in-hand with the UNESCO/IUGS-funded IGCP 648 project: Supercontinent Cycles and Global Geodynamics. In 2016 the project organised special sessions at four international conferences and published two special volumes on research outcome.

Paleomagnetic and geochronological study of Carboniferous forearc basin rocks in the Southern New England Orogen (Eastern Australia)

Pisarevsky et al. (2016) have carried out a paleomagnetic study from Carboniferous forearc basin rocks that occur at both limbs of the Texas Orocline. Using thermal and alternating field demagnetizations, two remanence components have been isolated from rocks sampled from the Emu Creek terrane, in the eastern limb of the orocline. A middle-temperature Component M is post-folding and was likely acquired during low-temperature oxidation at 65–35 Ma. A high-temperature Component H is pre-folding, but its comparison with the paleomagnetic data from coeval rocks in the northern Tamworth terrane on the other limb of Texas Orocline does not indicate rotations around a vertical axis, as expected from geological data. A likely explanation for this apparent discrepancy is that Component H postdates the oroclinal bending, but predates folding in late stages of the 265–230 Ma Hunter Bowen Orogeny. A paleomagnetic study of volcanic and volcaniclastic rocks in the Boomi Creek area (northern Tamworth terrane) revealed a stable high-temperature pre-folding characteristic remanence, which is dated to c. 318 Ma using U–Pb zircon geochronology. The combination of new paleomagnetic and geochronological data resulted in a revised kinematic model of the New England Orogen from 340 Ma to 270 Ma, which compared to the previous model, incorporates a different orientation of the northern Tamworth terrane at 340 Ma.

Pisarevsky S.A., Rosenbaum G., Shaanan U., Hoy D., Speranza F., Mochales T. (2016). Paleomagnetic and geochronological study of Carboniferous forearc basin rocks in the Southern New England Orogen (Eastern Australia). *Tectonophysics* 681, 263-277.

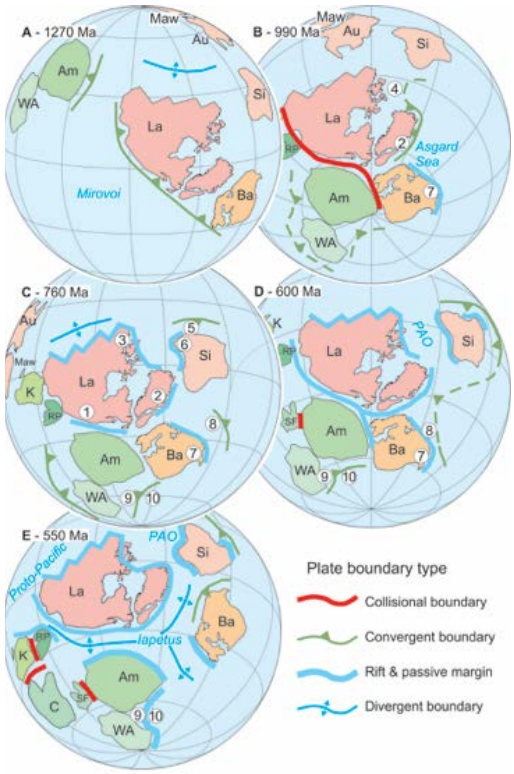


Linking collisional and accretionary orogens during Rodinia assembly and breakup: Implications for models of supercontinent cycles

Periodic assembly and dispersal of continental fragments has been a characteristic of the solid Earth for much of its history. Geodynamic drivers of this cyclic activity are inferred to be either top-down processes related to near surface lithospheric stresses at plate boundaries or bottom-up processes related to mantle convection and, in particular, mantle plumes, or some combination of the two.

Analysis of the geological history of Rodinian crustal blocks suggests that internal rifting and breakup of the supercontinent were linked to the initiation of subduction and development of accretionary orogens around its periphery. Thus, breakup was a top-down instigated process.

The temporal link between external subduction and internal extension suggests that breakup was initiated by a top-down process driven by accretionary tectonics along the periphery of the supercontinent. Plume-related magmatism may be present at specific times and in specific places during breakup but is not the prime driving force.



Palaeogeographic reconstructions for the time period from 1270Ma to 550Ma covering the assembly and dispersal of Rodinia.

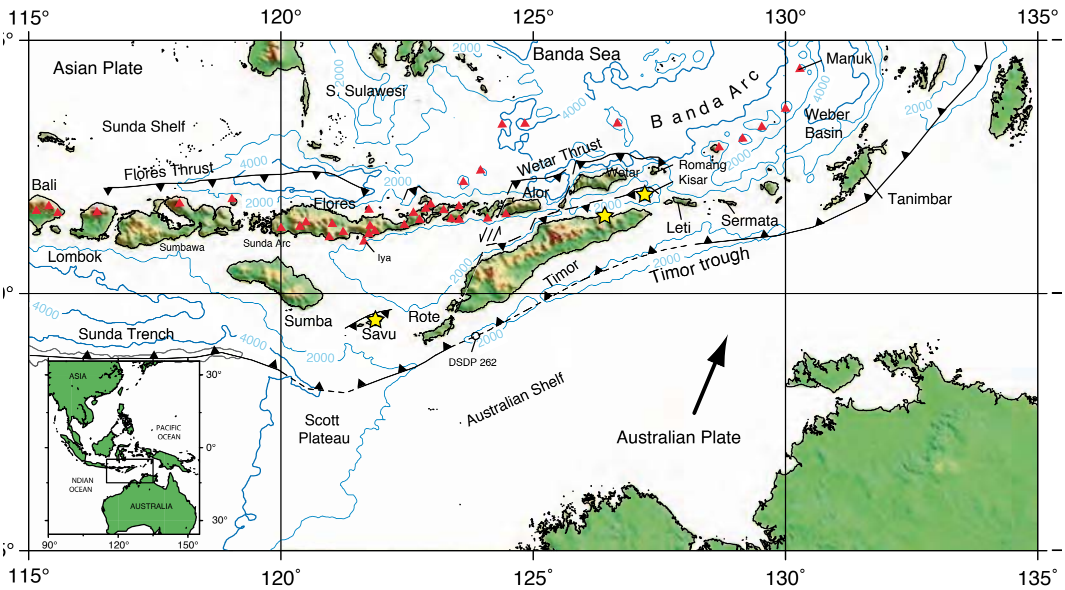
Cawood, P.A., Strachan, R., Pisarevsky, S.A., Gladkochub, D.P., Murphy, J.B., 2016. Linking collisional and accretionary orogens during Rodinia assembly and breakup: Implications for models of supercontinent cycles. *Earth and Planetary Science Letters* 449,118-126.

Using Zircon U-Pb and Hf isotopes in zircon to to track the provenance of sediments accreted to the Banda Arc

As the Australian continent has plowed northward and collided with the Banda volcanic arc the overlying sedimentary cover was scraped off at the subduction zone. Sediment that was originally deposited off the northern Australian margin now forms much of the island of Timor in a spectacular succession of deformed sedimentary rocks. Identifying the original source of these sediments is important to understanding the pre-collision geometry and history of the NW continental margin of Australia.

Spencer et al. (2016) analysed these sediments using detrital zircon geochronology, isotope geochemistry, and sedimentary petrology, and hypothesized that these sediments share an affinity similar to that of continental fragments now found in central Asia. This paper further supports the paleogeography of these fragments and their juxtaposed with Australia prior to the breakup of Gondwana.

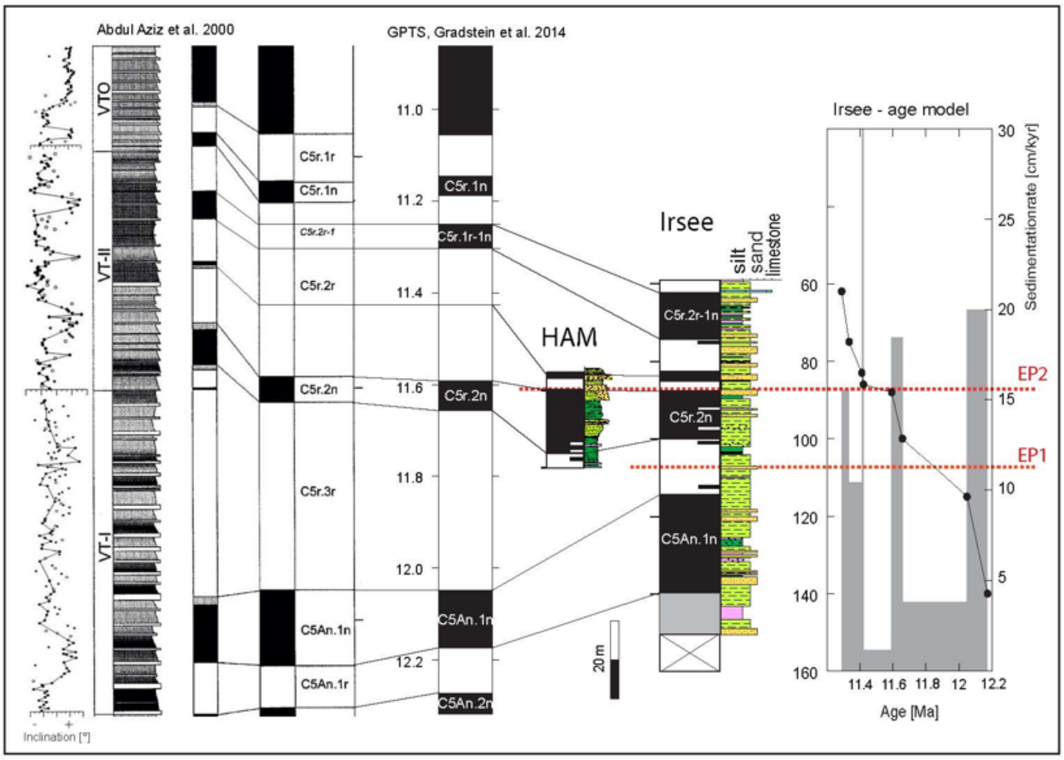
Spencer, C.J., Harris, R.A., Major, J.R. (2016) Provenance of Permian-Triassic Gondwana sequence unit accreted to the Banda Arc: constraints from zircon U-Pb and Hf isotopes. In press in *Gondwana Research*, 38, 28-39.



Magnetostratigraphy of sediments of the North Foreland Basin in Bavaria

Kirscher et al. (2016) successfully applied a magnetostratigraphic approach to correlate and date Miocene sediments of Central Europe. A chronostratigraphic framework is vital for sediments of this age to unravel the detailed paleoclimatic and paleoanthropologic history of Europe during an interval when the last major climatic optimum occurred and in addition major evolutionary steps in the hominid evolution took place.

Kirscher, U., Prieto, J., Bachtadse, V., Abdul-Aziz, H., Doppler, G., Hagmaier, M., and Böhme, M. (2016). A biochronologic tie-point for the base of the Tortonian stage in European terrestrial settings: Magnetostratigraphy of the topmost Upper Freshwater Molasse sediments of the North Alpine Foreland Basin in Bavaria (Germany). *Newsletters on Stratigraphy*, 49(3), 445-467.

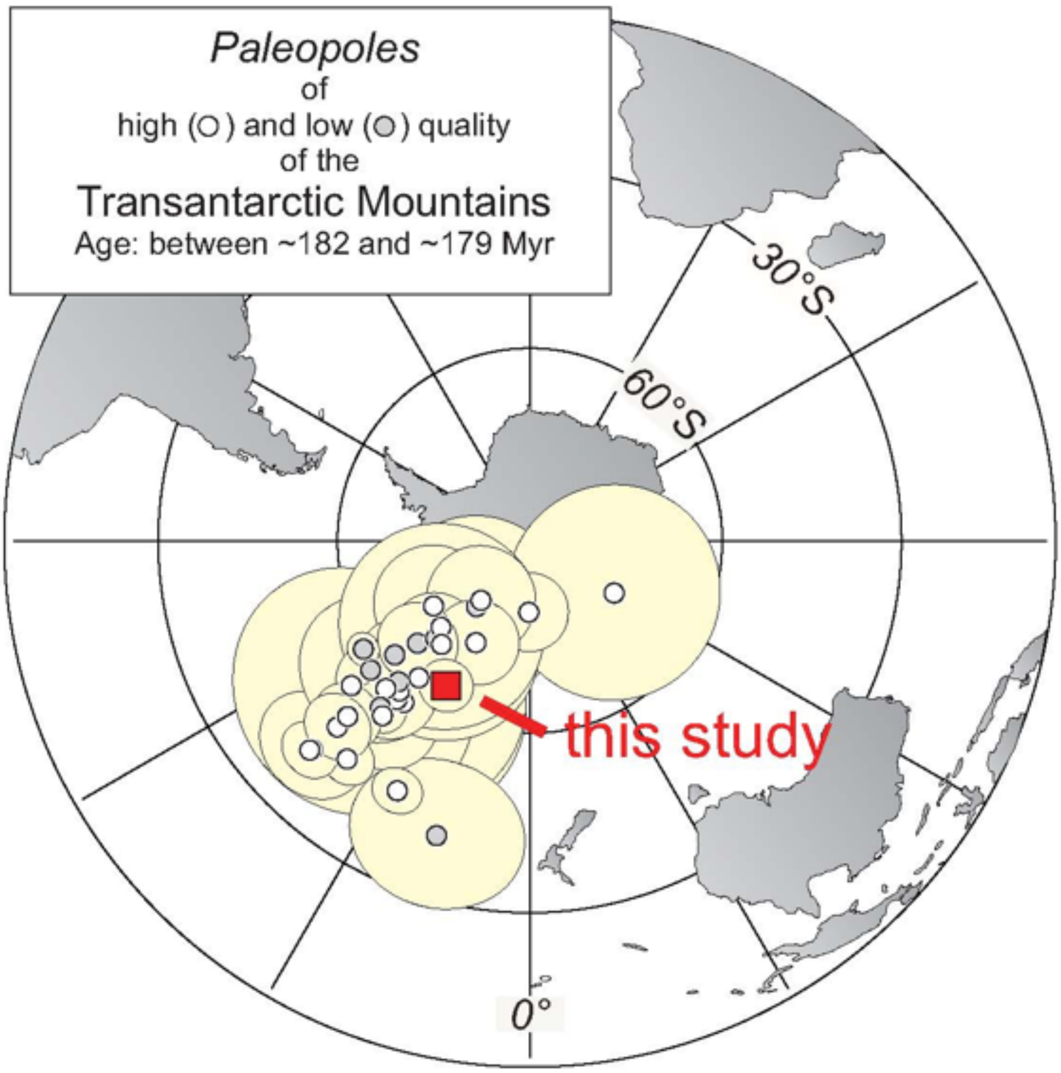


Final correlation of our sections based on our magnetostratigraphic polarity results with the Global Polarity Timescale (GPTS).

Paleomagnetism of the Jurassic Transantarctic Mountains

Lemna et al. (2016) present a paleomagnetic study of a Jurassic Large Igneous Province from Antarctica (Karroo/Ferrar LIP). They report new high quality data and compare them with published results. We point out that a considerable spread of ~30° in the paleomagnetic data exists, which cannot be explained by low quality data, for a time interval as short as 3 Ma. This study stresses the importance and the existence of yet unresolved parts of the global paleomagnetic dataset.

Lemna, O.S., Bachtadse, V., Kirscher, U., Rolf, C., Petersen, N. (2016). Paleomagnetism of the Jurassic Transantarctic Mountains revisited - evidence for large dispersion of apparent polar wander within less than 3 Myr. *Gondwana Research*, 31, 124-134.



The Australia-China Joint Research Centre for Tectonics and Earth Resources (ACTER)

ACTER's 2016 annual field symposium was successfully held in Xi'an and the adjacent Qinling orogen, China, between 20-29 October 2016. The event focused on the theme of "Orogenesis during Supercontinent Cycles". It started with a one-and-half day indoor meeting, featuring talks covering most aspects of orogenic cycles and their roles in supercontinent cycles and Earth evolution in general, and record of orogenic events in both the Asia-Pacific region and elsewhere. Talks were also given on latest developments in analytical methods such as isotopic and thermo- and geochronological analyses. A number of talks were specifically dedicated to the evolution and architect of the nearby Qinling orogen – main target of the field symposium. The Vice Prescient of Northwest University, Professor Ling Gao, and academician Professor Guowei Zhang, opened the event and participated in part of the indoor discussions (see group photo in front of Northwest University's Geology Department)

An eight-day field excursion followed, led by Prof. Yunpeng Dong of Northwest University. The traverse started form the northern foreland region on the southern margin of the North China block, crossed the mighty Qinling orogen, and finished in the southern foreland region at the northern margin of the South China block. Traditional development of concepts and latest scientific findings were constantly discussed on and off the outcrops, and participants agreed on disagreements over many controversial topics. Along the way key scientific issues have been identified, some collaborative arrangement were made to work together to address such issues, and professional connections were established between members of various career stages, disciplines, and institutions. The unseasonal rainy weather was a challenge at times, but it did not damp participants' enthusiasms in learning about the evolution of the mighty Qinling ranges, or the ancient and colourful cultural and history that packed the entire trip.

Western Australia Palaeomagnetic and Rock-Magnetic Facility

The Western Australia Palaeomagnetic and Rock-magnetic Facility, recently upgraded and relocated to Curtin University's Bentley campus, is a national research infrastructure with the latest upgrade co-funded by the Australian Research Council and collaborating institutions including Curtin University, the University of Western Australia (UWA), the Australian National University, Macquarie University and University of Queensland.

The latest upgrade includes the construction of a magnetically shielded room in mid-2015 by Dr Gary Scott’s team, which provides a laboratory space with ambient magnetic fields less than 0.5% of the local geomagnetic field. Within this shielded room we now have a new 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories attached to it (automated AF demagnetiser, susceptibility meter, etc.).

The RAPID system, the first and only one in Australia, was installed and commissioned in February 2017. Other systems now operating inside the shielded room include an AGICO JR-6A spinner magnetometer and ASC TD-48SC and MAGNETIC MEASUREMENTS thermal demagnetisers. The day-to-day operation of the facility is overseen by the recently appointed Technical Officer, Dr Josh Beardmore.

The new purchases represent a major enhancement to the productivity and capabilities of the facility. Apparatus which is now available in the facility include:

- a 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories (including; AF coils, susceptibility meter, and ARM system),
- a second 2G 755 cryogenic magnetometer upgraded (LE0668377) to a 4K DC SQUID system (currently returned to 2G enterprises for a minor upgrade and for repair of the lightning-damaged cold head),
- An AGICO JR-6A spinner magnetometer
- 1x MMTD80, 2x MMTD18 and a TD-48-SC thermal demagnetiser,
- a Petersen Instruments Variable Field Translation Balance (VFTB),
- an AGICO MFK-1FA kappabridge,
- a Bartington MS2 susceptibility meter with MS2W furnace, and
- a MAGNETIC MEASUREMENTS MMPM5 pulse magnetiser.

The facility supports a wide range of research topics, including reconstruction of global palaeogeography (the configuration and drifting history of continents) through Earth's history, studying the evolving geomagnetic field (e.g., palaeointensity) through time, analyses of regional and local structures and tectonic histories, dating sedimentary rocks and thermal/chemical (e.g. mineralisation) events, studying past climate changes, and orienting rock cores from drill-holes.

Closure of the Paleo-Asian Ocean and Amalgamation of the Central Asian Orogenic Belt

The Central Asian Orogenic Belt (CAOB) is one of the largest accretionary orogens in the world, yet the timing of final amalgamation remains controversial. It appears that closure commenced in the west and progressively evolved eastward in a scissor-like motion, with the final segment – the Mongol-Okhotsk Belt in NE Russia – closing in the mid-Jurassic. The Inner Mongolia segment in northern China had closed by the late Permian (~250 Ma), as evidenced by I-type granites and adakites along the Solonker-Xar Moron suture, but the actual location of the main suture remains to be defined, since the Xar-Moron shear zone lies approximately 50 km south of the Solonker shear zone. The Xar Moron segment is a zone of intense deformation, whereas the Solonker shear zone contains considerably less-deformed rocks. A suite of samples from both the Solonker and Xar Moron sutures was collected in late 2015 and prepared for geochemical and geochronological analysis in 2016.

The geochemical data are now complete and half of the samples have also been run for U-Pb zircon geochronology.

Wang, B., Zhou J.B., Wilde, S.A., Zhang, X.Z., Ren, S.M., 2016, The timing of final closure along the Changchun–Yanji suture zone: Constraints from detrital zircon U–Pb dating of the Triassic Dajianggang Formation, NE China. *Lithos* 261, 216-231.

Li, S, Wilde, S.A., Wang, T., Xiao, W., Guo, Q., 2016. Latest Early Permian granitic magmatism in southern Inner Mongolia, China: Implications for the tectonic evolution of the southeastern Central Asian Orogenic Belt. *Gondwana Research*, 29, 168-180.

Li, S., Chun, S.L., Wilde, S. A., Wang, T., Xiao, W.J., Guo, Q.Q.2016, Linking magmatism with collision in an accretionary orogen. N*ature Scientific Reports*, 6: 25751, 12 pp.

Li, S., Chung, S.L., Wilde, S.A., Wang, T., Xiao, W.J., Guo, Q.Q., 2016. How Central Asian Orogeny evolves: New insights from the end-Permian to Middle Triassic magmatic record along the Solonker Suture Zone. *Acta Geologica Sinica*, 90, 1907-1908 (English Edition).

Mylonitic gneisses along the Xar Moron suture zone, Inner Mongolia.

Tibetan Geology

Initial work on the volcanic rocks in the northern Qiangtang Terrane of Tibet has been extended to include the relationship between the Tibetan Plateau and the terrains to the east in Northwest China. In particular, an investigation was undertaken of the complex arc system in the eastern Tibetan Plateau.

Wu, T, Xiao, L., Wilde, S.A., Ma, C.Q., Li, Z.L., Sun, Y.., Zhan, Q.Y., 2016. Zircon U–Pb age and Sr–Nd–Hf isotope geochemistry of the Ganluogou dioritic complex in the northern Triassic.

Geology of the Tarim Craton, North China

The Tarim Craton lies to the west of the North China Craton and shares characteristics with both the North and South China cratons. The northern part of the Tarim Craton contains many rocks that have similar characteristics and ages to rocks reported from the North China Craton and indicate a possible linkage of the two areas in the Archean and Paleoproterozoic. However, the Neoproterozoic rocks indicate a link to the South China Craton and these have been investigated with respect to the craton's position within Rodinia. Work also continued on the oldest rocks in the Tarim, with the identification of a unit of TTG with an age of 3.7 Ga, making it one of the oldest rock units recognised in China.

Close-up of 3.7 Ga TTG outcrop in the northeastern Tarim Craton.

