

**THERMOCHRONOLOGY AND NOBLE GAS GEOCHEMISTRY
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ABSTRACT VOLUME



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DETRITAL ZIRCON U-Pb GEOCHRONOLOGY OF CAPRICORN INTRAOROGENIC BASINS, NEW AGE CONSTRAINTS AND PROVENANCE

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The Capricorn region experienced a number of deformational and depositional events between 2215 Ma and 955 Ma in response to the relative movements of the bounding Yilgarn and Pilbara Cratons. The Mesoproterozoic 1620-1456 Ma Edmund Basin comprises a sequence of sedimentary rocks formed in the later stages of the evolution of the Capricorn Orogen. Its sediments include the stratabound Pb–Zn–Fe–Ba–Cu Abra deposit. The c. 2.1 Ga Yerrida rift-basin, on the north margin of the Yilgarn Craton, was deformed during the c. 2.0-1.9 Glenburgh Orogeny.

U-Pb ages of the detrital phases, measured by LASS-ICPMS, constrain the maximum and minimum depositional ages of the sedimentary packages, and vertical fluctuation on the sediment source. The detrital minerals ages, coupled with trace element compositions, are used to identify sediment source region and place temporal constraints on basement erosion. These results yield valuable information on near-surface tectonic evolution of the Capricorn region, which complements information from deeper, higher-temperature systems.

TRACE ELEMENT DIFFUSION IN ACCESSORY MINERALS DURING PROTRACTED UHT METAMORPHISM: IMPLICATIONS FOR GEOCHRONOMETERS

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Traditional geochronometers (e.g. zircon) whilst very resistant to most geological processes are effected by long timescales at high temperatures; with the perturbation of U–Pb and trace element systems being increasingly identified within high-grade terranes. The geological history of the Rogaland–Vest Agder Sector (RVA) in SW Norway is well constrained, making this region an ideal case study. U–Pb geochronology (SHRIMP) and REE compositions (LA-ICP-MS) of zircon and garnet were analysed. A comparison between the data recorded in this study and previous experimental work (zircon) was also conducted. At ~900°C modification of REE and Pb is inefficient but with appropriate timescales small zircons (20–50 µm) may be perturbed. At higher temperatures, 1–5 Myr may be sufficient to perturb larger grain sizes. During UHT conditions the length-scale and temperature of metamorphism combined with the

grain size of the geochronometer is very important when interpreting geochronological and trace element data.

PHYSICOCHEMICAL PROCESSES IN THE MAGMA CHAMBER UNDER THE BLACK MOUNTAIN PORPHYRY CU-AU DEPOSIT (PHILIPPINES): INSIGHTS FROM MINERAL CHEMISTRY

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In situ elemental analyses were conducted on magmatic minerals to constrain processes of magma chamber underlying the Black Mountain porphyry Cu-Au deposit, Philippines. All rocks contain widespread disequilibrium textures. High and consistent crystallization temperature and pressure in felsic (~880°C; ~2.8 kbar) and mafic (~1030°C; ~7.7 kbar), reflect phenocryst crystallization in magma chamber, and a long-lived, hot felsic magma chamber. All plagioclase profiles display oscillatory variations of An, Fe and Sr with large Δ An variations (>20 mole%) and positive correlation between An and FeO. Amphibole chemistry shows two distinct types and transitional compositions in disequilibrated grains. These evidences indicate repeated mafic magma recharge in felsic magma chamber. Widespread rounded or elongated sulfide inclusions in megacrystic amphibole from mafic rocks, indicate the enrichment of metals. Therefore, large-scale mafic magma recharge probably introduced metals to the long-lived felsic magma chamber, contributing to the fertility of felsic rocks, and ultimately, to Cu-Au mineralization.

TOWARDS DATING SHOCK-TWIN FORMATION IN ZIRCON

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Deformation twinning in shocked zircon is now recognized as a diagnostic indicator that can confirm a meteorite impact event. The {112} twin microstructure in zircon has been reported from seven impact environments. However, analysis of shock-twinned zircon domains for U-Pb age by SIMS using a ~25 μ m diameter spot size has demonstrated that determination of impact age is not achievable at this scale. Here we describe an approach to dating shock-

twinning in zircon at the atom scale using U-Pb geochronology. We selected a 3.0 Gyr zircon from the Vredefort impact structure (South Africa) that was shocked at 2.0 Ga. The grain contains both {112} shock-twins and neoblastic domains, providing evidence for shock deformation and post-shock heating. Twin-host boundaries and neoblast-host boundaries were targeted for atom probe analysis (Curtin University), and transmission electron microscopy (Arizona State University), with the goal of determining if Pb mobility caused by the 2.0 Ga impact is preserved. Results to date will be discussed.

CAMECA IMS 1300-HR3 KLEORA: THE NEW GENERATION ION MICROPROBE FOR GEOCHRONOLOGY APPLICATIONS

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CAMECA's large geometry magnetic sector SIMS (or ion microprobe) has been extensively used for a wide range of geochronology applications, from precise age determination of zircon to dating of other U-rich minerals. Thanks to proven instrumental advantages and dedicated geochronology data reduction software, the CAMECA ion microprobe provides benchmark sensitivity for in-situ isotopic analysis at high spatial resolution.

The IMS 1300-HR³ (High Reproducibility, High spatial Resolution, High mass Resolution) is the latest generation of CAMECA's ion microprobe, successor to the internationally recognized IMS 1280-HR. The 1300-HR³ delivers unmatched analytical performance for a wide range of applications in Geosciences due to a series of innovative instrumental developments.

In order to meet a growing demand from geochronologists, CAMECA also introduces the KLEORA, which is a fully optimized ion microprobe for advanced mineral dating derived from the IMS 1300-HR³.

Instrumental developments and data obtained for geochronology applications will be presented in detail.

NEW APPLICATIONS OF RESOCHRON IN-SITU HELIUM ANALYSIS

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Although the RESOchron instrumentation suite is primarily used to obtain in-situ (U-Th-Sm)/He and U-Pb ages on zircon and apatite crystals, in-situ Helium analysis offers some other

exciting applications. These include qualitative and quantitative imaging of Helium distribution in minerals, the development of new dating methods for platinum group minerals based on ^{190}Pt - ^4He decay scheme, and more comprehensive reconstructions of cooling trajectories in dated minerals based on inversion of directly measured Helium diffusional profiles and the integration of U-Pb data. In our talk we will present the status of the development of these applications pursued in Auscope AGOS GeoHistory Facility of John de Laeter Centre.

DATING DEFORMATION EVENTS USING MONAZITE

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In situ U-Th-Pb analyses targeting specific monazite microstructures identified by EBSD provides a new method for dating a variety of deformation events. EBSD analysis of tectonically strained monazite from the Sandamata Complex, India, identified a variety of microstructures in monazite. Monazite contain deformation twins in {100}, {001} and {122}, low-angle boundaries formed by subgrain rotation, and neoblasts that nucleated in high strain domains and grew via grain-boundary migration. Shocked monazite grains from the Araguainha (Brazil) and Vredefort Dome (South Africa) impact structures contain low-angle boundaries, planar deformation bands, microtwins and neoblasts. Shock twins were found in the orientations reported in tectonically deformed monazite and in 8 orientations that have not been previously described. SHRIMP U-Th-Pb analysis of deformed monazite from both tectonically-deformed and shock-deformed monazite found partial Pb-loss associated with crystal-plastic microstructures, and complete age resetting in the neoblast domains, highlighting the capacity of deformed monazite to date deformation events.

APATITE THERMOCHRONOLOGY OF THE BOLE-NANGODI SHEAR ZONE (NORTHERN GHANA): INSIGHTS INTO THE THERMAL HISTORY OF EQUATORIAL ATLANTIC RIFTING

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The Bole-Nangodi (BN) shear zone in northern Ghana is thought to represent the continental extension of an equatorial Atlantic transform fault. This study applies low temperature thermochronology to constrain the thermal history of the BN shear zone with relation to Gondwana break-up during the Mesozoic. Apatite Fission track data obtained across the primary NE-SW structural trend of the BN shear zone suggests a complex two phase cooling history of: (1) heating in the late Triassic – early Jurassic, related with the emplacement of the Central Atlantic Magmatic Province (CAMP), and (2) cooling associated with rift shoulder exhumation during Cretaceous rifting. The thermal history is differentially exposed with respect to the BN shear zone, preserving older (CAMP) signatures to the south and younger (rifting) signatures to the north, respectively. This indicates that the BN shear zone has been reactivated during Cretaceous rifting and associated strain build-up in the Equatorial Atlantic.