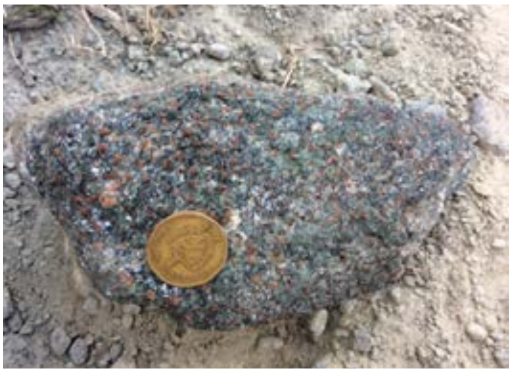
Ge, R.F., Zhu, W.B., Wilde, S.A., 2016. Mid-Neoproterozoic (ca. 830-800 Ma) metamorphic P-T paths link Tarim to the circum-Rodinia subduction-accretion system. *Tectonics*, 35, 1465-1488.

Geology of the Nadanhada and Sikote-Alin terranes of NE China and Far East Russia

The coastal terranes in NE China and the Russian Far East reflect the onset of Paleo-Pacific subduction following closure of the Paleo-Asian Ocean and amalgamation of the Central Asian Orogenic Belt (CAOB). Closure of the Paleo-Asian Ocean in China at ~250 Ma resulted in a cessation of the northward drift of continental masses from a peri-Gondwana position. The onset of a tectonic regime dominated by westward-directed Paleo-Pacific subduction was initiated in the Late Triassic to Early Jurassic and has dominated since that time. Importantly, the timing of accretion on either side of the Jiamusi-Khanka-Bureya Massif, at the eastern margin of the CAOB was coeval in the Middle Jurassic, with a rift basin closing between the massif and the CAOB in the west and subduction of the Paleo-Pacific Plate commencing in the east. Work in 2016 was in association with cotutelle PhD student Kai Liu of Peking University who undertook sample collection from the Russian segment of the terrane. The first paper has been accepted for publication early in 2017 (Tectonics) and the second paper is in revision.

Subduction/Accretionary Complexes in Cuba

An Ar-Ar study of the Escambray Complex in central Cuba utilising white micas has revealed the timing of subduction/accretion of various nappes that compose the Escambray Complex. In 2016, work continued on compiling structural data and has been prepared for publication in Tectonophysics (in revision). Work on the nature of the serpentinites within the Escambray Complex is planned for 2017, as is work on the eclogites.



Fresh eclogite sample composed of omphacite and garnet from the Escambray Complex, central Cuba.

Despaigne-Diaz, A.I., Garcia-Gasco, A., Caceres Govea, D., Jourdan, F., Wilde, S.A., Trujillo, G.M., 2016. Twenty-five million years of subduction-accretion-exhumation during the Late Cretaceous-Tertiary in the northwestern Caribbean: The Triniad Dome, Escambray Complex, Central Cuba. *American Journal of Science*, 316, 203-240.

Did the Albany-Fraser Orogen go West?

One of the outstanding problems from field mapping in the 1970's of southwestern Australia was whether the north-trending gneisses at Windy Harbour on the south coast were part of the Proterozoic Albany-Fraser Orogen or part of the Archean Balingup metamorphic belt. A suite of samples was collected in 2016 for geochemistry and geochronology in order to resolve this issue.

Measuring the gneissic foliation at Windy Harbour.

The Role of Siberia in the Evolution of the Paleo-Asian Ocean

Research in China has established that most of the terranes in the Central Asian Orogenic Belt in China and Mongolia were initially accreted to the Siberia Craton. The consequence of this is that all terranes north of the terminal suture (the Solonker-Xar Moron Suture) were once attached to Siberia. The question arises as to whether these terranes drifted across the Paleo-Asian Ocean or whether closure was driven by northward drift of the North China Craton in the Paleozoic. Work in the Yenisei Ridge and Baikal region will provide answers to how the Siberian margin reacted to these potential events.

Defining the Nature of Earth's Oldest Crust

Over the past two decades a massive amount of data have been acquired from the Hadean zircons of the Jack Hills metasedimentary belt. However, the nature of the oldest crust remains unconstrained and a multitude of hypotheses have been proposed to explain the zircon assemblage. In 2016, we have gone back to basics and re-looked at the original sample from which the 4404 Ga zircon was obtained in order to precisely define the isotopic systematic of the most pristine Hadean zircons. In addition, the results from a traverse across the whole of the Jack Hills belt were prepared for publication, indicating that much of the belt may have been deposited in the Proterozoic.

Timing of Uriconian Volcanism in the Welsh Borderlands, UK

The Uriconian rocks of Shropshire represent Avalonian activity prior to the opening of the Atlantic Ocean, with the better-studied portion occurring in Newfoundland. As one of the few examples of Precambrian geological events in England, the precise age of magmatic activity needs to be constrained. Previous studies have utilised the Rb-Sr system, but we have undertaken U-Pb zircon analysis on rocks from all outcrops of the Uriconian.

The famous unconformity between Proterozoic Ercall Granophyre to the left and Lower Cambrian Wrekin Quartzite to the right. Dating of these two units was instrumental in re-defining the Precambrian/Phanerozoic boundary.

Research reports

PLANETARY SCIENCE

Planetary science

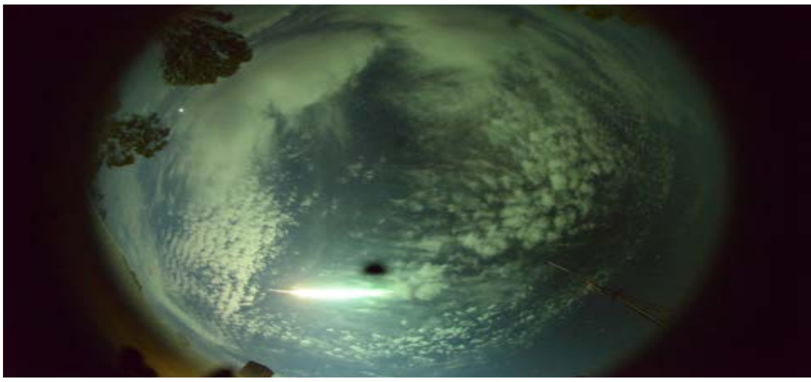
Planetary science is a historical area of strength at Curtin: John de Laeter was a world-renowned cosmochemist and planetary scientist. That strength continues through to the present day. TIGeR is home to the largest planetary science group in Australia, with 14 members of staff publishing in the field, 7 as their principal area of interest. 6 PhD students are full time on planetary projects, with 4 more starting in 2016. We also direct the Australia node for the NASA Solar System Exploration Research Virtual Institute, representing Australia's planetary research community to NASA.

Desert Fireball Network

The DFN is a distributed network of fully autonomous observatories spread across outback Australia. It is able to observe a sample of solar system objects that we cannot see in any other way. We can determine where they come from in the solar system by triangulating trajectories of bright fireballs made by large debris, to derive a precise pre-entry orbit. From fireball brightness, deceleration and fragmentation, we can calculate mass and physical properties. If it survives to the surface, we can pinpoint the fall site, recover it, and analyse it in the lab. Not only are these objects too small to image with a telescope, no telescope can deliver this suite of data. Most recently we have developed a completely automated software pipeline for data reduction.

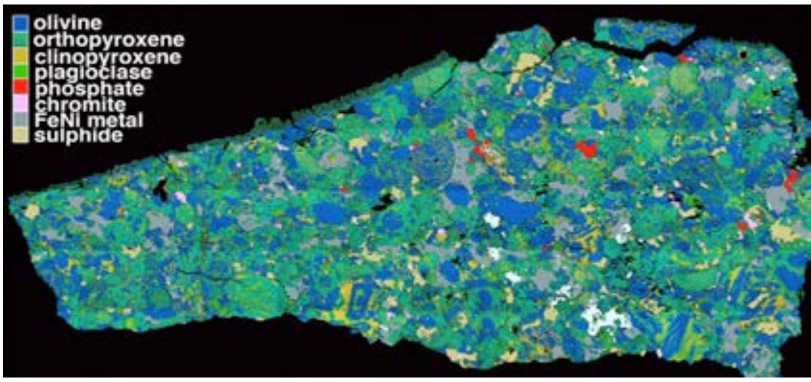
Successes during 2016 included the recovery of Murrili meteorite at beginning of year, with a second meteorite, "Dingle Dell" collected in WA wheatbelt in November, after only 6 days on the ground, making it one of the most un-contaminated meteorites in the world.

Images: From tracking, to recovery, to microscopic study.



Tracking the Dingle Dell meteorite.

Recovery of the Dingle Dell meteorite.



Thin section mineral map of the Dingle Dell meteorite.

The Mason Gully meteorite – the second recovered fall from the Desert Fireball Network

Dyl et al. (2016) characterised Mason Gully, the second meteorite recovered using the Desert Fireball Network using petrography, mineralogy, oxygen isotopes, bulk chemistry, and physical properties.

Geochemical data are consistent with its classification as an H5 ordinary chondrite. Several properties distinguish it from most other H chondrites. Its 10.7% porosity is predominantly macroscopic, present as intergranular void spaces rather than microscopic cracks. Modal mineralogy (determined via PS-XRD, element mapping via energy dispersive spectroscopy [EDS], and X-ray tomography [for sulfide, metal, and porosity volume fractions]) consistently gives an unusually low olivine/ orthopyroxene ratio (0.67_ 0.76 for Mason Gully versus ~ 1.3 for typical H5 ordinary chondrites). Widespread "silicate darkening" is observed.

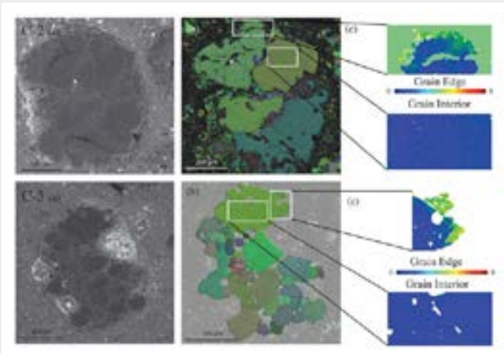
While Mason Gully has some unique properties, its geochemistry indicates a similar thermal evolution to other H chondrites.

Dyl, K. A., G. K. Benedix, P. A. Bland, J. M. Friedrich, P. Spurný, M. C. Towner, M. C. O'Keefe, K. Howard, R. Greenwood, R. J. Macke, D. T. Britt, A. Halfpenny, J. O. Thostenson, R. A. Rudolph, M. L. Rivers and A. W. R. Bevan (2016). "Characterization of Mason Gully (H5): The second recovered fall from the Desert Fireball Network." *Meteoritics and Planetary Science* 51: 596-613.

The deformation resulting from impact in the Allende meteorite

Although the CV3 Allende is classified as unshocked, Forman et al. (2016) have made a detailed study using Electron Backscatter Diffraction (EBSD) mapping and identify previously unseen crystal-plastic deformation microstructures.

Their results demonstrate that forsterite-rich chondrules commonly preserve crystal-plastic microstructures (particularly at their margins); that low-angle boundaries in deformed matrix grains of olivine have a preferred orientation; and that disparities in deformation occur between chondrules, surrounding and non-adjacent matrix grains. They find heterogeneous compaction effects present throughout the matrix, consistent with a highly porous initial material. Given the spatial distribution of these crystal-plastic deformation microstructures, they suggest that this is evidence that Allende has undergone impact-induced compaction from an initially heterogeneous and porous parent body.



Backscatter electron (BSE) images and Euler maps showing the orientation of each grain in terms of the three Euler angles, and (c) texture component showia vast increase in deformation at grain edges when compared to grain interiors (scale bar is shown in degrees).

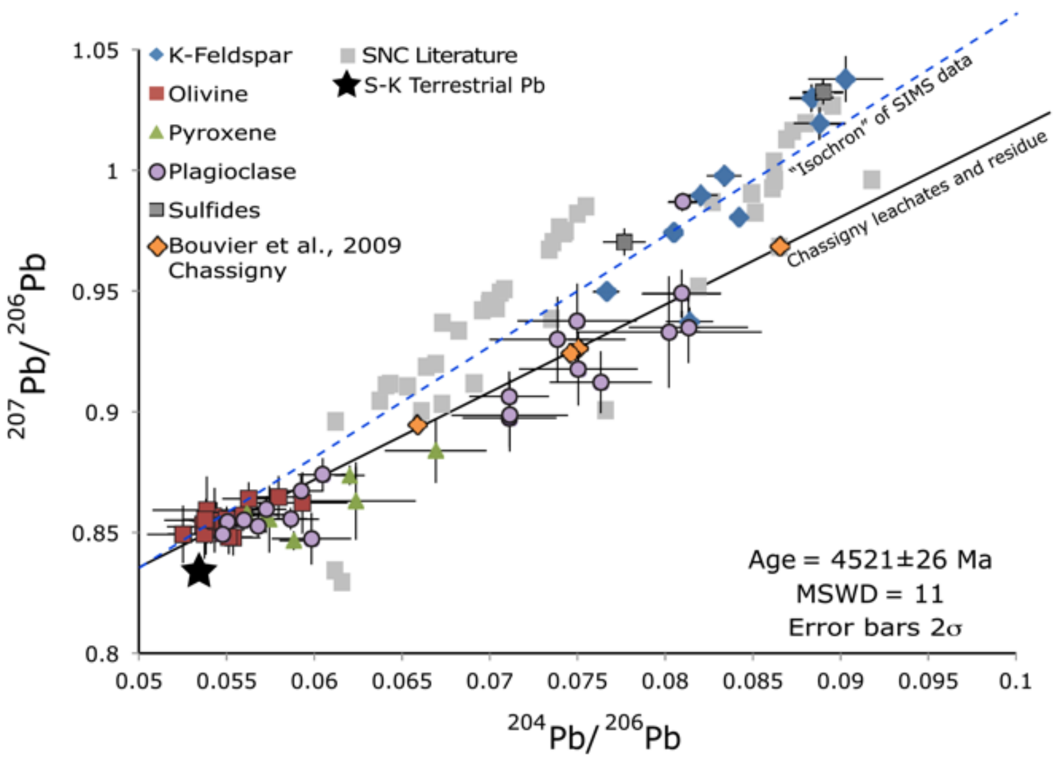
Forman, L.V., Bland, P.A., Timms, N.E., Collins, G.S., Davison, T.M., Benedix, G.K. (2016). Hidden secrets of deformation: Impact-induced compaction within a CV chondrite. *Earth and Planetary Science Letters*, 452, 133-145.

A Pb isotopic resolution to the Martian meteorite age paradox

Determining the chronology and quantifying various geochemical reservoirs on planetary bodies is fundamental to understanding planetary accretion, differentiation and global mass transfer. Bellucci et al. (2016) measured Pb isotope compositions of individual minerals in the Martian meteorite Chassigny by Secondary Ion Mass Spectrometry (SIMS). The new data were used to calculate a crystallisation age 4.526 ± 0.027 Ga that is clearly in error as it conflicts with all other isotope systems that yield a widely accepted age of 1.39 Ga.

The data suggest that Chassigny has mixed with a radiogenic component and that this component is Martian and that mixing occurred on the surface of Mars. This further suggests that this component is likely to be present in virtually every Martian meteorite. The presence of this radiogenic reservoir on Mars resolves the paradox between Pb isotope data and all other radiogenic isotope systems in Martian meteorites. Importantly, Chassigny and the Shergottites are likely derived from the northern hemisphere of Mars, while NWA 7533 originated from the Southern hemisphere, implying that the U-rich reservoir, which most likely represents some form of crust, must be widespread.

Bellucci, J. J., A. A. Nemchin, M. J. Whitehouse, J. F. Snape, R. B. Kielman, P. A. Bland and G. K. Benedix (2016). "A Pb isotopic resolution to the Martian meteorite age paradox." *Earth and Planetary Science Letters* 433: 241-248



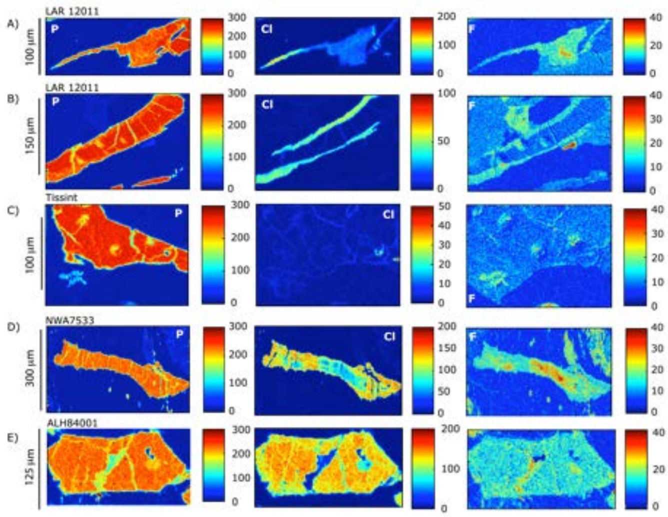
$^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ isochron0 (blue dashed line) through all Chassigny data.

Halogens in Martian phosphates: Implications for halogen reservoirs on the Mars surface.

Bellucci et al. (2016) have measured, *in situ* by Secondary Ion Mass Spectrometry (SIMS) the Cl isotopic compositions and halogen (Cl, F, Br, and I) abundances in phosphates from eight Martian meteorites. The distribution of halogens has also been documented by x-ray mapping. Halogen concentrations range over several orders of magnitude up to some of the largest concentrations yet measured in Martian samples or on the Martian surface, and the inter-element ratios are highly variable. Similarly, Cl isotope compositions exhibit a larger range than all pristine terrestrial igneous rocks.

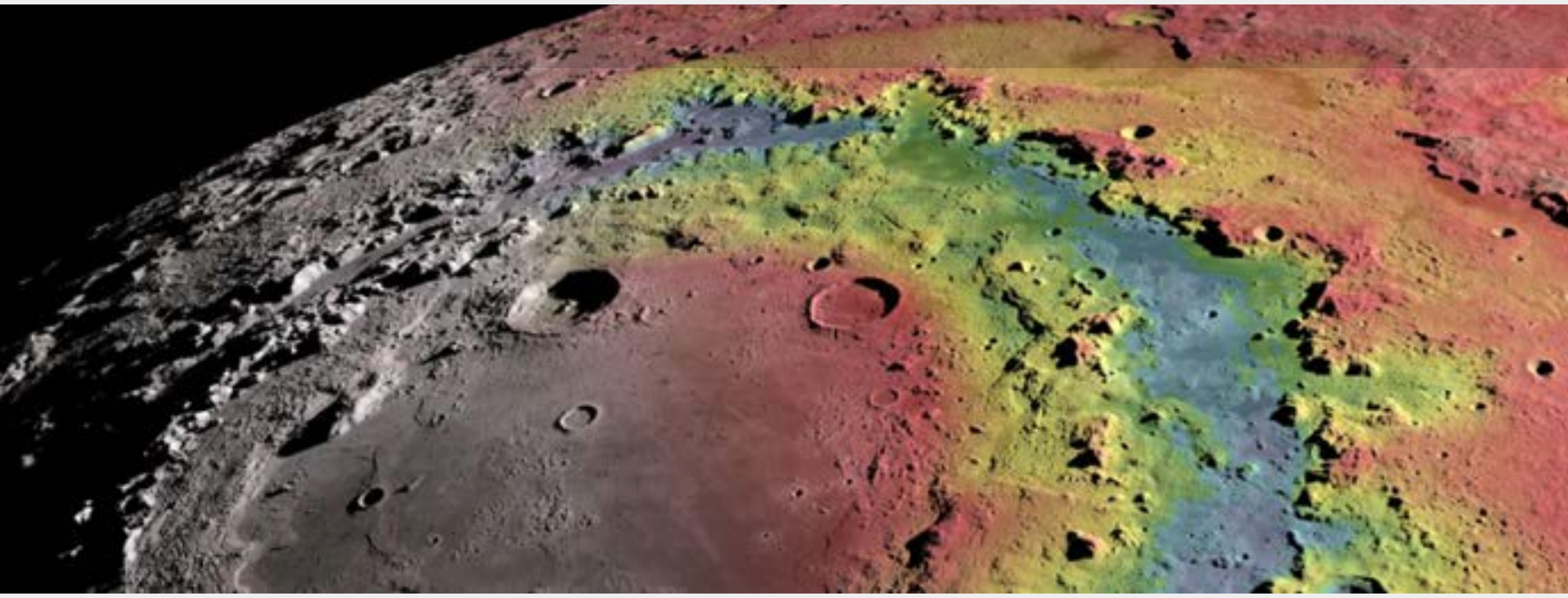
Phosphates in ancient (>4 Ga) meteorites (orthopyroxenite ALH 84001 and breccia NWA 7533) have positive δ37Cl anomalies. These samples also exhibit explicit whole rock and grain scale evidence for hydrothermal or aqueous activity. The phosphates in the younger basaltic Shergottite meteorites (<600 Ma) have negative δ37Cl anomalies. Phosphates with the largest negative δ37Cl anomalies display zonation in which the rims of the grains are enriched in all halogens and have significantly more negative δ37Cl anomalies suggestive of interaction with the surface of Mars during the latest stages of basalt crystallization.

Oxidation and reduction of chlorine are the only processes known to strongly fractionate Cl isotopes, both positively and negatively, and perchlorate has been detected in weight percent concentrations on the Martian surface. The age range and obvious mixing history of the phosphates studied here suggest perchlorate formation and halogen cycling via brines, which have been documented on the Martian surface, has been active throughout Martian history.



Electron microprobe x-ray maps of P, Cl, and F in phosphates from some Martian meteorites. The enriched areas must have formed via a fluid mediated replacement process during interaction with surface brines during the final stages of phosphate crystallization.

Bellucci J. J., Whitehouse M. J., John T., Nemchin A. A., Snape J. F., Bland P. A. and Benedix G. K. (2016) Halogen and Cl isotopic systematics in Martian phosphates: Implications for the Cl cycle and surface halogen reservoirs on Mars. *Earth and Planetary Science Letters*, 458, 192–202.



The 930-kilometer Orientale impact basin on the Moon. The image shows the gravitational anomalies with red indicating stronger (blue-weaker) than average gravity due to the topography and density of the underlying rocks.

The formation of the Orientale basin – a major lunar multi-ring impact crater

The Orientale basin is a major impact crater on the Moon. It is hard to see from Earth because it is right on the western edge of the lunar nearside. Relatively undisturbed by later events, Orientale serves as a prototype for understanding large impact craters throughout the solar system.

Zuber et al. (2016) used the Gravity Recovery and Interior Laboratory (GRAIL) mission to map the gravitational field around the crater in great detail by flying the twin spacecraft as little as 2 km above the surface.

Johnson et al. (2016) performed a sophisticated computer simulation of the impact and its subsequent evolution, designed to match the data from GRAIL. Together, these studies reveal how major impacts affect the lunar surface and will aid our understanding of other impacts on rocky planets and moons.

Johnson, B.C., Blair, D.M., Collins, G.S., Melosh, H.J., Freed, A.M., Taylor, G.J., Head, J.W., Wieczorek, M.A., Andrews-Hanna, J.C., Nimmo, F., Keane, J.T., Miljkovic, K., Soderblom, J.M., Zuber M.T. (2016) The formation of the Orientale lunar multi-ring basin, *Science*, 354, 441-444.

Zuber, M.T., Smith, D.E. Neumann, G.A., Goossens, S., Andrews-Hanna, J.C., Head, J.W., Kiefer, W.S., Asmar, S.W., Konopliv, A.S., Lemoine, F.G., Matsuyama, I., Melosh, H.J., McGovern, P.J., Nimmo, F. Phillips, R.J., Solomon, S.C., Taylor, G.J., Watkins, M.M., Wieczorek, M.A., Williams, J.G., Jansen, J.C., Johnson, B.C., Keane, J., Mazarico, E., Miljkovic, K., Park, R.S., Soderblom, J.M., Yuan, D.-N. (2016). Gravity Field of the Orientale Basin from the Gravity Recovery and Interior Laboratory (GRAIL) Mission, *Science*, 354, 438-441.

Research reports

SEDIMENTARY ENVIRONMENTS, BASINS AND ENERGY RESOURCES

Sedimentary environments, basins and energy resources

Research into sedimentary environments, basins and energy resources at Curtin University continues to develop with an petroleum geoscience research group of three staff, four PhD students, an active programme of honours projects and a taught masters programme. The main focus is on the evolution of sedimentary basins on the various continental margins of Australia, and forms a contribution to the ARC Research Hub for Basin Geodynamics and Evolution of Sedimentary Systems (Basin Genesis Hub), a showcase of connecting "Big Data" analysis and high-performance computing in an open innovation framework. The aim of the hub is to fuse multidimensional data into 5D basin models (space and time, with uncertainty estimates) by coupling the evolution of mantle flow, crustal deformation, erosion and sedimentary processes using open-source modelling tools.

Evolution of the North West Shelf and Perth Basin

The North West Shelf of Australia is an unusual passive margin. It has been located close to a continental margin throughout much of its history, and has been subject to numerous rift events. Research on the Northwest Shelf and in the Perth Basin is aimed at understanding basin evolution on a regional scale, with particular emphasis on:

- The tectonic setting, timing and distribution of Carboniferous and Permian extension in onshore and offshore basins, and the extent to which it forms the fundamental architecture for subsequent rift events
- The significance or otherwise of the "Fitzroy Movement" beyond the well documented transpressional structures that occur in the Canning Basin
- Variations in the distribution, timing and orientation of Jurassic extension in the Perth, Northern Carnarvon, Browse and Bonaparte Basins, and its relation to rifting of micro-continental fragments from the North West Shelf margin
- Variations in the distribution, timing and orientation of Lower Cretaceous extension in the Perth, Northern Carnarvon, Browse and Bonaparte Basins, and its relation to the separation of Greater India from Australia
- The distribution of uplift and erosion during each of these rift events, and the implications of this for syn-rift sediment distribution and pathways
- The distribution, timing and tectonic significance of post break-up compression on the NW Shelf and in the Perth Basin
- The response of salt to these different tectonic events in the Petrel Basin.

The results of part of this research has been published as:

Yang X., Elders C. (2016). The Mesozoic structural evolution of the Gorgon Platform, North Carnarvon Basin, Australia. *Australian Journal of Earth Sciences* 63, 755-770. doi: 08120099.2016.1243579 and has been presented at the following conferences in 2016:

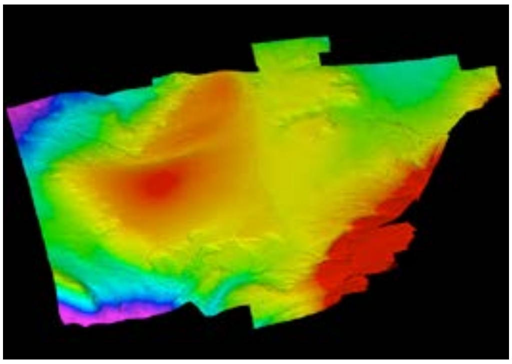
Passive Margins 2016, Royal Holloway, University of London, April 2016

The NW Shelf of Australia - an unusual passive margin (Chris Elders).

Fault growth and linkage on the northern margin of the Dampier Sub-basin (Sam McHarg).

ASEG-PESA, Adelaide, August 2016

Fault Geometry and Deformation History, Northern Carnarvon Basin (Chris Elders).



A map of the sea bed compiled from 2D and 3D seismic data showing the Exmouth arch – an anticline that continues to grow at the present day, resulting in the development of extensive slumps around its margins. The field of view is c. 300 km across.

Evolution of the Southern Margin of Australia

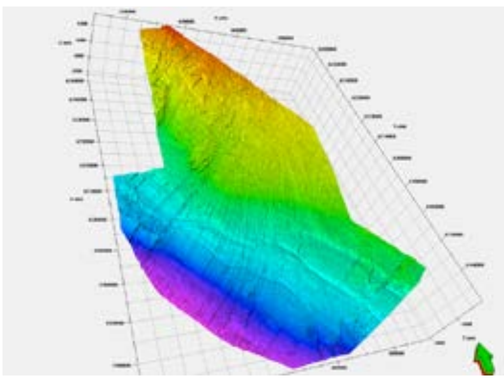
In comparison to the North West Shelf, the southern margin of Australia is a more "typical" passive margin. Despite this, there are many complex aspects of its evolution which are yet to be understood and which have implications for understanding petroleum systems in this frontier hydrocarbon province. Our current research is focussed on:

- Understanding the role played by Proterozoic structures on the geometry and segmentation of the margin
- Evolution of the outer basin high of Ceduna Shelf
- The extent and significance of the regional Eocene unconformity and associated igneous activity
- The occurrence and distribution of submarine slumps and slides in the near surface in the Ceduna Shelf

The results of this research have been presented at the following conferences in 2016:

ASEG-PESA, Adelaide, August 2016

Basement influences on structural style in the Bremer and Eyre Sub-basins, southern Australia (Jane Cunneen).



Eocene-aged submarine slide in the Ceduna Shelf, southern Australia.

Research reports

SPATIAL SCIENCES

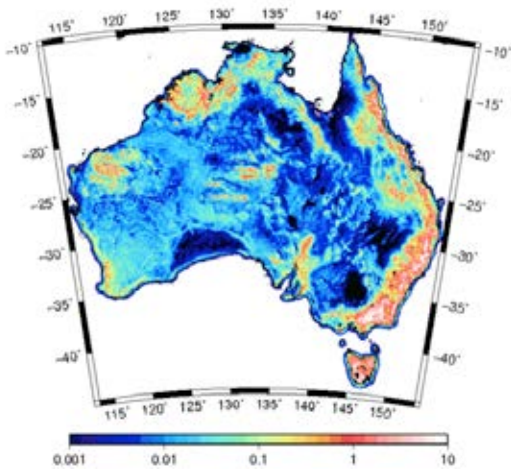
Geodesy and Spatial Sciences

Geodesy

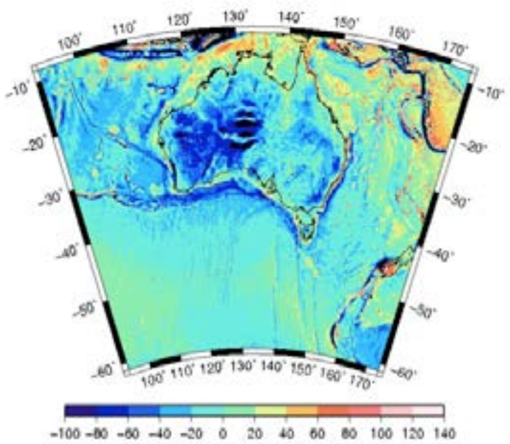
Geodesy involves the study of the Earth's shape and gravity field. It forms the scientific basis for precise positioning over large areas, navigation, mapping and charting, and studies of the physics and dynamics of the Earth. It therefore contributes to the Earth-present theme in TIGeR. Australia’s planetary research community to NASA.

Gravimetric geoid determination

The geoid is the equipotential surface of the Earth’s gravity field that corresponds most closely with mean sea level. Curtin has produced the last two Australian gravimetric geoid models, which have been adopted by Geoscience Australia as national standards. A common application of a geoid model is to transform the heights delivered by a GPS receiver so that they relate to mean sea level. We are currently computing a new model for release in 2017, called AUSGeoid2020. It includes a combination of the EGM20008 global gravity model, land gravity observations, marine gravity anomalies from satellite radar altimetry, and terrain corrections from a 1” (~30 m) digital elevation model. It will also include error estimates with geographic specificity propagated from uncertainty values in the above data sources.



30-m-resolution gravimetric terrain corrections over Australia (mGal).

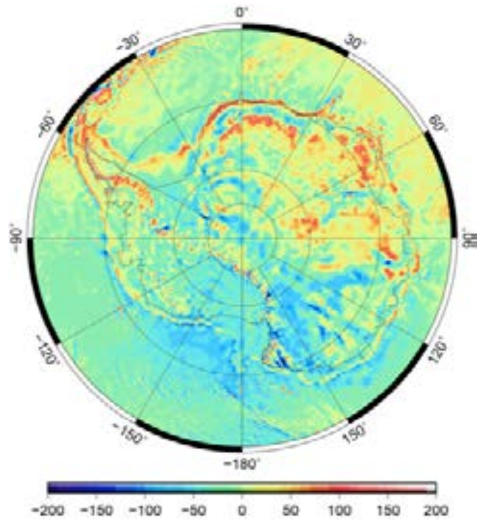


Gravity anomalies over Australia and its surrounds (mGal).

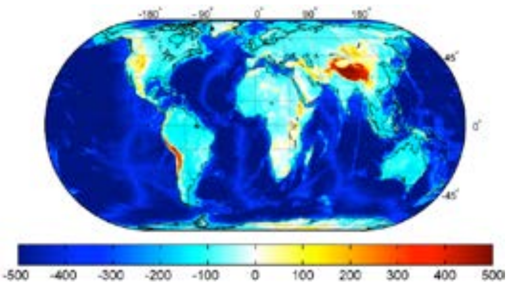
Ultra-high resolution spectral topographic modelling of gravitational fields

Modelling of the Earth's topographic gravitational potential is a classical problem in geodesy and geophysics relevant to a range of applications including gravity interpretation, isostatic hypothesis testing, and combined high or ultra-high resolution gravity modelling. Much progress has been made in 2016 on the spectral approach to topographic potential modelling.

A layer-based method with volumetric mass layers in both spherical and ellipsoidal approximation is developed by Rexer et al. (2016). This paper shows the significant benefits of the layer-based method over the frequently used rock-equivalent topography method avoiding 10-20 mGal errors, and confirms the notion that ellipsoidal approximation is required for high-accuracy or high-resolution applications. The spectral approach is strongly reliant on a new analytical method for the computation of a truncated series of solid spherical harmonic coefficients from data on an oblate ellipsoid of revolution by Claessens (2016). This method uses a transformation between surface and solid spherical harmonic coefficients, and was shown to achieve sub-micrometre precision in terms of height anomalies for a model to degree and order 2239. Hirt et al. (2016) apply spectral topographic modelling to compute a high-resolution gravity model for Antarctica using a combination of GRACE and GOCE satellite data with the Bedmap2 topography/ice thickness/bedrock model. The new gravity model for Antarctica provides estimated improvement rates ranging between 9 and 75% over previous satellite-only models. This improved knowledge of the Antarctic gravity field is of use for several geoscience and environmental applications, such as ice mass monitoring, topographic heighting with satellite systems, establishment and unification of underlying height reference systems, investigation and modelling of the crustal thickness, estimation of ice thickness through inversion, and investigation of geological signatures.



Gravity disturbances over Antarctica (in Mgal) (Hirt et al. 2016).



Topographic gravity disturbances from layer-based ellipsoidal topographic potential model (in mGal) (Rexer et al. 2016).

Claessens S.J. (2016). Spherical Harmonic Analysis of a Harmonic Function Given on a Spheroid. *Geophysical Journal International,* 206, 142-151.

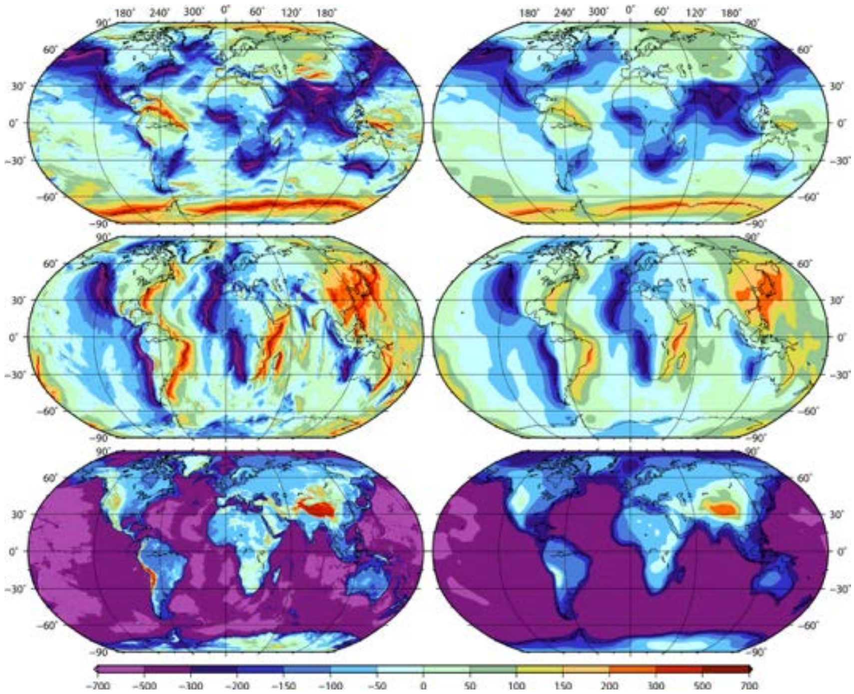
Hirt C., Rexer M., Scheinert M., Pail R., Claessens S.J., Holmes S.A. (2016). A New Degree-2190 (10 km resolution) Gravity Field Model for Antarctica Developed from GRACE, GOCE and Bedmap2 Data. *Journal of Geodesy*, 90, 105-127.

Rexer M., Hirt C., Claessens S.J., Tenzer R. (2016). Layer-based Modelling of the Earth's Gravitational Potential up to 10-km Scale in Spherical Harmonics in Spherical and Ellipsoidal Approximation. *Surveys in Geophysics*, 37, 1035-1074.

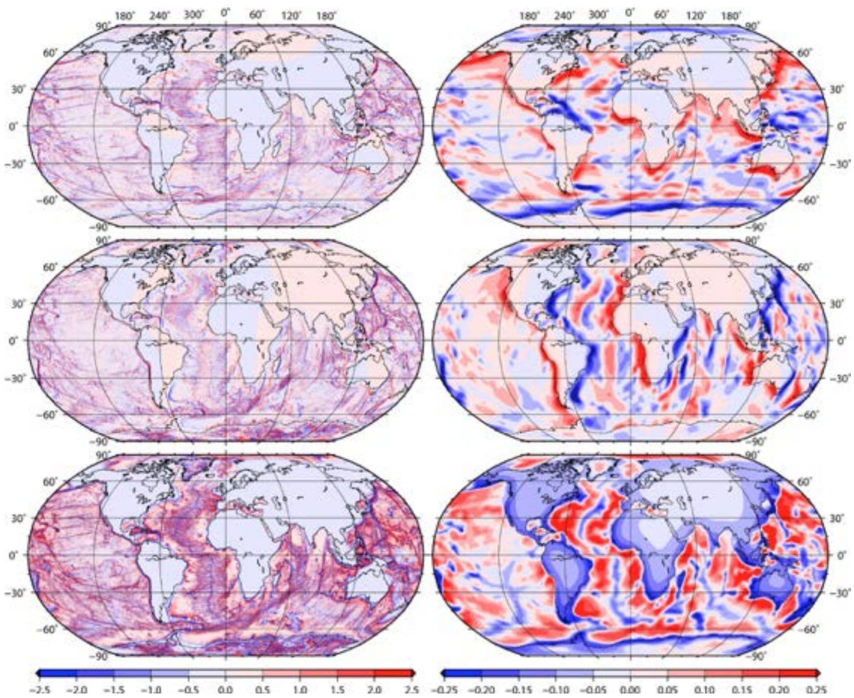
Topographic gravity modelling approximation errors

Kuhn and Hirt (2016) have scrutinized approximation errors introduced in topographic gravity modelling when using the concept of Rock-Equivalent-Topography (RET) often used to simplify the computation of gravity implied by rock, water, ice and other topographic masses. While several studies acknowledged the approximate character of the RET concept only few have attempted yet to quantify and analyse the approximation errors in full detail for various gravity field functionals and heights of computation points. This shortcoming has been addressed by this study providing a very comprehensive analysis for the topographic gravitational potential, and its first- and second-order derivatives evaluated on the Earth's surface, 3km above the Earth's surface and at a constant height of 250km. The study found that the RET concept can provide acceptable results when evaluating at a location far away (several hundred km) from the RET compression masses but for locations on or near the RET compression masses (e.g. on the Earth's surface) considerable approximation errors may render the RET concept as unusable. The approximation errors are found to be largest at the Earth's surface over RET compression areas (e.g. oceans and ice shields) and to increase for the first- and second-order derivatives. For locations on the Earth's surface, maximum relative errors are ~0.08% for the gravitational potential, ~7% for the first-order derivatives (cf. Figures 1 and 2) and up to ~110% for the second-order derivatives. This study was made possible with the availability of supercomputing resources provided by the Pawsey Supercomputing Centre.

Kuhn M., Hirt C. (2016). Topographic gravitational potential and second-order derivatives: an examination of approximation errors caused by rock-equivalent topography (RET). *Journal of Geodesy* 90, 883-902.



First-order derivatives of the topographic potential evaluated on the Earth's surface (left column) and at the constant height of 250km (right column). From top to bottom the figures in each column represent derivatives in latitude, longitude and vertical directions. Units in mGal (1 mGal = 1×10^{-5} ms^{-2}).

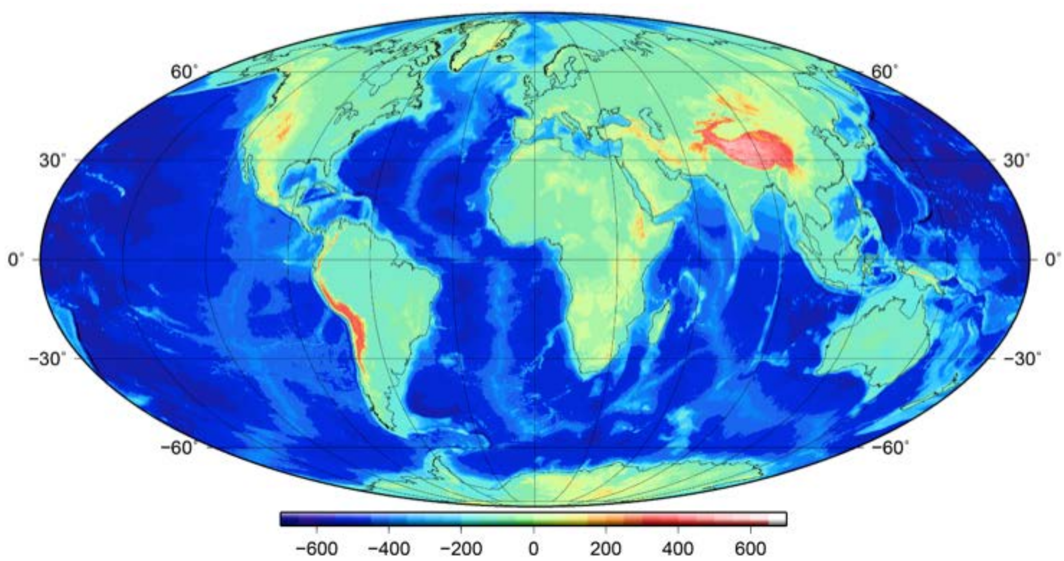


Differences of the first-order derivatives between rigorous calculation (cf. Figure above) and RET approximation evaluated on the Earth's surface (left column) and at the constant height of 250km (right column). From top to bottom the figures in each column represent derivatives in latitude, longitude and vertical directions. Units in mGal (1 mGal = 1×10^{-5} ms^{-2}).

Topographic gravity modelling for Bouguer maps

Hirt et al. (2016) provided and applied a rigorous framework to validate topographic gravity implied by a high-resolution (up to degree and order 2160) spherical harmonic model of the Earth's topography (cf. Figure 1). The study explained currently reported discrepancies between spectral modelling und Newtonian (numerical) integration with unacceptable magnitudes reaching beyond the 10 mGal-level. Neglected in many previous studies based on spectral techniques, Hirt et al. (2016) demonstrate that the addition of un-modelled spectral constituents is required to obtain a spectrally complete model for the topographic gravity. Based on this a numerical study demonstrates excellent agreement (8 microgal RMS) between gravity from both spectral and spatial forward modelling techniques, but also indicates convergence issues associated with spectral modelling of gravity signals at very short scales (few km). As key conclusion, the study successfully validates the spectral-domain forward gravity modelling technique for degree-2160 topography models required for the derivation of Bouguer gravity anomalies from a global Earth gravity model such as the EGM2008.

Hirt C., Reußner E., Rexer M., Kuhn M. (2016). Topographic gravity modeling for global Bouguer maps to degree 2160: Validation of spectral and spatial domain forward modelling techniques at the 10 µGal level. *Journal of Geophysical Research* 121, 6846–6862.



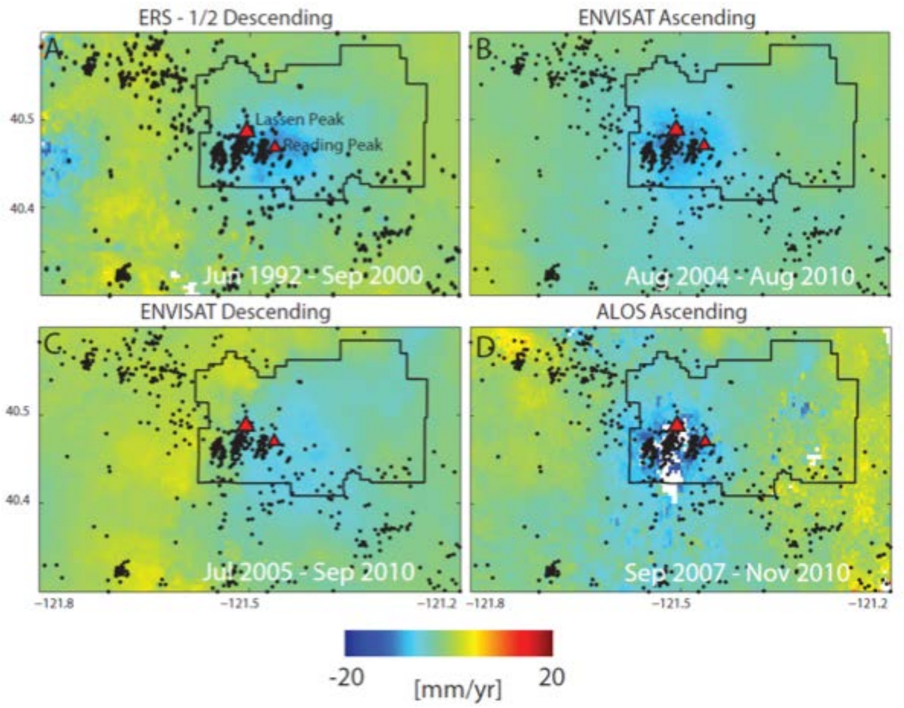
Global topographic gravity (e.g. gravity disturbances) from Newtonian integration at 5 arc-min resolution. Unit in mGal.

Time-scale and mechanism of subsidence at Lassen Volcanic Center, CA, from InSAR

Observations of ground displacement at volcanoes have contributed to our understanding of the eruption cycle, hydrothermal systems and the formation of continental crust. Lassen Volcanic Center, located in northern California, is known to have subsided in recent decades, but the onset, temporal evolution, and cause of subsidence remain unconstrained.

Parker et al. (2016) used multiple sets of satellite InSAR data to determine the temporal and spatial characteristics of deformation between 1992 and 2010. Throughout this period all datasets reveal subsidence of a broad, 30 - 40km wide region at rates of ~10mm/yr. Evaluating past geodetic studies we suggest that subsidence may have been ongoing since the 1980s, before which it is unlikely that significant ground deformation occurred. By combining multiple tracks of InSAR data we find that the ratio of horizontal to vertical displacements is high (up to 3:1), and source inversions favour a point source located at ~8km depth. Time-series analysis suggests that the rate of volume change of this source may have varied over time. They evaluated possible causes of subsidence at Lassen Volcanic Center in light of tectonic setting and hydrothermal activity. This methodology is now being applied to InSAR data in the Perth Basin, to measure and understand ground displacements related to groundwater extraction.

Parker A.L., Biggs J., Lu Z. (2016). Time-scale and mechanism of subsidence at Lassen Volcanic Center, CA, from InSAR. *Journal of Volcanology and Geothermal Research*, 320, 117-127.



Ground displacements calculated from different satellite datasets collected over two decades and showing subsidence of Lassen Volcanic Center in northern California. Subsidence is coincident with the volcano peaks (red triangles) and clusters of seismicity (black circles). The black line delineates the boundary of Lassen Volcanic National Park.

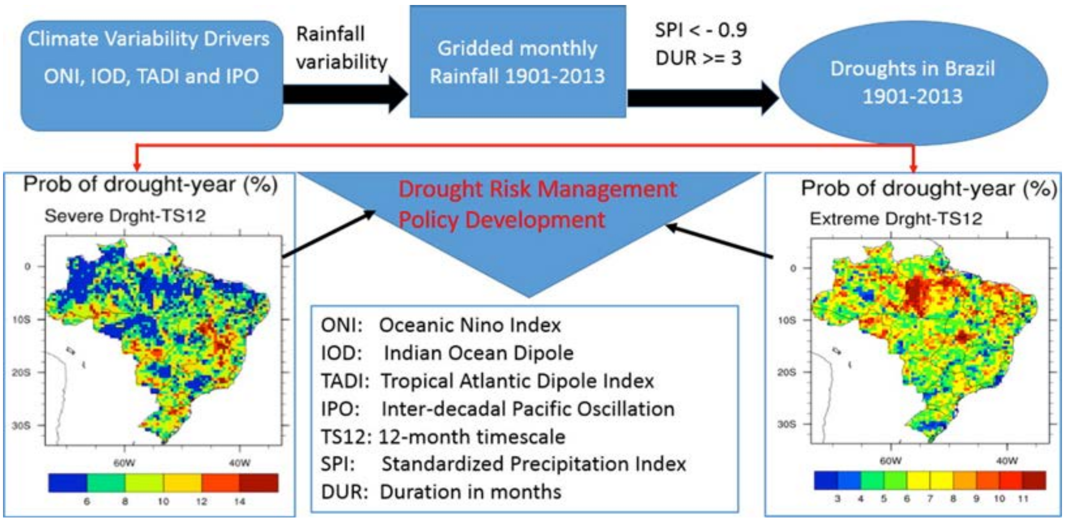
When every drop counts: Analysis of droughts in Brazil 1901-2013

With Brazil just coming out of a severe drought that has affected many areas of the country over the past two years, Awange et al. (2016) undertook research to study drought and rainfall patterns in that country. The first part of the study analysed the long-term sequence of drought events in Brazil based on monthly rainfall between 1901 and 2013.

In the study, approximately 25km x 25km grids were derived from the monthly rainfall data at four timescales (short: 3-month and 6-month; medium to long: 12-month and 24-month). Subsequently, the probability of drought occurrences, intensity, duration and areal-extent were calculated.

One of the main conclusions of this study is that probabilities of extreme droughts are 1 in 9 over northern Brazil, and 1 in 12 over southern Brazil, respectively. In general, no evidence of significant trend is detected in drought frequency, intensity, and duration over the last 11 decades at all four time-scales.

Awange, J. L., Mpelasoka F, Goncalves R (2016) When every drop counts: Analysis of Droughts in Brazil for the 1901-2013 period. *Science of the Total Environment*, 566-567:1472-88.



Monitoring the motion of the Australian Tectonic Plate using the Global Navigation Satellite System (GNSS)

El-Mowafy and Bilbas (2016) have monitored the motion of the Australian tectonic plate using Global Navigation Satellite System (GNSS) measurements collected at the newly established Continuously Operating Reference Stations (CORS) network in Western Australia. Changes of coordinates in a dynamic datum with time were computed over a three year period. Results showed that the Australian Plate had a rate of motion of 6.9cm/year with a precision of 2mm/year and an azimuth of 29.6º on average. These results, when compared with older studies, show that the Australian plate is moving with a steady rate during the recent past decades.

El-Mowafy, A. and Bilbas, E. (2016). Quality Control in Using GNSS CORS Network for Monitoring Plate Tectonics: A Western Australia Case Study. *Journal of Surveying Engineering*, 142(2), 05015003/1-9.

Precise Point Positioning

In precise point positioning (PPP), El-Mowafy et al. (2016) investigated various types of biases in GNSS that preclude integer ambiguity fixing and degrade solution accuracy when not being treated correctly. They discuss these biases that include satellite and receiver hardware biases, differential code and phase biases, initial phase biases, inter-system receiver biases and system time scale offset. They suggest that the satellite-related code biases be handled as calibrated quantities that are obtained from the Multi-GNSS project (MGEX) products and the fractional phase cycle biases to be obtained from a network. Some receiver-related biases are removed using between-satellite single-differencing, whereas other receiver biases such as inter-system biases are lumped with differential code and phase biases and need to be estimated. This will significantly improve solution convergence and leads to ambiguity-fixed PPP within a few minutes.

El-Mowafy, A., Deo, M., Rizos, C. (2016). On Biases in Precise Point Positioning with Multi-Constellation and Multi-Frequency GNSS Data. *Measurement Science and Technology*, 27(3), 035102.

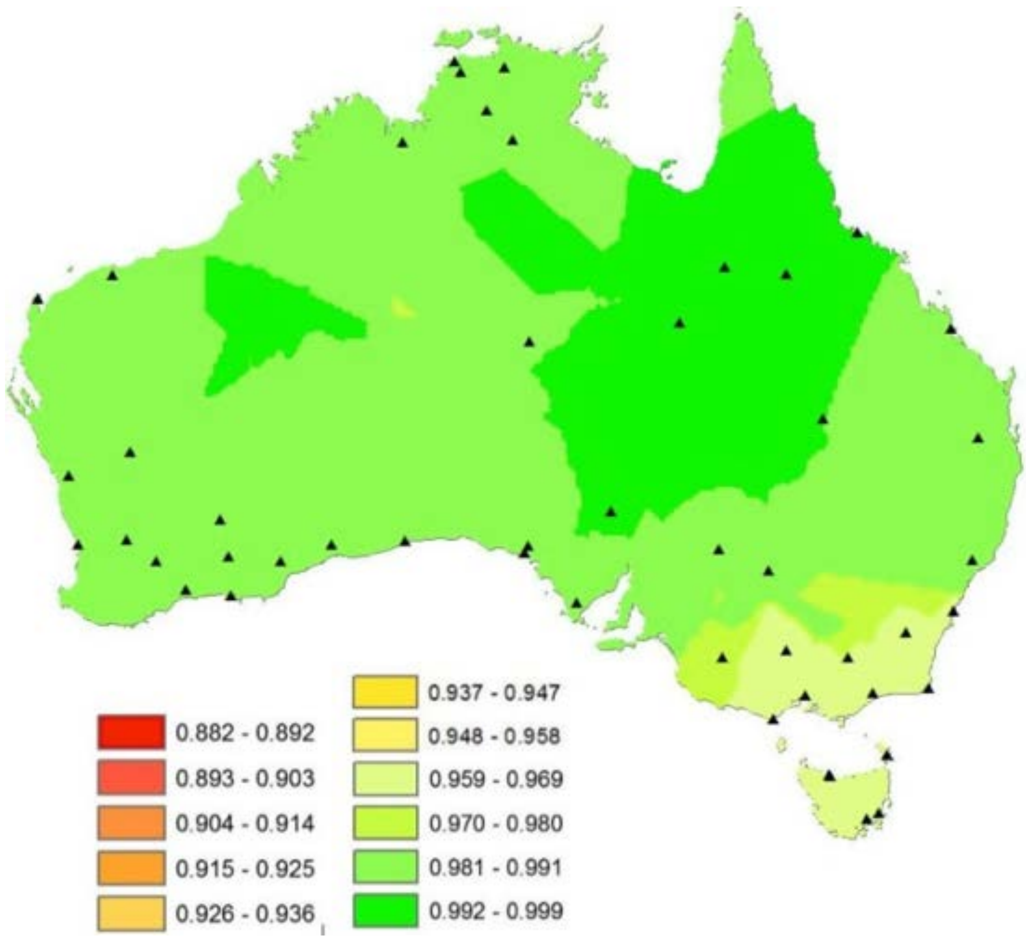
Participants in the summer school at TUMSAT.

The ARAIM method for localizer performance

El-Mowafy and Yang (2016) investigated the current availability of the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) method for localizer performance with vertical guidance (LPV-200) in aviation across Australia using GPS measurements collected at 60 stations. They showed that the use of GPS alone is not sufficient to achieve LPV-200 Australia wide. Therefore, El-Mowafy (2016) further investigated ARAIM when integrating Galileo, GLONASS and BeiDou with GPS. One month of real data was collected at stations of known positions, located in regions that have different satellite coverage levels. Results show that the vertical position error was always bounded by the protection level during the test and the ARAIM availability can reach 100% of the time when using all constellations even though some constellations are yet incomplete.

El-Mowafy, A., Yang, C. (2016). Limited Sensitivity Analysis of ARAIM Availability for LPV-200 over Australia using real data. *Advances in Space Research*, 57(2), 659–670.

El-Mowafy, A. (2016). Pilot Evaluation of Integrating GLONASS, Galileo and BeiDou with GPS in ARAIM. *Artificial Satellites*. 51(1), 31-44.



ARAIM availability for LPV-200 over Australia.

Research reports

COMPUTATIONAL GEOSCIENCES

Computational Geochemistry

The incorporation of the Computational Geochemistry group led by Professor Julian Gale is a major addition to the strengths of TIGeR.

The computational geochemistry group, in the Department of Chemistry provides an important new perspective on the problem of crystal growth mechanisms. They work at the atomic level, looking at the fundamental processes by which materials and minerals form. The computations involve up to a million atoms or more, and can test how their behaviour changes in response to different experimental conditions. Such research is made possible by through accessing the petascale computer at the Pawsey Centre.

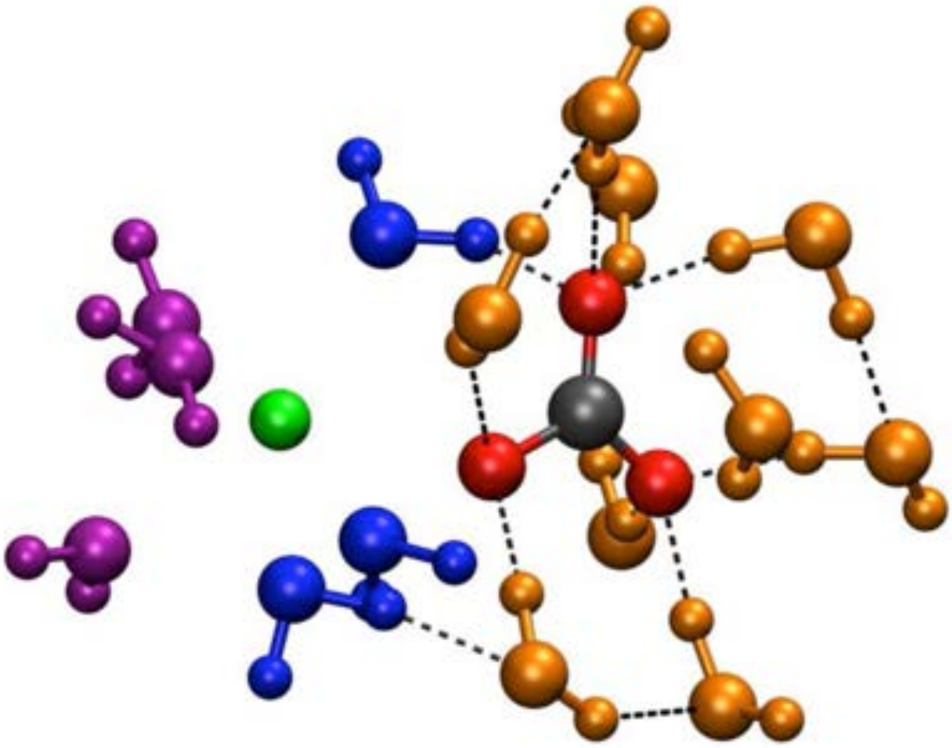
The research in computational geochemistry involves studying the nucleation and growth of minerals from aqueous solutions using computer simulations based on both force fields and *ab initio* quantum mechanics. In particular, they are focusing on minerals relevant to biomineralisation including those composed of calcium in combination with carbonate, oxalate, sulphate or phosphate. This spans processes from ion pairing and formation of pre-nucleation clusters through to mineralogy and polymorphism.

During the past year they have reported several significant findings. Firstly, analysis of the temperature dependence of calcium carbonate ion pairing has shown that the association of ions to form mineral precursors is entropically driven. Secondly, they have characterised the rates of water exchange at steps on the calcite surface, finding that there is a variation of up to 3 orders of magnitude in the kinetics of this process. Thirdly, using a combination of quantum mechanics and *in situ* X-ray diffraction they have identified a candidate structure for a transient polymorph of anhydrous calcium oxalate.

Entropy drives calcium carbonate ion association in aqueous solution

Understanding the molecular mechanisms underlying the early crystallisation of calcium carbonate is still incomplete. Experimental and computational evidence suggests that the early stages of phase separation in the aqueous solution involves the formation of pre-nucleation clusters (PNCs). The formation of PNCs challenges the classical nucleation theory on which most crystallisation models are based, and a fundamental question is the thermodynamic stability of such clusters. Kellermeier et al. (2016) have made a thorough thermodynamic analysis of the enthalpic and entropic contributions to the free energy and concluded that solute clustering is driven by entropy. The entropy arises from the release of water molecules from the ion hydration layers of ions in solution and should therefore be a general phenomenon at the earliest stages of phase separation in aqueous solutions.

Kellermeier M., Raiteri P., Berg J., Kempfer A., Gale J.D., Gebauer D. (2016). Entropy drives calcium carbonate ion association. *ChemPhysChem,* 17, 3535-3541



Snapshot of the hydration environment of the $CaCO_3$ ion pair taken from a molecular dynamics simulation. The calcium, carbon and oxygen atoms of the ion pair are coloured green, black and red, respectively. Water molecules are coloured according to the species to which they are coordinated: purple and orange represent water bound to Ca^{2+} and hydrogen-bonded (indicated by dashed black lines) to CO_3^{2-}, respectively, while blue-coloured water molecules are those that are bridging between calcium and carbonate. The total average number of water molecules in the first shell is 15, only the water molecules within 3.5 Å of the Ca and carbonate oxygen are shown.

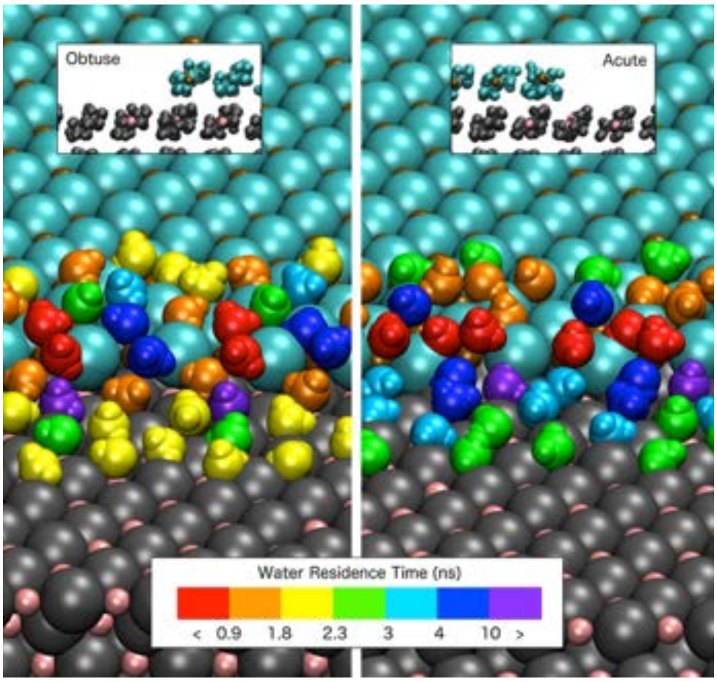
The structure and dynamics of water at the step edges on the calcite cleavage surface

De La Pierre et al. (2016) investigated the behaviour of liquid water around obtuse and acute step edges on a calcite (10-14) cleavage surface by means of classical molecular dynamics simulations performed with a force-field fitted against thermodynamic properties. Water density maps, radial distribution functions, and water average residence times have been investigated.

The structure and dynamics of the first two ordered hydration layers, which have been previously observed for the cleavage surface of calcite, are found to be disrupted by the presence of the steps over a range of five molecular rows either side of the step edge. Calcium sites along the step top edge can coordinate up to three water molecules, as compared with just the single water molecule that can be adsorbed per calcium ion on the flat surface.

Water residence times at calcium sites in the vicinity of the step span greater than 2 orders of magnitude, from tenths to several tens of ns, as compared to 2 and 0.2 ns for the flat surface and a calcium ion in aqueous solution, respectively. The occurrence of water molecules with long residence times at the step corners points toward the possible role of step dehydration as a rate-limiting factor in calcite crystal growth. The different distributions of slow and fast water molecules along the obtuse and acute steps appear to correlate with the different rates of growth observed for the two types of steps.

De La Pierre M., Raiteri P., Gale J.D. (2016) Structure and dynamics of water at step edges on the calcite (10-14) surface. *Crystal Growth and Design* 16, 5907-5914



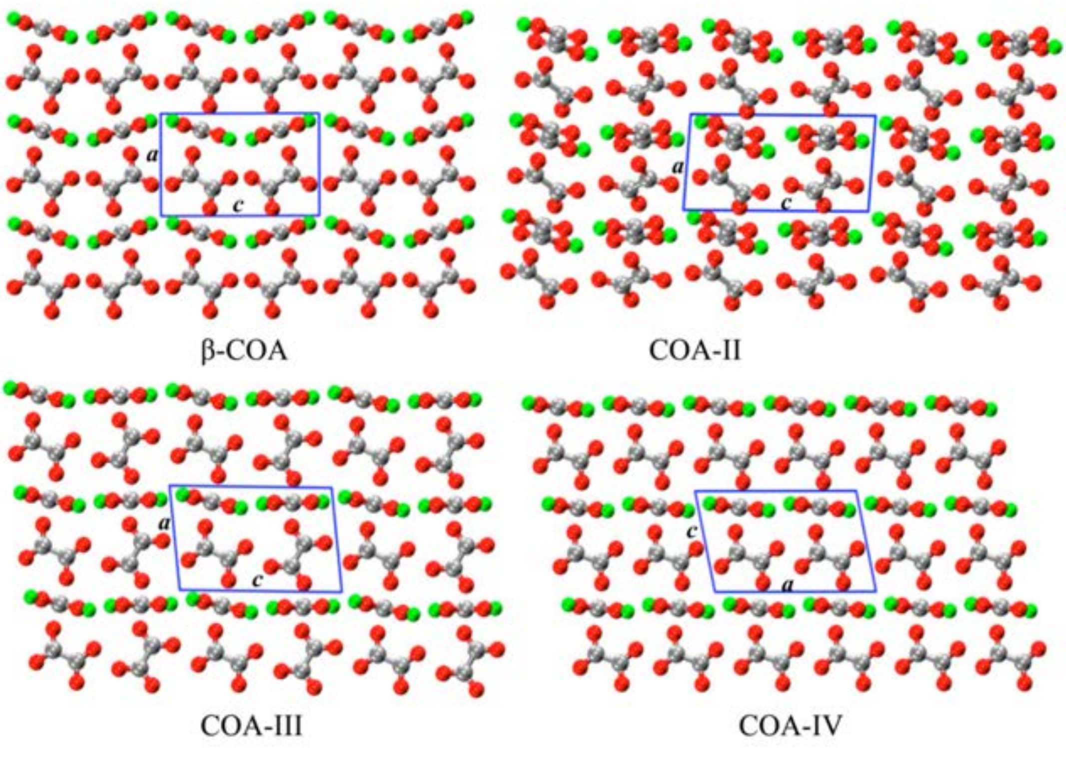
Views of the obtuse (left) and acute (right) steps on the calcite surface. In the upper terrace, calcium ions and carbonate units are shown as ochre and cyan spheres, respectively; in the lower terrace, they are in pink and grey, respectively. Water molecules coordinated to the calcium sites have been shown up to those bound to the fourth row from the step. Molecules are coloured according to their residence time.

Calcium oxalate polymorphism

Zhao et al. (2016) have explored four possible models for anhydrous calcium oxalate polymorphs using ab initio quantum mechanical methods. They analysed and compared the structural properties, their IR and Raman spectra and thermodynamic stability in the range 0 – 800K. As well as the known β–calcium oxalate structure, they found two models to be possible candidates for the α and γ polymorphs that are found during the dehydration of weddellite (calcium oxalate dehydrate).

This work is relevant to understanding the formation of kidney stones as well as an example of the application of computational methods to polymorphism.

Zhao W., Sharma N., Jones F., Raiteri P., Gale J.D., Demichelis R. (2016) Anhydrous calcium oxalate polymorphism: a combined computational and synchrotron X-ray diffraction study. *Crystal Growth and Design* 16, 5954-5965.



Optimized structures of calcium oxalate, COA.


Crystallisation
Down Under
NRI
The Leverhulme Trust


2016
Curtin University

Experimental Crystal Growth at the Nanoscale

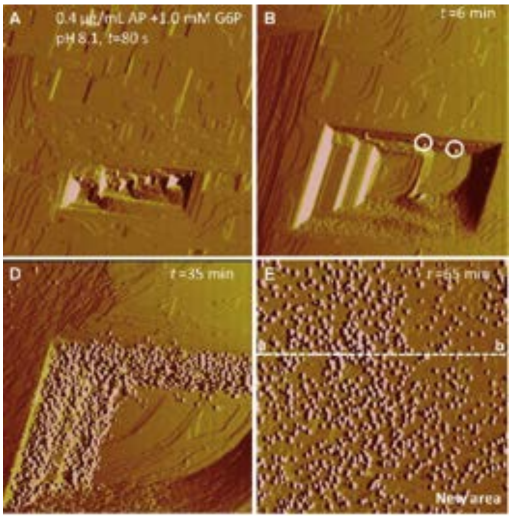
Computations and experiments are complementary and Atomic Force Microscopy (AFM) enables crystal growth to be observed in situ in a fluid cell at the nanoscale. The results of such experiments identify research questions that can be resolved with modelling techniques as well as provide constraints on the molecular modelling. In turn, molecular modelling provides the theoretical basis to explain the experimental observations. Some examples of published work during 2016 are given below.

Organophosphate precipitation at the calcite-water interface visualized by in situ Atomic Force Microscopy

Esters of phosphoric acid constitute a large fraction of the total organic phosphorus (OP) in the soil environment and thus play an important role in the global phosphorus cycle. These esters, such as glucose-6-phosphate (G6P), exhibit unusual reactivity toward various mineral particles in soils, especially those containing calcite. Little is known about the kinetics of specific mineral-surface-induced adsorption and precipitation of organophosphates.

Wang et al. (2016) used in situ atomic-force microscopy (AFM) to visualize the dissolution of calcite (1014) faces, and showed that the presence of G6P results in morphology changes of etch pits from the typical rhombohedral to a fan-shaped form. This can be explained by a site-selective mechanism of G6P– calcite surface interactions that stabilize the energetically unfavorable (0001) or (0112) faces through step-specific adsorption of G6P. Continuous dissolution at calcite (1014) – water interfaces caused a boundary layer at the calcite – water interface to become supersaturated with respect to a G6P – Ca phase that then drives the nucleation and growth of a G6P – Ca precipitate. These direct dynamic observations of the transformation of adsorption - and complexation-surface precipitation and enzyme-mediated pathways may improve the mechanistic understanding of the mineral-interface-induced organophosphate sequestration in the soil environment.

Wang L., Qin L., Putnis C.V., Ruiz-Agudo E., King H., Putnis A. (2016) Visualizing organophosphate precipitation at the calcite-water interface by in situ *Atomic Force Microscopy. Environmental Science and Technology* 50, 259-268.



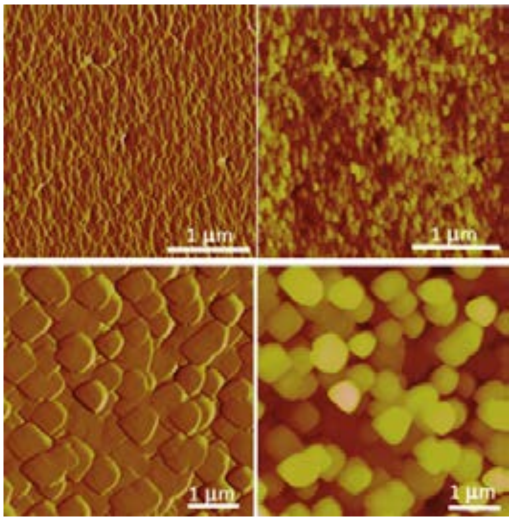
A time sequence of AFM images showing dissolution of the calcite surface and precipitation of Ca-phosphate nanoparticles.

Direct Nanoscale Imaging of the Growth of Calcite Crystals via Amorphous Nanoparticles

The formation of calcite ($CaCO_3$), the most abundant carbonate mineral on Earth and a common biomineral, has been the focus of numerous studies. While recent research underlines the importance of non-classical crystallization pathways involving amorphous precursors, direct evidence is lacking regarding the actual mechanism of calcite growth via an amorphous phase.

Rodriguez et al. (2016) show, using *in situ* atomic force microscopy and complementary techniques, that faceted calcite can grow via a non-classical particle-mediated colloidal crystal growth mechanism that at the nanoscale mirrors classical ion-mediated growth, and involves a layer-by-layer attachment of amorphous calcium carbonate (ACC) nanoparticles, followed by their restructuring and fusion with the calcite substrate in perfect crystallographic epitaxy. The ACC-to-calcite transformation occurs by an interface-coupled dissolution–reprecipitation mechanism and obliterates or preserves the nanogranular texture of the colloidal growth layer in the absence or presence of organic (macro)molecules, respectively. These results show that, in addition to classical ion-mediated crystal growth, a particle-mediated growth mechanism involving colloidal epitaxy may operate in the case of an inorganic crystal such as calcite. The gained knowledge may shed light on the mechanism of $CaCO_3$ biomineralization, and should open new ways for the rational design of novel biomimetic functional nanomaterials.

Rodriguez-Navarro C., Burgos Cara A., Elert K., Putnis C.V., Ruiz-Agudo E. (2016) Direct nanoscale imaging reveals the growth of calcite crystals via amorphous nanoparticles. *Crystal Growth and Design,* 16, 1850-1860.



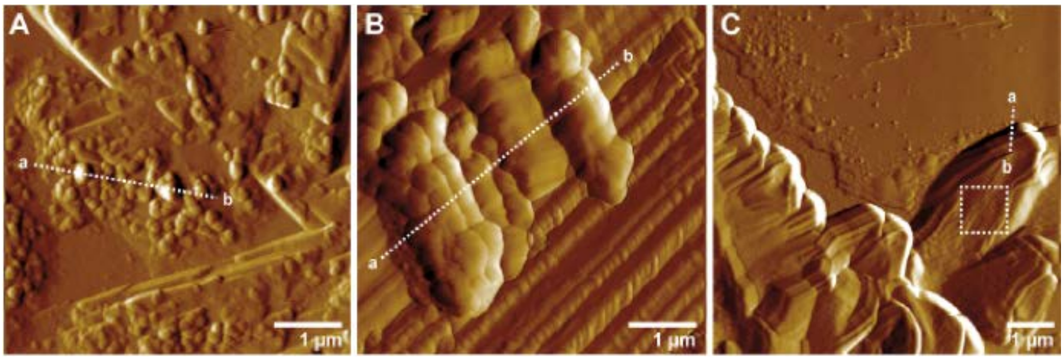
A sequence of AFM deflection (left) and height (right) images of the growth of calcite nanoparticles. Lower two images 1 hour after the upper images.

Nanoscale imaging of struvite formation during the dissolution of natural brucite

The recovery of phosphorus from wastewaters through the controlled crystallization of struvite ($MgNH_4PO_4 \cdot 6H_2O$), a potential slow-release fertilizer, is highly attractive, but costly if large amounts of Mg have to be added. Natural Mg-minerals like brucite ($Mg(OH)_2$) could provide more cost-effective Mg-sources compared to high-grade Mg-compounds such as $MgCl_2$.

Hövelmann and Putnis (2016) used *in situ* atomic force microscopy (AFM) to study the interactions of ammonium phosphate solutions with brucite (001) cleavage surfaces. Brucite dissolution was strongly enhanced in the presence of $H_2PO_4^-$ ions, most likely due to the formation of negatively charged surface complexes. Simultaneously with brucite dissolution, they directly observed the formation of struvite. Their results suggest that brucite dissolution and struvite precipitation were coupled at the mineral-fluid interface within a thin fluid boundary layer. An interpretation is proposed where the heterogeneous nucleation and growth of struvite occurs via a particle-mediated process involving the formation of primary nanoparticles, followed by their continuous aggregation, fusion and possible transformation to crystalline struvite. These observations have implications for the feasibility of using brucite in phosphorus recovery processes.

Hövelmann J., Putnis C.V. (2016). In situ nanoscale imaging of struvite formation during the dissolution of natural brucite: Implications for phosphorus recovery from waste waters. *Environmental Science & Technology*, 50, 13032-13041.



AFM deflection images showing struvite precipitates formed on brucite surfaces.

Computational Geoscience

In 2016 Professor Victor M. Calo was appointed to the joint CSIRO/Curtin Chair of Computational Geoscience and together with his research group, has joined TIGeR.

Multiscale Modelling

In 2016, the group published seven papers on multiscale methods [7, 12–14, 17–19]. In [13, 14, 18, 19], they applied model reduction techniques to reservoir simulations. They also developed problem specific techniques to assess the impact of local material heterogeneities on the overall behaviour of a system. In particular, they modelled heterogeneous transport [12], separation with asymmetric membranes [7], and heat conduction in the presence of inclusions with drastically different material conductivities [17].

Materials Modelling

In 2016, the group focussed on the multiscale and multiphysics modelling of materials. First, with Luis Espath they modelled density currents and their impact on sedimentary basins. With Dr Vignal, they reformulated several proveably-stable time integrators for many popular phase-field models using a Taylor series expansion in time [1]. With Luis Espath, we have used the multi-field implementation of PetIGA [2, 9] to analyse the energy exchanges that occur when droplets merge in viscous suspensions [10]. With Dr Moreno and Prof Nunes, we modelled di-block copolymer self-assembly in solution using particle methods, in particular, we developed a multiscale version of the dissipative particle dynamics method [8].

[1] P Vignal, AMA Cortes, N Collier, L. Dalcin, D.L. Brown, V.M. Calo, "An energy-stable time-integrator for phase-field models," *Comp Meth App Mech Eng*, in Press, 2016.

[2] AF Sarmiento, AMA Cortes, DA Garcia, L Dalcin, N Collier, VM Calo, "PetIGA-MF: a multi-field high- performance toolbox for structure-preserving B-splines spaces," *J Comp Sci*, 18:117-131, 2017.

[3] A Cortes, L Dalcin, A Sarmiento, N Collier, V Calo, "A scalable block-preconditioning strategy for divergence-conforming B-spline discretizations of the Stokes problem," *Comp Mth App Mech Eng*, Acc, 2016

[4] M Barton, VM Calo, "Gauss-Galerkin quadrature rules for quadratic and cubic spline spaces and their application to isogeometric analysis," *Computer-Aided Design*, 82:57-67, 2017.

[5] D Garcia, D Pardo, L Dalcin, M Paszynski. N Collier, VM Calo, "The value of continuity: Refined Isogeometric Analysis and fast direct solvers," *Comp Meth App Mech Eng*, in Press, 2016.

[6] M Paszyski, H AbouEisha, VM Calo, K Jopek, M Moshkov, A Paszynska, M Skotniczny, "Element Partition Trees for 2D and 3D *h*-Refined Meshes and Their Use to Optimize Direct Solver Performance. Part I. Dynamic Programming," *Int J App Maths Comp Sci*, accepted, 2017.

[7] M Shi, G Printsypar, PHH Duong, VM Calo, SP Nunes, "3D Morphology Design for Forward Osmosis", *J Membrane Science*, 516:172-184, 2016.

[8] Y Xie, N Moreno, VM Calo, H Cheng, P-Y Hong, R Sougrat, AR Behzad, R Tayouo, SP Nunes, "Synthesis of highly porous poly(tert-butyl acrylate)-b-polysulfone-b-poly(tert-butyl acrylate) asymmetric membranes", *Polym Chem* 7:3076-3089, 2016

[9] L Dalcin, N Collier, P Vignal, AMA Cortes, VM Calo, "PetIGA: A framework for high-performance isoge- ometric analysis", *Comp Meth App Mech Eng*, 308:151-181, 2016.

[10] LFR Espath, A Sarmiento, P Vignal, B Varga, AMA Cortes, L Dalcin, and VM Calo, "Energy exchange in droplet dynamics for the Navier-Stokes-Cahn-Hilliard model", *J Fluid Mech*, acc 2016.

[11] M Barton, VM Calo, "Optimal quadrature rules for odd-degree spline spaces and their application to tensor-product-based isogeometric analysis", *Comp Meth App Mech Eng*, 305:217-240, 2016.

[12] VM Calo, ET Chung, Y Efendiev, WT Leung, "Multiscale stabilization for convection-dominated diffusion in heterogeneous media", *Comp Meth App Mech Eng*, 304:359-377, 2016.

[13] Y Yang, M Ghasemi, E Gildin, Y Efendiev, VM Calo, "Fast multiscale reservoir simulations using POD- DEIM model reduction", *SPE J*, 21:6:SPE-173271-PA, 2016.

[14] VM Calo, Y Efendiev, JC Galvis, G Li, "Randomized oversampling for generalized multiscale finite element methods", *Multiscale Modeling and Simulation*, 14(1):482501, 2016.

[15] D Pardo, J A´ lvarez-Aramberri, M Paszynski, L Dalcin, VM Calo, "Impact of Element-Level Static Condensation on Iterative Solver Performance", *Comp Math App*, 70(10):23312341, 2016.

[16] M Barton, VM Calo, "Gaussian quadrature for splines via homotopy continuation: rules for C2 cubic splines", *J Comp App Math*, 296:709-723, 2016

[17] L Poveda, JC Galvis, VM Calo, and S Huepo,"Asymptotic expansions for high-contrast linear elasticity", *J Comp App Math*, 295:25-34, 2016.

Refereed Conference Proceedings

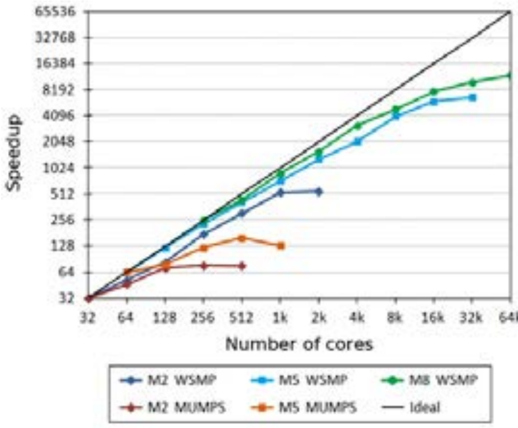
[18] Y Yang, E Gildin, Y Efendiev, V Calo. "Online adaptive local-global POD-DEIM model reduction for fast simulation of flows In heterogeneous media", SPE-RSC 20-22 Feb, 2017, Montgomery, TM

[19] Ghasemi, Y Yang, E Gildin, Y Efendiev, VM Calo, "Fast multiscale reservoir simulations using POD-DIEM model reduction SPE-173271-MS, 2016.

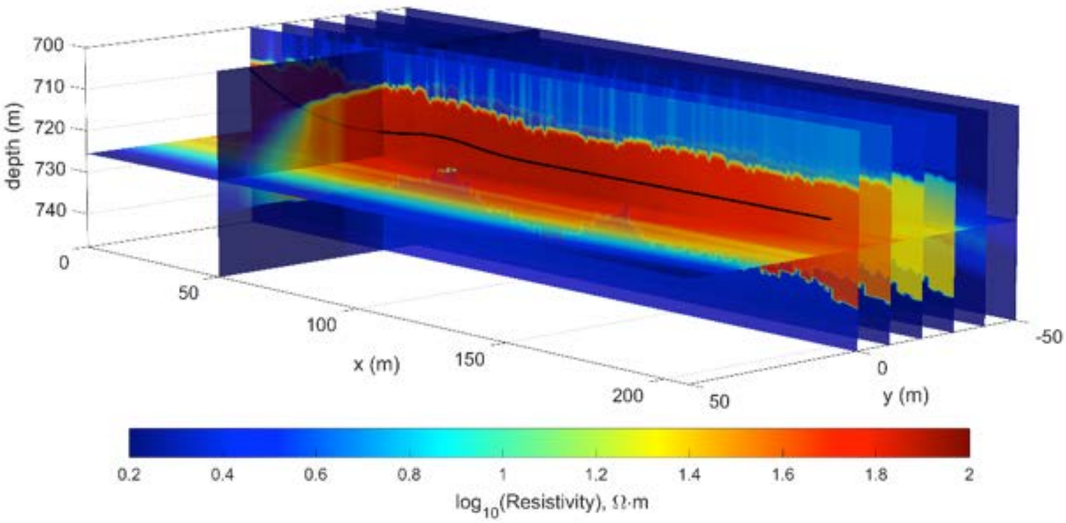
Evaluation of parallel direct sparse linear solvers in electromagnetic geophysical problems

High performance computing is absolutely necessary for large-scale geophysical simulations. In order to obtain a realistic image of a geologically complex area, industrial surveys collect vast amounts of data making the computational cost extremely high. A major computational bottleneck of modeling and inversion algorithms is solving the large sparse linear systems with multiple right hand sides. Puzyrev et al. (2016) evaluated modern parallel direct solvers on large-scale modeling examples that previously were considered unachievable with these methods. Capable of a peak performance of 13 PFlops, Blue Waters at University of Illinois' National Center for Supercomputing Applications, USA was one of the most powerful supercomputers in the world. Performance and scalability tests utilizing up to 65,536 cores clearly illustrated the robustness, efficiency and competitiveness of direct solvers compared to iterative techniques. Wide use of direct methods utilizing modern parallel architectures will allow modeling tools to accurately support multi-source surveys and 3D data acquisition geometries, thus promoting a more efficient use of the electromagnetic methods in geophysics.

Puzyrev V., Koric S., Wilkin S. (2016). Evaluation of parallel direct sparse linear solvers in electromagnetic geophysical problems. *Computers and Geosciences*, 89, 79-87



Parallel speedup of the direct solvers.



Resistivity model of the reservoir monitoring scenario (3D inversion of borehole deep directional resistivity measurements).

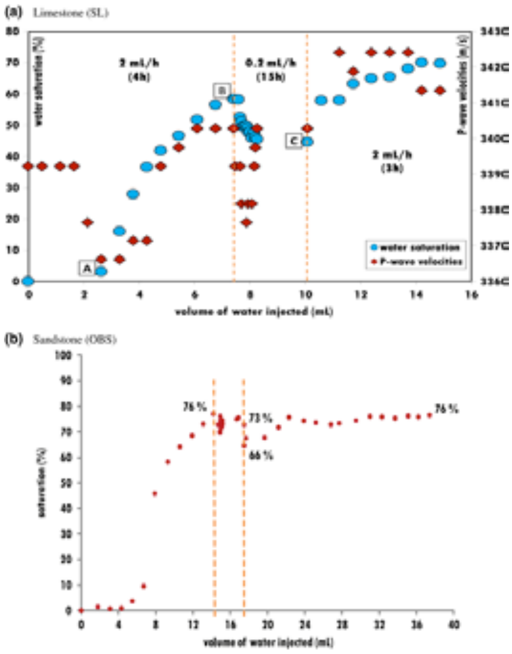
Research reports

EXPLORATION GEOPHYSICS

Seismic signatures of patchy saturation

A major effort of the group is focused on the study of the effects of patchy saturation on seismic signatures. The relationship between P-wave velocity and fluid saturation in a porous medium is of importance for reservoir rock characterisation. Forced imbibition experiments in the laboratory reveal rather complicated velocity–saturation relations, including rollover-like patterns induced by injection rate changes. Poroelasticity theory-based patchy saturation models using a constant fluid patch size are not able to describe these velocity–saturation relations. Liu et al. (2016) incorporate a saturation-dependent patch size function into two models for patchy saturation. This recipe allows them to model observed velocity–saturation relations obtained for different and variable injection rates.

Liu J., Müller T.M., Qi Q., Lebedev M., Sun W. (2016) Velocity-saturation relation in partially saturated rocks: Modelling the effect of injection rate changes. *Geophysical Prospecting* 64, 1054-1066.



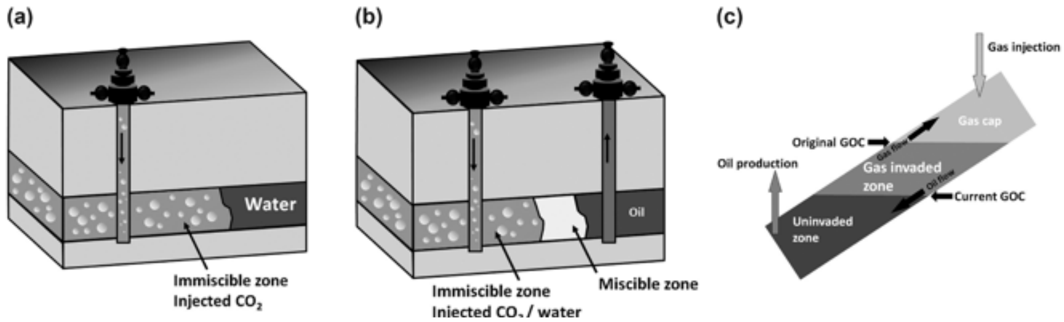
Gravity anomalies over Australia and its surrounds (mGal).

Saturation scale effect on time-lapse seismic signatures

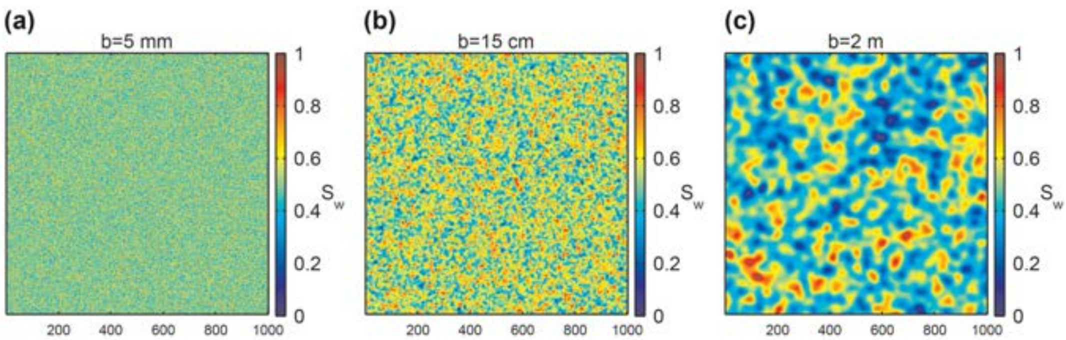
Quantitative interpretation of time-lapse seismic signatures aims at assisting reservoir engineering and management operations. Time-lapse signatures are thought to be primarily induced by saturation and pressure changes. Core-flooding and reservoir flow simulations indicate that a change of the driving forces during dynamic fluid injection gives rise to a varying saturation scale. This saturation scale is yet another variable controlling the time-lapse seismic signal.

Qi et al. (2016) investigate the saturation scale effect on time-lapse seismic signatures by analysing simple modelling scenarios. They consider three characteristic saturation scales, ranging from few millimetres to metres, which may form during gas injection in an unconsolidated water-saturated reservoir. Using the random patchy saturation model, they compare the corresponding acoustic signatures, i.e., attenuation, reflectivity, and seismic gather associated with each saturation scale. The results show that the millimetre saturation scale produces minimum attenuation and the same seismic signatures with those obtained from the elastic modelling. The centimetre saturation scale produces maximum attenuation, whereas the metre saturation scale causes highest velocity dispersion. They show that including the effects of capillarity and residual saturation into the rock physics modelling can potentially reduce the interpretation uncertainty due to the saturation-scale change.

Qi Q., Müller T.M., Gurevich B. (2016). Saturation scale effect on time-lapse seismic signatures. *Geophysical Prospecting*, 64, 1001-1015.



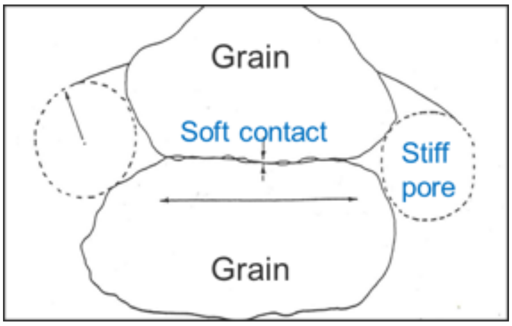
Three gas injection scenarios that are likely to induce patchy saturation. (a) CO_2 sequestration. (b) Enhanced oil recovery using water alternating with gas. (c) Gas injection in the gas cap for secondary oil recovery.



Synthetic saturation images of a rock with 50% gas saturation. The fluid distribution is exponentially correlated with a correlation length of 5mm for image (a), 15cm for image (b), and 2m for image (c).

Modelling of attenuation and dispersion due to squirt flow in rocks saturated with fluid

Glubokovskikh et al. (2016) have developed a new squirt flow model in which all parameters can be independently measured or estimated from measurements. The pore space of the rock is assumed to consist of stiff porosity and compliant (or soft) pores present at grain contacts. The effect of isotropically distributed soft pores is modelled by considering pressure relaxation in a disk-shaped gap between adjacent grains. This derivation gives the complex and frequency-dependent effective bulk and shear moduli of a rock, in which the soft pores are liquid-saturated and stiff pores are dry. The resulting squirt model is consistent with Gassmann's and Mavko-Jizba equations at low and high frequencies, respectively. As expected, the dispersion and attenuation are the strongest at low effective stress and much smaller at higher effective stress.



In a dry rock at low confining stress the grain contacts are soft. In a liquid-saturated rock at low frequencies the fluid pressure can equilibrate; the contacts are still soft (Gassmann). At high frequencies, the pressure has no time to equilibrate thus contacts are stiff, which leads to dispersion. Confining pressure closes the soft pores (reduces dispersion) producing Squirt flow.

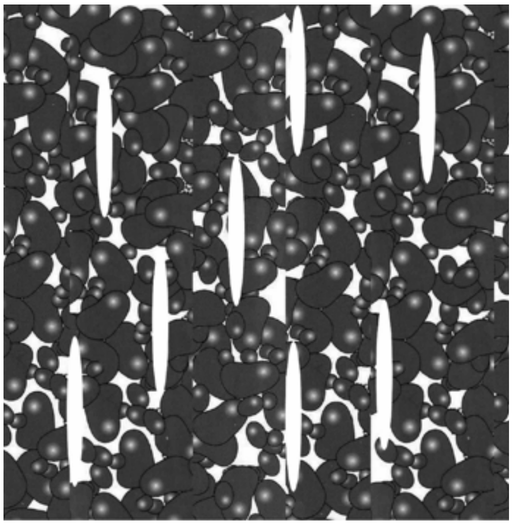
Predicted versus measured saturated bulk moduli for the pressure range from 5 to 50 MPa. Gassmann (crosses) predictions underestimate and Mavko -Jizba model (open circles) overestimates the experimental data. The prediction of the newly developed squirt-flow dispersion model (solid circles) with the intermediate porosity gives in a better agreement with the data for the clean sandstones.

Glubokovskikh S., Gurevich B., Saxena N. (2016). A dual-porosity scheme for fluid/solid substitution. *Geophysical Prospecting*, 64(4), 1112-1121.

Modelling elastic properties of fractured reservoirs

A major effort of the department's rock physics group is directed towards modelling attenuation, dispersion and frequency dependent anisotropy of porous reservoirs permeated by aligned fractures. Over the last decade, this group has developed a methodology of fluid substitution in fractured reservoirs, which is based on the combination of anisotropic Gassmann equations and Schoenberg's linear slip parameterisation of the effect of fractures on rock properties. The group has developed a model for attenuation and dispersion of P-waves propagating perpendicular to a periodic system of parallel planar fractures and validated this model with numerical simulations using a poroelastic extension of the reflectivity method. These simulations helped to extend the attenuation/dispersion model to randomly spaced fractures and to oblique incidence. The group also developed a model for seismic attenuation and dispersion caused by the presence of sparsely distributed finite fractures in the porous reservoirs. The model is based on the combination of Biot's theory of poroelasticity with the ideas of a multiple scattering theory.

While all of the above models are designed for a single set of aligned fractures, real reservoirs often contain multiple fracture sets. Moreover, similar phenomena (fluid flow between pores and fractures) lead to frequency dependent attenuation and dispersion in isotropic rocks with micro-cracks, compliant grain contacts, etc. These effects are being studied by extending the aligned fracture models to arbitrary angular distributions of fractures.



A porous medium containing a sparse distribution of circular cracks.

Modelling stress-dependent properties of rocks

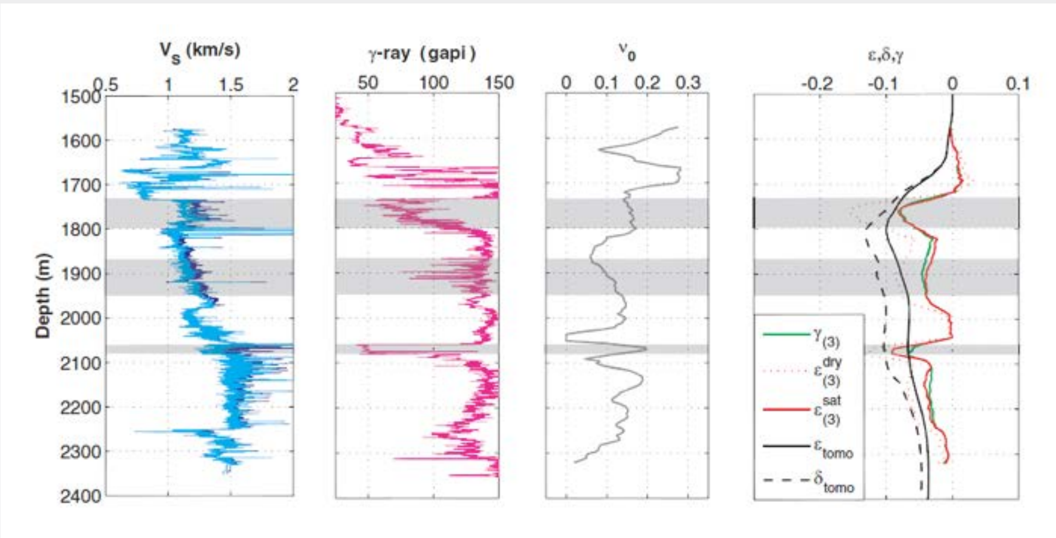
Stress is one of the major causes of anisotropy in the earth. Understanding it is important for imaging, reservoir characterisation and monitoring. There is a need to be able to distinguish stress-induced from fracture-induced anisotropy.

Glubokovskikh et al. (2016) have developed theoretical models of stress-induced anisotropy of rocks. They first considered an isotropic linearly elastic medium (porous or nonporous) permeated by a distribution of discontinuities with random (isotropic) orientation (such as randomly oriented compliant grain contacts or cracks). When this isotropic rock is subjected to a small compressive stress (isotropic or anisotropic), the number of cracks along a particular plane is reduced in proportion to the normal stress traction acting on that plane. This effect is modelled using the Sayers-Kachanov non-interactive approximation.

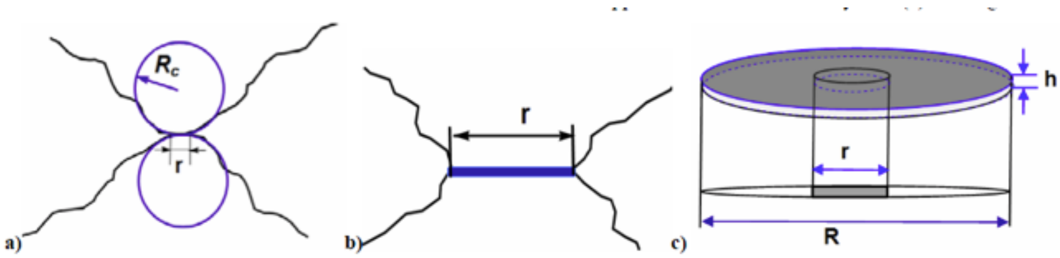
The model predicts that such an anisotropic crack closure yields elliptical anisotropy, regardless of the value of the ratio of the normal to shear compliance. It also predicts the ratio of Thomsen's anisotropy parameters as a function of the compliance ratio and Poisson's ratio of the unstressed rock.

The model is tested using laboratory data. In addition, it has been extended to large stresses, and also to a general triaxial stress state (leading to orthotropic symmetry). The results can potentially be used for differentiating between stress and fracture induced anisotropy, and also for predicting P-wave anisotropy from S-wave anisotropy; the latter may be estimated from shear-wave splitting as measured by modern sonic logs or VSP.

They are also exploring micro-mechanical mechanisms of stress dependency of elastic properties of rocks based on the analysis of deformation of individual asperities.



Stybarrow 2 well: (a) S-wave velocity log showing the fast (dark blue) and slow (light blue) wave velocities; (b) γ -ray log; (c) inverted Poisson's ratio of the dry unstressed rock; (d) azimuthal anisotropy parameters obtained using the methodology developed in the present work (green and red curves) compared with those estimated by orthorhombic tomography (black curves).



Geometries corresponding to a) Hertz contact; b) welded-area contact and c) annular crack.

Collet O., Gurevich B., Duncan G. (2016) Estimating azimuthal stress-induced P-wave anisotropy from S-wave anisotropy using sonic log or vertical seismic profile data, *Geophysical Prospecting*, 2015, doi: 10.1111/1365-2478.12307

Glubokovskikh, S., Gurevich, B., Lebedev, M., Mikhaltsevitch, V., Tan, S. (2016) Effect of asperities on stress dependency of elastic properties of cracked rocks, *International Journal of Engineering Science* 98, 116-125.

The frequency dependence of anisotropy in fluid-saturated rocks

A major cause of attenuation in fluid-saturated media is the local fluid flow (or squirt flow) induced by a passing wave between pores of different shapes and sizes. Several squirt flow models have been derived for isotropic media. For anisotropic media however, most of the existing squirt flow models only provide the low- and high-frequency limits of the saturated elastic properties. Collet and Gurevich (2016a) have developed a new squirt flow model to account for the frequency dependence of elastic properties and thus gain some insight into velocity dispersion and attenuation in anisotropic media.

They focus on media containing aligned compliant pores embedded in an isotropic background matrix. The low- and high-frequency limits of the predicted fluid-saturated elastic properties are respectively consistent with Gassmann theory and Mukerji–Mavko squirt flow model. It turns out that the P-wave anisotropy parameter ε tends to zero in the high-frequency limit, whereas the δ parameter remains the only indicator of P-S⊥ anisotropy. The S-wave anisotropy parameter γ is not affected by the presence of fluid and remains the same for all frequency ranges. A new definition for attenuation anisotropy parameters is also proposed to quantify the attenuation anisotropy. In the most important case of liquid saturation, analytical expressions are derived for elastic properties, velocity anisotropy parameters, quality factors, and attenuation anisotropy parameters. Collet and Gurevich (2016b) considers the case of cracks with an ellipsoidal distribution of orientations resulting from the application of anisotropic stress.

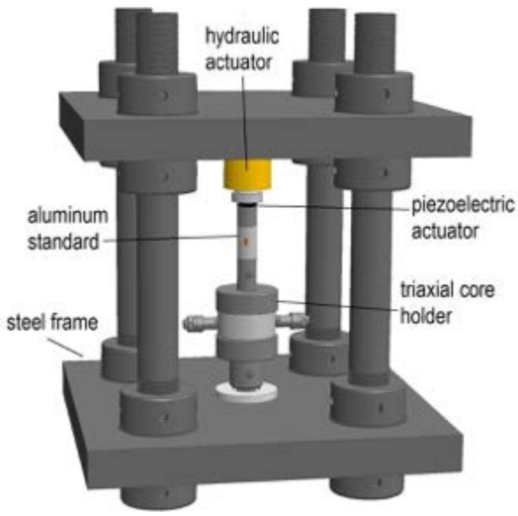
Collet O., Gurevich B. (2016a). Frequency dependence of anisotropy in fluid saturated rocks – Part I: aligned cracks case. *Geophysical Prospecting*, 64(4), 1067-1084.

Collet O., Gurevich B. (2016b). Frequency dependence of anisotropy in fluid saturated rocks – Part II: Stress-induced anisotropy case. *Geophysical Prospecting*, 64(4), 1085-1097.

Experimental rock physics

Broadband acoustic measurements: from seismic to ultrasonic frequencies

Theoretical rock physics models need to be tested and calibrated using laboratory measurements. To this end, the department is performing comprehensive experimental testing of these theories using broadband measurements of dynamic elastic properties (elastic moduli) and attenuation of rock samples (Mikhaltsevitch, Lebedev and Gurevich, 2016). Experiments are conducted at reservoir conditions using a combination of patent protected forced-oscillation ultra-sensitive strain gauge measurements (0.01 Hz – 200 Hz) and ultrasonic testing (1 MHz). The results are being compared with theoretical predictions computed using numerical simulations.



Seismic frequency apparatus at the Rock Physics Lab.

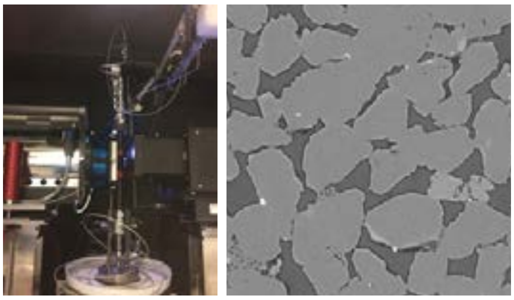
Mikhaltsevitch V., Lebedev M., Gurevich B. (2016). Validation of the laboratory measurements at seismic frequencies using the Kramers-Kronig relationship. *Geophysical Research Letters*, 43, 4986-4991.

Mikhaltsevitch V., Lebedev M., Gurevich B. (2016). Laboratory measurements of the effect of fluid saturation on elastic properties of carbonates at seismic frequencies. *Geophysical Prospecting*, 64, 799-809.

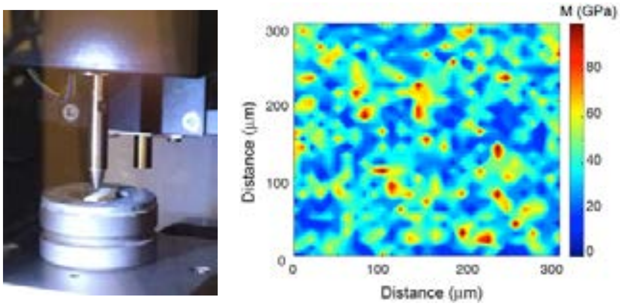
Quantitative microstructure characterization from micro-CT and nano-indentation

Rocks exhibit a complex microstructure, which is the result of both transport and deposition of various minerals and diagenetic alterations. This complexity in microstructure will translate in complex relationships between geophysical observables and rock parameters (e.g. elastic moduli vs. porosity, permeability vs. porosity) and thus makes reservoir quality prediction difficult. The Rock Physics laboratory is equipped with a 3D X-ray Microscope Versa XRM 500 (Zeiss - XRadia), which allows imaging of rocks and sediments with a resolution down to 0.6um. In-house built flow cells enable the department to reproduce reservoir conditions of temperature and pressure and to circulate various fluids though the rock (single or multiphase conditions). Various rock parameters such as porosity, connectivity, saturations, etc., can then be obtained with the use of visualization and computation software accessible through the Pawsey Supercomputing Center. Within the department and through collaborative projects, we are developing methods to compute rock properties, such as elastic wave velocity or electrical conductivity, from the 3D X-ray images.

The department also owns a nano-indentation system (IBIS Fisher-Crips Laboratories Pty.Ltd.). This technique provides static and dynamic Young's moduli at the micro-meter scale as well as various mechanical parameters such as hardness, fracture toughness or creep behavior. We have used nano-indentation tests to map and quantify mechanical weakening due to exposure of the rock to CO_2-rich fluids as well as to map heterogeneities in Young's moduli of carbonates and relate it to microstructure heterogeneities acquired by SEM. Through a statistical analysis of the data, and with the use of rock physics models and micro-CT images, we are currently developing techniques to upscale these data at the core- and reservoir-scale.



High pressure cell inside microCT; Right: microCT images of Bentheimer sandstone performed at a confining pressure 20 MPa (right hand side). The physical size of the shown slices is 0.95mm * 0.95mm.

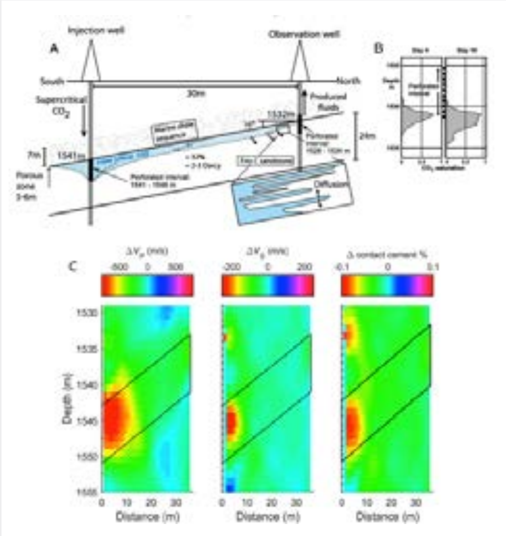


Nano-indentation measurement on a carbonate sample; Right: Map of indentation moduli.

Rock weakening after CO_2 injection into subsurface reservoirs

CO_2 injection into subsurface reservoirs leads to pressure and saturation changes and could also result in dissolution or reprecipitation of rock frame-forming minerals. Observed time-lapse seismic associated with CO_2 injection into poorly consolidated sandstone at the Frio CO_2 injection site (Texas, USA) could not be predicted using classical rock-physics models (i.e., models involving elastic changes in the rock frame due to saturations and/or pressures changes only, and assuming no changes in the rock microstructure). That, and the changes in the fluid chemistry after CO_2 injection, suggests that the assumption of a constant rock microstructure might be violated.

Using high-resolution time-lapse crosswell data, Al Hosni et al. (2016) have developed a methodology for estimating changes in the rock frame by quantifying the rock-frame drained moduli before and after CO_2 injection. Based on rock microstructure diagnostics, they found that the changes in the drained frame elastic properties are due to the changes in the grain contact-cement percentage. Their rock-physics analysis may allow improved interpretation of time-lapse seismic for CO_2 saturation in the context of other poorly consolidated sandstones with similar geomechanical properties. Having the P- and S-wave velocity time-lapse data is key to improve saturation estimates with this analysis method.



A - Overview of the Frio brine pilot project injection site (Texas). B – CO_2 saturations logs, 4 days and 16 days after CO_2 injection. C - Time-lapse crosswell traveltime tomography for P- and S-wave velocities, and corresponding computed contact cement change from rock physics diagnostics.

Al Hosni M., Vialle S., Daley T., and Gurevich B. (2016). Estimation of rock frame weakening using time-lapse crosswell: Frio brine pilot project. *Geophysics* 81, B235-B245.

Research reports

EXTRACTIVE METALLURGY

Extractive metallurgy

Process Metallurgy (pyro-, hydro-, and electrometallurgy), Minerals Engineering, Waste Processing and Geometallurgy constitute the related fields in the broad church of Extractive Metallurgy which features in the broader field of Resources Engineering and involves the study, evaluation, development and design of processes used in the extraction and beneficiation of economically important metals and minerals from their concentrates and ores. As such it utilises the knowledge areas of geology and mineralogy, chemistry, microbiology, chemical (process) engineering, electronic engineering and mechanical engineering. As it relates to the chemical environments in which minerals and rocks interact and react with aqueous solutions (in the case of hydrometallurgy and mineral processing) or high temperature melts such as molten slags, mattes and alloys (in the case of pyrometallurgy), it strongly intersects the earth sciences and the processes often similar, albeit at accelerated reaction rates, to the ore genesis, metamorphosis and weathering processes occurring during the formation of mineral deposits. Conversely, these ore genesis, metamorphosis and weathering processes often inspire and serve as reference cases for the development of industrial metal and mineral extraction processes.

Gold Ore on a screen deck. Paddington Gold Mine.

Extractive metallurgy research is chaired by Prof Jacques Eksteen, who manages the Gold Technology Group (GTG) and who is the project manager of the AMIRA P420F project. The research work has been sponsored either directly, or indirectly (through AMIRA, ARC Linkage or MRIWA) by Anglogold Ashanti, Barrick Gold, Newmont Mining, Newcrest Mining, Northern Star Resources, Mining and Process Solutions, St Barbara, Orica, Kemix, Gekko Systems, Vega Industries, CSBP-AGR, Pionera, FLSmidth, Lhoist, Mineral Research Institute of Western Australia, Panoramic Resources, and Lynas Corporation. The AMIRA P420E project was completed by May 2016 and the new AMIRA P420F project commenced in June 2016. Like the P420E project, the P420F project has 14 industry sponsors. In addition it obtained financial support from the Cooperative Research Centre for the Optimisation of Resource Extraction (CRC ORE). The current project (cash, excluding in-kind) budget for the 3-year project is circa $4.9 million. During 2016, another amino acid based processing patent was progressed to the PCT level (Eksteen and Oraby, 2016), and the various amino-acid based technologies are being commercialised through Mining and Process Solutions Pty Ltd. In addition, Curtin University assigned the marketing rights of the "Carbon Scout" carbon meter developed by the GTG team members to Gekko Systems. The GTG is also performed the research in two Mineral Institute of Western Australia (MRIWA) sponsored research grants (M458 and M434). Prof Eksteen and Dr Oraby have also been awarded an ARC Linkage Grant (LP160101121 based upon funding support by Newcrest Mining and Mining and Processing), titled: "A benign alkaline process for scarce metal extraction and reagent recycle".

Leach tanks and elution column. Tongon Mine Cote d'Ivoire.

Precious Metals Research

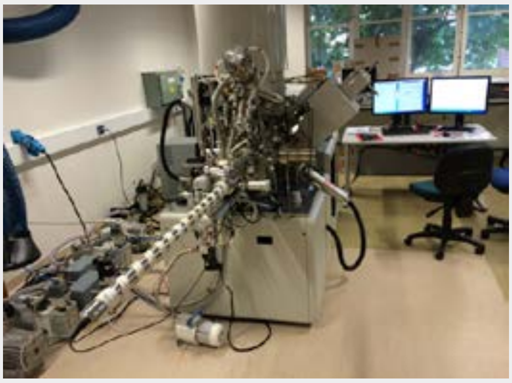
Precious metals (gold, silver and platinum group metals) are often associated ore deposits with large spatial geometallurgical variation which significantly impacts downstream metallurgical processing. As such, the metallurgist have to be able to characterise the ores with regards to the anticipated process impacts, and design and operate the processes in such a way as to be robust with regards to the geometallurgical variations. In addition, for leach processes, it becomes important that dissolution is selective to prevent excessive reagent consumption.

In the case of copper ores, it is exceedingly hard to dissolve chalcopyrite selectively while not co-dissolving iron (from the chalcopyrite or associated iron minerals such as pyrite, pyrrhotite, marcasite and arsenopyrite). Eksteen, Oraby and Tanda (2016) investigated the selective leaching of copper from chalcopyrite bearing resources using alkaline glycinate solutions as lixiviant, while minimising the co-dissolution of iron, and has shown that this refractory mineral can be dissolved selectively at mild temperature (60ºC) and ambient pressure within a feasible leach duration. The work was reported and presented at the International Mineral Processing Congress, Quebec City, Canada.

In the processing of gold-copper ores, gold-copper gravity concentrates rich in copper minerals are quite problematic for the intensive cyanidation of these concentrates due to excessive reagent consumption. Oraby and Eksteen (2016) have shown that at the same alkaline pH, the use of high sodium leach systems significantly suppresses copper co-dissolution over the high calcium and high ammonia systems, while gold leaching rates are enhanced. The research was reported on and presented to the 14 AMIRA P420E sponsors at the May 2016 Sponsor Review Meeting (SRM).

During comminution of gold-bearing sulfide ores, convoluted interactions occur between grinding media (e.g. forged steel, high chromium and ceramic media), the process water used and gold-bearing sulfide ores. Rabieh, Eksteen and Albijanic (2016) reviewed theses interactions with regards to the formation of surface coatings and their impacts on gold-bearing sulfide mineral flotation. Further research investigated the formation and types of mineral coatings that form on gold-bearing pyrite using X-Ray photoelectron spectroscopy (XPS) and an Ethylene Diamine Tetra-acetic Acid (EDTA) extraction technique, and the impacts of these coatings on pyrite flotation. This, and additional research on the impacts of these coatings on leaching kinetics were also presented to 14 AMIRA P420F sponsors at the December 2016 SRM meeting.

Flotation Froth, Tongon Mine.



X-ray Photoelectron Spectroscopy (XPS) at Curtin.

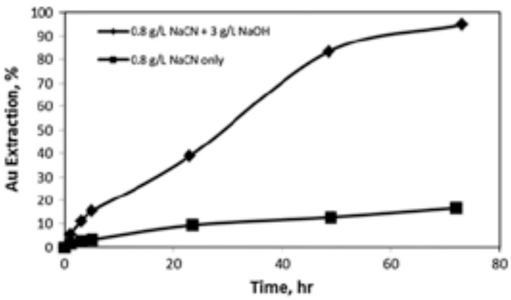
One of the key developments in the modelling of gold processing is the development of an ore characterisation method and a modelling method that takes into account the dual impacts of gold liberation upon gravity recovery and leach circuit recovery (with carbon adsorption) in a way that is practically expedient and computationally efficient. Teresa McGrath present this research at AMIRA P420E and P420F SRMs. The ore characterisation methodology was published in the AusIMM International Geometallurgy Conference (Bax et al., 2016a) and the mathematics of the modelling method was presented at the International Mineral Processing Congress (Bax et al., 2016b). The application of both the characterisation methodology and the modelling to a real gold operation (Paddington, WA) was demonstrated at the AusIMM Mill Operators Conference (McGrath, 2016a).

Many gold deposits are associated with significant levels of silver and copper. These metals compete with gold in terms of reagent consumption and, once dissolved, they compete with gold adsorption onto activated carbon, potentially leading to soluble gold losses to tailings impoundment facilities. Bax et al. (2016b) developed a process model to predict the behaviour of gold and silver during competitive adsorption onto activated carbon in a multi adsorption tank system.

Evaluation of activated carbon at fine carbon removal.

Key to the management of precious metals adsorption in carbon-in-pulp (CIP) and carbon in leach (CIL) systems is the ability to accurately measure the amount of activated carbon in a given tank in the presence of the mineral pulp. The Gold Technology Group developed a "Carbon Scout" carbon meter to perform this task automatically in multi-tank CIP/CIL operations. Staunton et al. (2016) reported on this work at the AusIMM Mill Operators Conference.

Due to the declining grades of most gold ore deposits, inordinate amounts of energy, reagents and water are used per troy ounce of precious metal produced. This problem has become quite acute in recent years with rapidly declining resource grades. Subsequently, there has been a significant focus to reduce the amount of ore that has to ground, floated, leached, and of which the tailings have to be disposed, whilst still maintaining high gold (and copper and silver) recoveries. The Gold Technology Group has been involved in research in the preconcentration, or coarse particle gangue rejection, whereby barren coarse gangue is liberated (through appropriate crushing technologies) and separated (using technologies that employ differences in density particle size and particle shape). One of the initial steps in this research is the development of amenability tests to ascertain if a significant portion of the barren gangue can (1) be liberated and (2) be separated. McGrath et al. (2016b) presented this research at the International Mineral Processing Congress.



Gold extraction from copper–gold concentrate in 0.8 g/L NaCN solutions in the absence and presence of 3 g/L NaOH (pH 12.6).

Platinum Group Metals (PGMs) are normally associated with complex polymetallic ores that shows significant geometallurgical variation "along strike" (horizontal) and "down-dip" (vertical). Eksteen (2016a) showed how these geometallurgical variations impacts downstream smelting and refining operations for PGMs, and how associated processing risks can be mitigated. Cleophace Mpinga is continuing with his MRIWA-sponsored PhD on the research into the direct leaching of PGMs from high chromium PGM deposits such as the Panton Sill deposit in the Kimberly. He has prepared various papers due for publication in 2017. Prof Eksteen (2016b) also contributed a book chapter in the field of the process mineralogy of PGM smelting and converting and downstream hydrometallurgical processing.

Critical Metals Research

Critical metals, in the field of mineral economics normally refers to high technology metals of which their supply chains are at risk due to either natural scarcity, high processing costs and high geopolitical or other risks associated with the primary sources of the materials. Typically, Rare Earth Elements (REEs), niobium, tantalum, lithium and cobalt fall within this category.

Hazel Lim is doing her PhD on the novel extraction routes for the leaching and recovery of Rare Earth Elements (REE's), zirconium and niobium and tantalum from REE-bearing eudialyte deposits, focussing on the eudialytes found in the Dubbo region of New South Wales and the southern areas of Greenland. In particular the emphasis of the research has been on the identification and evaluation of more benign lixiviants and reagents for the leaching of the targeted metals and their recovery from solution. She published some of her research in the Journal of Rare Earths (Lim et al., 2016).

In addition Prof Eksteen has been working with Prof Elizabeth Watkin, Dr Melissa Corbett and Mr Homayoun Fathollahzadeh in the development of a process whereby REE bearing phosphate minerals, such as monazite and xenotime, and their ores are leached using phosphate solubilising micro-organisms. Recent research has identified micro-organisms with significant potential to release REE's and further research is being performed to obtain a better understanding of the mechanisms of REE leaching, focussing on monazite minerals. Research papers have been accepted for publication and will be reported on in the 2017. The research was sponsored by MRIWA and Panoramic Resources and a final project report was issued to MRIWA.

Bax, A.R. Barbetti, K. Staunton, W.P. Avraamides, J. Eksteen, J.J., 2016a. Characterisation and Modelling of the Behaviour of Gold-Silver Competitive Co-Adsorption in CIL/CIP Circuits. IMPC 2016: Proceedings of the XXVIII International Mineral Processing Congress, The Canadian Institute of Mining, Metallurgy and Petroleum, 11-15 September, Quebec City, Quebec,10 p.

Bax, A.R., McGrath, T.D.H., Eksteen, J.J., Staunton, W., Oraby, E.A., and Wardell-Johnson, G., 2016b. An Integrated Liberation-leach Model and Ore Characterisation Procedure for Gold Ores. Proceedings of the 3rd AusIMM International Geometallurgy Conference, 15-16 June, Perth, Western Australia, pp. 315-320.

Bax, A.R., McGrath, T.D.H., Eksteen, J.J., Staunton, W.P., Oraby, E.A. and Wardell-Johnson, G. 2016c. An Integrated Liberation-Leach Model (ILLM) to Evaluate Gold Liberation and its Impacts on Gravity Recovery and Leaching. IMPC 2016: Proceedings of the XXVIII International Mineral Processing Congress, The Canadian Institute of Mining, Metallurgy and Petroleum, 11-15 September, Quebec City, Quebec,11 p.

Eksteen, J.J., 2016a. Impact of Mineralogical Variation on the Smelting of Cu-Ni-PGM Concentrates. Proceedings of the 3rd AusIMM International Geometallurgy Conference, 15-16 June, Perth, Western Australia, pp. 321-326.

Eksteen, J.J., 2016b. Chapter 28: Leaching in the Platinum Group Metals Industry. Process Mineralogy, Edited by M. Becker, E.M. Wightman, C.L. Evans., JKMRC Monograph Series in Mining and Mineral Processing: No. 6, JKMRC, University of Queensland, pp. 379-389.

Eksteen, J.J., and Oraby, E.A., 2016. Process for selective recovery of chalcophile group elements. PCT/AU2016/050171

Eksteen, J. J., Oraby, E. A., & Tanda, B. C. (2016). An Alkaline Glycine Based Process for Copper Recovery and Iron Rejection from Chalcopyrite. Proceedings of the 46th Meeting Annual Hydrometallurgy Meeting and the 4th International Symposium of Iron Control in Hydrometallurgy. Eds. E.M.L. Peek, M. Buarzaiga, & J.E. Dutrizac. 11-15 September, Quebec City, Quebec, pp. 349-358

Eksteen, J. J., Oraby, E. A., & Tanda, B. C., 2016. Developing Robust Hydrometallurgical Processes to Recover Metals from Deposits with Large Geometallurgical Variation. Proceedings of the 3rd AusIMM International Geometallurgy Conference, 15-16 June, Perth, Western Australia, pp. 15-20

Lim, H. Ibana, D., Eksteen J., 2016. Leaching of rare earths from fine-grained zirconosilicate ore. *Journal of Rare Earths*, 34(9), pp. 908-916.

McGrath, T. D. H., Staunton, W. P., Byleveld, R., and Eksteen, J.J., 2016a. Application of an Integrated Liberation Leach Model for Process Optimisation. Proceedings of the 13th AusIMM Mill Operators' Conference 2016, AusIMM, 10-12 October 2016, Perth, Western Australia, pp. 173-178.

McGrath, T.D.H. Wardell-Johnson, G.M. Bax, A.R. Eksteen, J.J., 2016b. Amenability of Gold Ores to Coarse Particle Gangue Rejection (Preconcentration) Processes. IMPC 2016: Proceedings of the XXVIII International Mineral Processing Congress, The Canadian Institute of Mining, Metallurgy and Petroleum, 11-15 September, Quebec City, Quebec,10 p.

Oraby, E.A., Eksteen, J.J., 2016. Gold dissolution and copper suppression during leaching of copper-gold gravity concentrates in caustic soda-low free cyanide solutions. *Minerals Engineering*, 87, pp. 10-17.

Rabieh, A., Albijanic, B. and Eksteen, J.J., 2016. A review of the effects of grinding media and chemical conditions on the flotation of pyrite in refractory gold operations. *Minerals Engineering,* 94, pp. 21-28

Staunton, W.P., McGrath, T.D.H., Ypelaan, C., Baker, O., and Eksteen, J.J., 2016. Optimising Carbon Management – Increasing Gold Recovery and Decreasing Costs with the Carbon Scout. Proceedings of the 13th AusIMM Mill Operators' Conference 2016, AusIMM, 10-12 October 2016, Perth, Western Australia, pp. 225-230.

Bioleaching

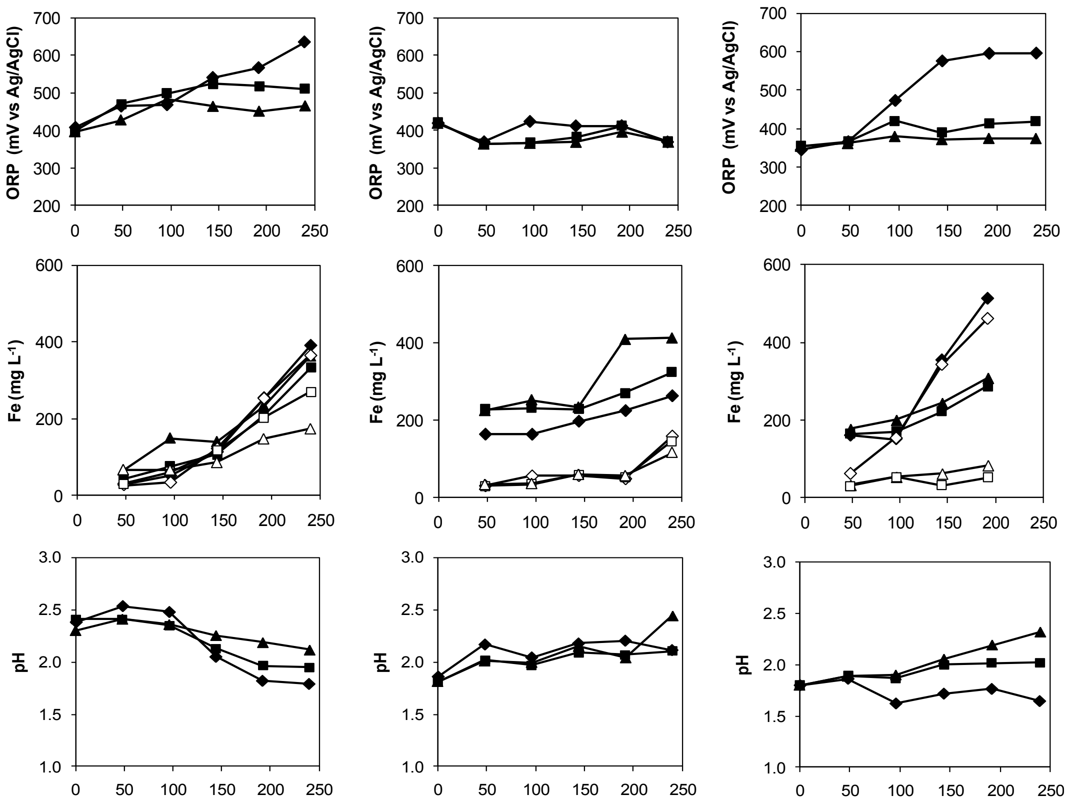
The bioleaching group at the School of Biomedical Sciences is led by Prof Elizabeth Watkin. Elizabeth Watkin is an environmental microbiologist and the overarching theme of her research is the microbial ecology of environmental systems and covers the fields of mining biotechnology and mineral resource recovery, microbial induced corrosion, microbial fouling of water (particularly within mining systems).

Her research team investigates biotechnological processes for environmental and industrial applications and approaches to mitigate microbially caused problems such as biocorrosion, biofouling and bioclogging.

Saline leaching of chalcopyrite with thermophilic microorganisms

Watling et al. (2016) investigated the application of thermoacidophiles for chalcopyrite ($CuFeS_2$) bioleaching in hot, acidic saline solution as a possible process route for rapid Cu extraction. The study comprised a discussion of protective mechanisms employed for the survival and/or adaptation of thermoacidophiles to osmotic stress, a compilation of chloride tolerances for three genera of thermoacidophiles applied in bioleaching and an experimental study of the activities of three species in a saline bioleaching system. The data showed that the oxidation rates of iron(II) and reduced inorganic sulfur compounds (tetrathionate) were reduced in the presence of chloride levels well below chloride concentrations in seawater, limiting the applicability of these microorganisms in the bioleaching of saline water.

Watling H.R., Collinson D.M., Corbett M.K., Shiers D.W., Kaksonen A.H., Watkin E.L.J. (2016). Saline-water bioleaching of chalcopyrite with thermophilic, iron(II)- and sulfur-oxidising microorganisms. *Research in Microbiology* 167:546-554.



Bioleaching tests using Metallosphaera hakonensis, Acidianus brierleyi or Sulfolobus metallicus in Basal Salts media without yeast extract containing 0.5% $CuFeS_2$. Open symbols, Fe^{3+}; closed symbols total Fe and all other data. Chloride (M): ◆ 0, ■ 0.06, ▲ 0.086.

RESEARCH GRANTS

How the Earth works – toward building a new tectonic paradigm

Prof. Z.X. Li, Curtin University.

ARC Australian Laureate Fellowship grant FL150100133

Half a century after the inception of plate tectonics theory, we are still unsure how the Earth 'engine' works, particularly the forces that drive plate tectonics. This project will build on the latest technological and conceptual advances to establish the first-order patterns of Earth evolution as far back as 2,000 million years ago, and use this information to examine a ground-breaking geodynamic hypothesis which links cyclic plate aggregation and dispersion to deep Earth processes. The project, a team effort involving extensive national and international collaboration, will potentially create a paradigm shift in our understanding of global tectonics, and will help to understand the formation and distribution of Earth resources.

IGCP project 648: Supercontinent cycles and global geodynamics

Professors Z.X. Li, Curtin University, D.A.D. Evans, Yale University, S. Zhong, University of Colorado, B. Eglington, University of Saskatchewan, plus over 150 members from many countries.

UNESCO-IUGS International Geoscience Program (IGCP) project 648, 2015–2019: up to USD50,000.

UNESCO-IUGS International Geoscience Program (IGCP) project 648, 2015–2019. Rapid recent progress in supercontinent research indicates that Earth's history has been dominated by cycles of supercontinent assembly and breakup. New developments in geophysical imaging power and computer simulation have provided increasingly clearer views of the Earth's interior, and how the moving plates on the Earth's surface interact with the deep planetary interior. In this project, we will bring together a diverse range of geoscience expertise to harness these breakthroughs in order to explore the occurrence and evolution history of supercontinents through time, and the underlying geodynamic processes. As part of this project, we will establish/improve global databases of geotectonics, palaeomagnetism, mineral deposits, and the occurrences of past mantle plume events, and examine how the supercontinent cycles interacted with the deep mantle to produce episodic and unevenly distributed Earth resources. The project builds on the success of a series of previous IGCP projects. It will not only lead to major scientific breakthroughs, but also develop user-friendly GIS-based databases that can be used by anyone who wants to reconstruct palaeogeography, test geodynamic models, model major climatic events such as Snowball Earth events, and predict exploration targets for Earth resources.

ARC Discovery grant DP130100130

Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation.

Rosenbaum, G. (University of Queenslnd), Pisarevsky, S.A. (Curtin University), Fielding, C. (University of Nebraska), Speranza, F. (Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy).

The main aim of this project is to unravel the history of the oroclinal bending of the Carboniferous – Permian New England Orogen in eastern Australia. To achieve this goal paleomagnetic, geochronological and structural studies are carried out.

ARC Discovery Project. DP160103449

Just add water – a recipe for the deformation of continental interiors.

CIs: A. Putnis (Curtin) T. Raimondo (Univ. South Australia) N. Daczko (Macquarie).

The plate tectonics paradigm argues that continental interiors are usually stable, rigid and undeformable, yet mountain belts have formed in these locations throughout Earth's history. Their existence suggests that strong crust can be significantly weakened to allow the accommodation of deforming forces, but the underlying causes for this change in behaviour are not clear. This project aims to investigate the largely unexplored impact of fluid flow on the characteristics of intraplate deformation. This outcome will improve our understanding of what modulates the strength of continental crust, including its susceptibility to seismic activity, and the ways in which fluids interact with the deep crust, including their mineralisation potential.

ARC LIEF Project LE160100103

Australian Virtual Experimental Laboratory: a multimode geoscience facility.

CIs: S. Foley (Macquarie) K.Evans (Curtin) John Mavrogenes (ANU) Andrew Putnis (Curtin) Joel Brugger (Monash) Simon Clark (Macquarie).

Seven types of high-pressure equipment will augment existing facilities to form a multi-node experimental laboratory at four locations across Australia (Macquarie, ANU, Monash and Curtin). These nodes will work as a team to further the effectiveness of high-pressure experimental geoscience research, coordinating the acquisition and use of a range of equipment relevant to research at all pressures from crust to core. Equipment includes hydrothermal and piston-cylinder systems for applications with fluids and melts relevant to the movement and deposition of precious metals, and multi-anvil and portable Laser-heated diamond-anvil systems for mantle and core pressures, some of which can also be used in synchrotron applications.

ARC Discovery Project DP150102773

Migmatites, charnockites and crustal fluid flux during orogenesis.

CIs: I.C.W. Fitzsimons (Curtin), M.B. Holness (Cambridge), C. Clark (Curtin).

Migration of volatile fluid and molten rock controls many Earth processes including rock deformation and the formation of mineral and energy deposits. Deep crustal fluids are hard to study directly, and their characteristics are usually inferred from lower crustal rock brought to the surface by erosion. For over 30 years one such rock called charnockite has been used to argue that lower crust is dehydrated by influx of CO_2-rich fluid, while other evidence supports dehydration by water extraction in silicate melt. This project will use the shape, distribution, and chemistry of mineral grains to trace the passage of volatiles and melt through charnockite, constrain the nature of lower crustal fluids, and resolve a long-standing controversy.

Australian Antarctic Science Project 4355

Reconstructing East Antarctica in Gondwana: ground-truthing a new tectonic model.

CIs: J.A. Halpin (University of Tasmania), N.R. Daczko (Macquarie), I.C.W. Fitzsimons (Curtin), J.M. Whittaker (University of Tasmania).

The sub-glacial geology of East Antarctica remains one of the most mysterious frontiers on Earth, and the Queen Mary Land and Wilkes Land sectors are particularly poorly understood although available data suggest that they comprise multiple continental fragments that collided to form part of the East Gondwana continent ~500 million years ago. This project will analyse rock samples previously collected near the collision zone to derive new age and geochemical constraints and to ground-truth a number of domains delineated by recent geophysical surveys. Determining the geometry, chemical composition and geological history of terranes in this sector of East Antarctica will lead to a greater appreciation of the role of ancient tectonic boundaries and geothermal heat flow on the behaviour of the Antarctic ice sheet.

ARC Discovery Project

Rehydration of the lower crust, fluid sources and geophysical expression.

CI: S. Reddy.

MRIWA Research Project

Mineral systems on the margin of cratons: Albany-Fraser Orogen / Eucla Basement case study.

CIs: C.L. Kirkland, C. Clark, K. Evans, S. Reddy.

Modern exploration requires a new integrated approach, utilizing a broad range of techniques, which can collectively enhance the geological knowledge of a region's mineral endowment. Craton margins host significant lithospheric discontinuities that focus fluids and heat and which, under favourable circumstances, may become mineralized corridors. Additionally, high-grade terrains are frequently viewed as less prospective for some mineralization (e.g. gold) than lower grade regions. However, recent discoveries in the Albany-Fraser Orogen highlight that many common models for mineral endowment are lacking and their resolution through cover limited. Significant ore systems with mantle tapping roots are the manifestation of physical and thermo-chemical processes associated with specific sites of fluid mobility, driven frequently by regional-scale tectonic activity. Hence, a means to enhance the discovery of new Australian resources, which may be buried, is to boost our detection of the distal signature carried within mineral phases. The aims of this project are to enhance petrochronology, crustal evolution and sulphur isotopic studies of the AFO and the covered Eucla basement.

MRIWA Research Project

Distal Footprints of Giant Ore Systems: "WA Case Study".

CI: S. Reddy.

SIEF Research Project

Distal Footprints of Giant Ore Systems: "UNCOVER Australia".

CI: S. Reddy.

Fok Ying Tung Education Foundation College and Higher Education Fellowship Project 151017

Oil generation and oil-source correlation in Neoproterozoic paleo-reservoir in Yanshan area: implication on Re-Os isotopes in petroleum system

CI: Zhen Li.

This three year project (2016-2019) is granted by China's Ministry of Education and Fok Ying Tung Education Foundation, focusing on Re-Os geochronology of ancient oil pools in the Yanshan Basin, North China.

ARC Discovery DP160102427

Developing and testing a new dating tool for Quaternary science.

CIs: Dr Martin Danisik; A/Prof Noreen Evans; Professor Dr Axel Schmitt; Associate Professor Phil Shane; Professor Takehiko Suzuki; Professor Shanaka de Silva.

ARC LIEF Project LE150100013

Laser ablation multiple split streaming. Installation and commissioning of the NPII multicollector, obtained through and occurred in March, 2016, enabling us to split stream ablated material simultaneously to both a quadrupole mass spectrometer and the multi-collector. Laser ablation split stream analysis facilitates isotopic and elemental analysis on the same volume of ablated material, permitting more accurate correlation of geologic processes.

CIs: Kemp, McCulloch, Fiorentini, McCuaig, Rate and 12 others.

ARC Discovery Project DP150101730

Building Central Asia: Linking the Growth of Asia to its Exhumation.

CIs: Glorie, Collins, Xiao and N.Evans.

ARC LIEF Project LE150100145

The South Australian Thermochronometry Hub.

CIs: Prof Collins, A/Prof Glorie, Prof Holford, A/Prof Evans, Prof McInnes, Prof Gleadow, Prof Reid.

ARC Discovery DP150101730

Building Central Asia: Linking the Growth of Asia to its Exhumation.

IODP grant 2016

Time constraints on the world's clearest oceanic curved fracture zone: implications for a global plate reorganisation in the Cretaceous (DSDP Legs 22 and 26).

H. Olierook, R. Merle, F. Jourdan and J. Whittaker.

NSFC Project 41373051

The preservation and exhumation of the Indonesian porphyry Cu deposits in the Zhongdian Arc, Northwest Yunnan: constraints from low-temperature thermochronology.

CIs: Zhang, McInnes, Evans, Zhu, Zhao, Wang, Wang and Leng.

Curtin Senior Research Fellowship to A/Prof N.J. Evans

(2015-2018): Laser GeoHistory: Insights into Minerals, Energy and Climate Change Research.

4-year salary and operating support at A/Professor level to complete a research program in laser-based elemental and chronological research.

ASI-Curtin RESOchron R&D Support

(2014-2017): 3 year salary and operating support for a Research Associate to develop protocols for (U-Th-Sm)/He *in situ* dating using the RESOchron facility. $780,000 with an option to extend to 5 years.

Australian Technology Network (ATN) – FAPESP (Brazil) grant

4D evolution of mineralization in Archean Terranes of Brazil.

CIs McNaughton, Rasmussen, Wilde.

This research is to provide reliable age information on key mineral deposits in Archean terranes of Brazil, and extends the decade-long collaboration in SHRIMP research between Curtin University and University of Campinas. It will be underpinned by the facilities and experience of Curtin researchers in dating ore deposits and related events, and the complementary experience in tectonics and ore genesis of Brazilian colleagues.

MRIWA Project M446

4D evolution of WA ore systems (WA4D): Re-Os sulphide geochronology.

CIs: McNaughton, Tessalina, McInnes, Jourdan.

This proposal seeks to utilize the Re-Os isochron method on sulphides to determine precise ages for two classes of metal deposits in WA: i.e. volcanic-hosted massive sulphide (VHMS) Zn-Pb-Cu deposits and orogenic gold deposits. Each deposit type typically contains ore-related pyrite+/- arsenopyrite, which apart from rare molybdenite, are the two most reliable common sulphides for Re-Os geochronology. Re-Os isochron ages will be complemented by precise U-Pb and Ar-Ar ages on the selected deposits and their environs, including host rock, stratigraphic ages, alteration and metamorphic ages, to build a precise 4D framework of ore formation.

MRIWA Project M448

4D evolution of WA ore systems (WA4D): Rutile – pathfinders to ore.

CIs: McNaughton, Evans, McInnes, Jourdan.

This proposal is about the development of rutile protocols for metals exploration in WA, and directly supports "Searching the deep earth: the future of Australian resource discovery and utilization" proposed by the Australian Academy of Sciences: i.e. the initiative on "Resolving the 4D geodynamic and metallogenic evolution of Australia". The proposal focusses on (1) establishing new trace element fingerprints carried by rutile grains to identify their environment of formation (i.e. ore-associated vs barren), and (2) the age of rutile formation, given that published and unpublished age data for known hydrothermal ore formation in WA tends to be synchronous within a terrain. The proposal seeks to build a database of these two independent indicators of mineralization in WA (i.e. chemical fingerprint and age), to provide a foundation for metals exploration using rutile grains encountered in rocks/drillcore, or as detrital grains in heavy mineral concentrates from field sampling.

MRIWA Project M467

Mineralogical and lithological controls on REE distribution in the Argyle diamond deposit.

CIs: O'Connor (WASM), McNaughton, Aldrich (WASM), Evans.

Mantle-derived alkaline and silica-undersaturated rocks such as kimberlites, lamproites and carbonatites naturally contain high REE-contents, compared to most other common rock types. However, with a few exceptions, very little is known about the REE-minerals in such rocks in WA. A PhD project has been established to characterise the REE minerals of the Argyle lamproite, AK1, which is currently mined for diamonds. The project is supported by the mine operators, Rio Tinto, and seeks to:

1) Identify REE-enriched zones within different areas of AK1, and determine REE concentration mechanisms, whether primary igneous or secondary alteration/weathering;

2) Identify REE-bearing minerals and the concentrations of the REEs in those minerals; and

3) Provide a case study for the potential development of REE resources in WA in similar rock types.

Petrochina

Multiple isotope system to dating hydrocarbon and source-rock correlation in Sichuan Basin.

CI: S. Tessalina.

Geoscience Australia

Sm-Nd isotope analysis of granites from Yilgarn craton.

CI: S. Tessalina.

Geochronology for the Greenland Ministry of Mineral Resources

CIs: C.L. Kirkland, N.J. Gardiner.

The aims of this one-year research proposal are to develop the structure of, and populate a geochronology database holding U-Pb information on Greenland. Additionally, new U-Pb geochronology will be acquired for a set of new Greenlandic samples. Subject to funding, it is envisaged that this project will be ongoing.

Crustal Evolution Research for the Geological Survey of Western Australia

CIs: C.L. Kirkland, N.J. Gardiner.

The aims of this three-year research proposal are to further develop GSWA's capacity in isotope geology and fully utilize isotopic datasets already collected and currently being collected by GSWA. To this end innovative analysis mechanisms will be applied to isotopic datasets and the results presented via client accessible spatially interpolated images and reports (including but not limited to, time evolving isotopic maps).

Sediment in the Great Australian Bight: Basement information recovered through detrital minerals and implications for the evolution of Australia's southern margin

CIs: C.L. Kirkland, M. Barham.

The exposed mineralised Gawler and Yilgarn cratons are separated by nearly one thousand kilometres of basement that represents a large prospective mineral province, but this region is buried by sedimentary basins formed during the development of Australia's southern margin. In this project new geochronology will be performed on legacy drill core material from the offshore Eucla basin to understand its provenance.

Iluka Research

Refractory mineral cargo of HMS deposits: modern analogues for fingerprinting, targeting and resolving depositional dynamics along palaeoshorelines.

CIs: M.Barham, C.L. Kirkland and M. O'Leary.

ARC Future Fellowship project FT140100826

Xuan-Ce Wang.

The main goal of this project is to test a provocative and potentially ground-breaking hypothesis that links fluid cycling, large-scale intra-continental magmatism, volcanic volatile flux, climate changes, mantle chemical geodynamics, plate tectonics, and slab stagnation in a self-consistent geodynamic system. This research will integrate geochemistry, petrology, geophysics, global tectonics, and thermodynamical modelling to reach a new level of understanding of the fluid cycling and Earth's dynamics through time. The outcomes will fill the knowledge gap of how fluids work in the Earth's system, and will help us to understand how deep-Earth's geodynamic processes influence paleoclimate changes. This work will also help us to identify ways to improve future mineral exploration success.

ARC LINKAGE Project (Woodside) Chronostratigraphic, molecular and isotopic approaches to age petroleum

CIs: Grice, Coolen and Murray.

The project aims to reduce the costs of drilling in deep-water offshore by better identifying potential drilling sites. The North-West shelf offshore Australia is the main supplier of liquefied natural gas. However, there is uncertainty about the age of petroleum (oil and gas) discovered in the region. It is not currently possible to constrain an age of fluids to a number of source rocks. The aims are to develop a high-level age discriminative tool for fluids. An interdisciplinary approach will be applied using state-of-the-art techniques including comprehensive two dimensional gas chromatography time-of-flight mass spectrometry, compound specific isotope analysis of hydrocarbons, clumped isotopes of methane and metagenomics.

ARC Discovery Project

The Pace and rhythm of climate: 600,000 years in a biological hot-spot.

CIs: Stevenson, Coolen.

This project aims to generate knowledge of long-term changes in vegetation and rainfall for the Indo-Pacific Warm Pool (IPWP). The IPWP exerts enormous influence on the Earth's climate through its interactions with the El Niño-Southern Oscillation, the Austral–Asian monsoons and the Inter-tropical Convergence Zone. Yet despite its importance, the response of the IPWP to global climate change remains uncertain. Through palynology, ancient sedimentary DNA and compound specific stable isotope analyses, this project aims to produce a terrestrial vegetation, fire and biodiversity record for the last 600 000 years in Sulawesi. The unrivalled length and resolution of this record for the region would make it a benchmark reconstruction of palaeoclimate that may transform our understanding of the IPWP.

Petrobras - International partner

Geochemical assessment of oil and rock-extract samples of the Brazilian basins based on saturate and aromatic biomarkers and isotope analysis.

CI: Grice.

ARC LIEFP

High resolution mass spectrometer for metabolics and proteinomics.

CIs: Millar, Clode et al., Grice.

IODP and ANZIC (2016-2017)

The establishment of ocean anoxia and ocean acidification during the PETM: Understanding the biological and chemical response on a regional and global scale (Expedition 342).

CIs: Johnson and Grice.

IODP and ANZIC (2016-2018)

IODP Expedition 364 entitled "The Chicxulub post-impact crater record: duration of a giant hydrothermal system and window into the resurgence and evolution of marine and terrestrial life".

CIs: Coolen and Grice.

ARC Discovery ANU led (2016-2019)

This project aims to generate knowledge of long-term changes in vegetation and rainfall for the Indo-Pacific Warm Pool (IPWP).

CIs: Stevenson, Coolen, Russell.

ARC LIEFP

High resolution mass spectrometer for metabolics and proteinomics.

CIs: Skrzypek, Grierson, Edwards, McCulloch, Grice.

ARC LIEFP (ODP)

Metatransciptomics, lipid biomarker and stable isotope geochemistry of microbial community structure of the Northern Carnarvon Basin.

CIs: Grice and Coolen.

ARC LINKAGE (2014)

Austin, Prof Andrew D; Cooper, Prof Steven J; Humphreys, Adj/Prof William F; Blyth, Dr Alison; Mitchell, Prof James G; Munguia, Dr Pablo; Harvey, Prof Mark S; Byrne, Dr Margaret; Halse, Dr Stuart A; Humphreys, Mr Garth.

ARC Discovery-DORA-3 ($710K) - (2012-2017)

Tackling the resurgences of life, advanced dating tools of oils by sophisticated molecular and isotopic analyses from major geological event.

CIs: Grice, Summons.

ARC Discovery Project

Sulfur cycling in modern microbialites, toxic oozes and petroleum.

CIs: Grice, Visscher, Sessions, Schwark.

Compound specific sulfur isotope analyses will be applied to sulfur-rich deposits from extreme environments: sulfidic black oozes (Peel-Harvey estuary); modern microbialites (for example, Shark Bay) and oils/source (established and frontier oil fields). Sulfur isotopic data, integrated with other stable isotopic and molecular data, will greatly assist our studies of sulfur biogeochemical cycles and mechanisms of organic sulfurisation at different diagenetic stages or geological ages. The research will address national concerns; a measure of the respective impact of anthropogenic and natural changes on environments; help understand the evolution of life on Earth; and contribute to efficient discovery of our natural petroleum systems.

ARC Discovery Outstanding Research Award-3 Fellowship

CIs: Grice, Summons.

Tackling the resurgences of life, advanced dating tools of oils by sophisticated molecular and isotopic analyses from major geological events.

The long-term impacts (over millions of years) of present global warming are poorly understood. However, recovery mechanisms evident in past related mass extinctions are invaluable in helping to understand the pace of recovery of marine and terrestrial ecosystems. Grice's world-leading expertise in biomarkers and stable isotopes will be applied to paleoclimate change, evolution and energy. Cutting-edge petroleum exploration technologies especially dating oil without having to drill it's source is important in addressing the global energy crisis. Strongly interrelated themes also support Grice's enthusiasm for training young scientists meeting Australia's Earth science research and industry needs.

CSIRO/ Minerals Collaboration Cluster Fund

Organic-Inorganic interactions

CIs: Grice, Evans, Rasmussen, Gale, McCulloch, Greenwood, McCuaig, Brocks, Moreau.

The Organic Geochemistry of Mineral Systems (OGMS) Cluster was a $6 million multi-institutional research initiative supported by the CSIRO National Flagships program which focused on understanding the role played by organic components and processes in the formation of major mineral deposits. The project was led by Curtin University, and involved the collaboration of researchers from the University of Western Australia, the University of Melbourne and the Australian National University. The academic group was collaboratively complemented by a large cohort of CSIRO researchers from the Minerals Downunder Flagship, and the unique expertise of several key international scientists.

ARC LINKAGE Project

Subterranean invertebrate communities of arid zone Western Australia: diversity, assessment and food-web structure.

CIs: Austin, Cooper, Humphreys, William; Blyth; Mitchell; Munguia, Harvey, Byrne, Halse, Humphreys, Garth.

This project uses a powerful combination of genetic data and isotopic analyses to elucidate the biodiversity and foodweb structure of unique subterranean fauna in WA, providing crucial information for the monitoring and management of groundwater in the area

Awarded $340K

AINSE/ANSTO fellowship

Molecular, stable isotopic and radiocarbon analyses of organic matter preserved in terrestrial records.

CI: Blyth.

ARC Discovery Project DP160100677

Uncovering molecular pathways to minerals for control of crystallization.

Prof J.D. Gale, Dr R. Demichelis, Dr D. Gebauer, Adj. Prof. C. Putnis.

ATN-DAAD Joint Research Co-operation scheme

Unlocking the secrets of mineral reactivity in acidic and basic environments through computer simulation.

Dr P. Raiteri, Dr. D. Donadio, Dr. R. Demichelis.

CSIRO, OCE Postdoctoral Fellowship Scheme

Metal speciation in Earth's golden plumes: quantum chemical simulations of ore-forming processes under extreme conditions.

Dr W. Liu, Prof. J.D. Gale, Prof. J. Brugger, Dr R. Hough.

ARC Discovery Project DP140101776

Imaging defects at atomic resolution via state-of-the-art atomic force microscopy and petascale simulations.

A.L. Rohl, J.D. Gale, P. Raiteri, T. Becker, A. Shluger, M. Watkins, F. Mugele.

ARC Future Fellowship FT130100463

P.Raiteri.

Science of the Future for the Russian Federation

Federal Agency, Scientfic Organisations and Public Research Centres, AU$1.5M grant, 2016-2019.

CI: V.M Calo.

Enterprise Future Science Platforms

Research Office, CSIRO, Australia, AU$15.5M grant, 2016-2019.

CI: V.M. Calo.

Marie Curie RISE GEAGAM European Program

Horizon 2020 Funding, European Research Commission,,2015-2017.

CI: V.M.Calo.

National Priorities Research Program, Qatar National Research Fund

$865,908 grant, 2014-2016.

CI: V.M.Calo.

DAAD (German Academic Exchange Service)

Joint Research Cooperation Scheme.

Gravity field validation in Australia using a German digital astronomical camera.

CIs: C. Hirt, M. Hauk, P. Schack (TU Munich), W.E. Featherstone, T.J. Lyon, A.L. Parker (Curtin).

ARC Discovery Project DP160104095

Lunar crustal structure from high-res gravity, topography, and seismic data.

CIs: S-C. Han (Newcastle University), W.E. Featherstone (Curtin), N. Schmerr (University of Maryland).

The Moon preserves the longest and cleanest records of surface geology in the Solar System's history, unlike the Earth. The lunar crust should exhibit strong heterogeneity in density (both porosity and composition) given its complex history of impact bombardment and volcanism. This project aims to determine radial and lateral heterogeneity in density and porosity within the Moon's crust, by analysing Gravity Recovery And Interior Laboratory gravity and spacecraft tracking data, Lunar Orbiter Laser Altimeter topography and in situ Apollo seismological data. This integrated analysis is anticipated to improve our knowledge on surface processes, interior structure, modification by geological processes and the creation/evolution of the Moon.

ARC Linkage Grant LP110100155

Geodetic and hydrogeological investigations of groundwater abstraction from confined aquifers: elastic response, heights, and sea level change.

CIs: W.E. Featherstone (Curtin), N.T. Penna (Newcastle University, UK), L.M. Morgan, B. McAtee, (Landgate), J-P. Pigois (WA Department of Water).

Parts of Perth are subsiding by as much as 5 mm/yr, thus accelerating sea level rise relative to the land from 3 mm/yr to 8 mm/yr. The subsidence is most likely due to increased groundwater abstraction. We plan to extend subsidence mapping in time and space using satellite-borne synthetic aperture radar, calibrated by complementary geodetic techniques, and coupled with new hydrogeological inputs from the WA Department of Water. We intend to provide science-based information to planners and managers on coastal vulnerability and determine the land response to groundwater abstraction. This will also allow for the correction of sea level change measurements from tide gauges.

CRC for Spatial Information Project 1.24

Development of AUSGeoid2020, the first in the world with uncertainty estimates as a function of location.

CIs: N.J. Brown (Geoscience Australia), W.E. Featherstone, S.J. Claessens (Curtin).

AUSGeoid provides the offset between the ellipsoid (realised by GNSS) and the Australian Height Datum (AHD), the national vertical datum. A major weakness with all previous national geoid models is that the uncertainty budget is poorly defined, and with little or no geographic specificity. The next version of AUSGeoid aims to include a rigorous uncertainty value associated with the offset between the ellipsoid and AHD, varying as function of location. The new AUSGeoid will also be augmented with a sea surface model offshore and include ellipsoid to local datum offsets on offshore islands (where data permits). This will be one of the tools required to implement the next generation geodetic datum that will underpin the National Positioning Infrastructure (NPI) in 3D.

Ongoing funded research project with the awarding body

Climate change impacts on the Brazilian water resources.

Funded by Brazilian Ministry of Education (CAPES: Grant no. 88881.068057/2014-01-Brazilian Science Without Borders Program/CAPES)).

CI: J.L. Awange.

Belmont Forum and G8 Research Councils Initiative on Multilateral Research Funding – International Opportunities Funds

Bangladesh Delta: Assessment of Causes of Sea-level Rise Hazards and Integrated Development of Predictive Modelling Towards Mitigation and Adaptation (BanD-AID).

PI: M.Kuhn.

BanD-AID is a collaborative research project that brings together an international, cross-disciplinary team of researchers to assess and mitigate hazards including sea level-rise in the Bangladesh Delta. The project, headed by Prof Shum of the Ohio State University, includes Investigators from seven institutions, including Curtin University, in five countries (USA, Germany, France, Australia and Bangladesh). Through a combination of local stake holders and international experts the project leverages upon ongoing regional and international environmental and social projects. Within the project, experts from natural and social sciences collaborate to build an Earth System Analysis and Prediction System for Bangladesh. This will be based on contemporary space geodetic sensors to quantify geodynamic changes and socio-economic tools to model human interactions that govern coastal vulnerability in Bangladesh.

ARC Discovery Project

Desert fireball network.

CI: Phil Bland, for the continuation and running of the desert fireball network in the Australian outback, to recover and exploit fresh meteorite falls with orbital context.

ARC 2016 LIEF

Global fireball camera network.

CI: Phil Bland, to construct a global Fireball Camera network, allowing researchers to track fireballs and observe the whole sky, 24 hours a day, from countries all around the globe. This will be a high profile, multinational program led by Curtin.

ARC Discovery Project

Decoding the Chronology of Mars.

CI: Gretchen Benedix, to produce new global maps of mars geology, using machine learning to date surfaces.

CO_2-CRC Otway Project Stage 2C

CIs: B Gurevich, R Pevzner, M Urosevic, A Bona, A Kepic, M. Lebedev, S Glubokovskikh, K Tertyshnikov, S Ziramov, et al.

CO_2-CRC Otway Project Stage 3 – Evaluate Phase

CIs: B Gurevich, R Pevzner, S. Glubokovskikh.

Petrobras

Development and Construction of Broad-Band Experimental Rigs for Measurements of Seismic Dispersion and Attenuation in Reservoir Rocks.

CIs: M. Lebedev, B. Gurevich.

Anlec R&D

The Lesueur, SWH: Improving seismic response and attributes.

CI: Boris Gurevich et al.

Esso (Australia)

Processing and analysis of 4C seismic data for Hinterland PNG.

CIs: Boris Gurevich and Aleksander Dzunic.

TIGeR PUBLICATION LIST

Books and book chapters

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Evans D.A.D., Li Z.-X., Murphy J.B.: Four-dimensional context of Earth's supercontinents. In: Li, Z. X., Evans, D. A. D. & Murphy, J. B. (eds.), Supercontinent Cycles Through Earth History. *Geological Society, London, Special Publications*, 424, 1–14, 2016.

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Herick Othieno and Awange J. L., (2016) Energy Resources in Africa. Distribution, opportunities and challenges. Springer, Berlin. ISBN 978-3-319-25185-1.

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