IN SITU SHRIMP GEOCHRONOLOGY OF MONAZITE AND XENOTIME TO DATE OROGENIC GOLD MINERALIZATION

Fielding, I.O.H.¹, Johnson, S.P.², Zi, J.-W.¹, Rasmussen, B.¹, Muhling, J.R.^{1,3}, Dunkley, D.J.¹, Sheppard, S.¹, Wingate, M.T.D.¹

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In situ sensitive High-Resolution Ion Microprobe (SHRIMP) U–Th–Pb analysis of monazite and xenotime is effective at dating orogenic gold mineralization and hydrothermal events. Both minerals yield precise ages, are resistant to isotopic resetting, and form during a variety of hydrothermal and mineralizing events.

The Paulsen mine is an orogenic gold deposit located in the Wyloo Inlier on the southern margin of the Pilbara Craton. Mineralized quartz–sulfide veins are hosted within a deformed gabbro dyke dated at ~2.7 Ga. Monazite and xenotime in the veins and hydrothermally altered country rocks identify three hydrothermal events. Textural relationships between the dated phosphate minerals and the auriferous veins show that gold mineralization occurred at ~2.4 Ga, coeval with pervasive alteration of the host rocks. Regional-scale hydrothermal events at ~1.73 Ga and ~1.68 Ga are linked to the replacement of metamorphic porphyroblasts in phyllitic rocks, and to carbonate veining and gold remobilization.

ULTRA-HIGH-VACUUM (UHV) ARGON DIFFUSION EXPERIMENTS

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Ultra-high-vacuum experiments are able to record diffusion parameters that mimic those in nature. These experiments are relatively easy to perform. The volume of ³⁹Ar released during a heating experiment is measured. Percentage release data are reduced using diffusion equations for specific geometries. Improved theoretical understanding allow estimates of activation energy and frequency factor to be obtained from Arrhenius data. Fundamental questions remain as to the behaviour of the mineral grains during such UHV heating experiments: 1) Can minerals remain in a metastable state with the lattice relatively intact during the step-heating experiment? 2) Can the data obtained in such experiments be related back to the behaviour of the mineral in the natural environment? The design of a step-heating experiment must take into account the need to populate the Arrhenius plot across a range of temperature values. This has the benefit of revealing sub-spectra, e.g., muscovite sub-spectra emerge from experiments with phengitic white mica.

IMAGING COMMON Pb IN MONAZITE BY ATOM PROBE MICROSCOPY

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Phosphate accessory minerals are widely used in geochronology and metamorphic petrology studies. The use of monazite (LREEPO₄) as a geochronometer relies on its ability to incorporate reasonable quantities of Th and U but negligible amounts of Pb (common Pb or Pb⁰) during crystallisation.

Using atom probe microscopy, we have investigated the distribution of major and trace elements at the sub-nanometre scale in a monazite grain from the granulite facies rocks of the Sandmata metamorphic complex, Rajasthan, India. Our results show the occurrence of distinct 10 nm clusters that are enriched in Ca, Si and Pb, which we interpret to be nano-inclusions of apatite. Pb isotopic measurements from these apatite clusters show a distinct Pb isotopic composition from the host monazite and is indicative of an ancient common lead component. The results have implications for the geochronology of monazite, particularly methods that assume that monazite contains no common Pb component.

THE Hf ISOTOPE PARADOX APPLIED TO CRUSTAL EVOLUTION OF THE EARLY EARTH

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Zircon Lu-Hf isotopes are a major tool for studying crustal growth and differentiation, in particular in the early Earth. Interpretations of Hf arrays use an isotopic evolution line representing magmatic reworking of pre-existing crust, defined by a $^{176}\text{Lu}/^{177}\text{Hf}$ ratio. The paradox of such an approach is that the very process defined by this evolution line is precisely that which may modify its isotopic trajectory due to variable degrees of anataxis and the differing compatibilities of Lu and Hf. We address this paradox through equilibrium modelling of Archaean rocks allied to a case study from the Pilbara Craton. The Hf isotopic evolution trajectory is highly sensitive to the degree of melting and the abundance of garnet in the melt residuum, resulting in a variance in evolutionary slope resolving to a difference of up to seven epsilon units per billion years. Such petrological control on Lu/Hf ratios has profound implications for the interpretation of Hf isotopic datasets since crustal reworking driven through partial melting cannot lie on an isotopic evolution line defined by fixed $^{176}\text{Lu}/^{177}\text{Hf}$ ratio.

LOW-TEMPERATURE THERMAL HISTORY OF THE YENISEY RIDGE AND LINKS TO MINERAL PROSPECTIVITY

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The Capricorn region experienced a number of deformational and depositional events between 2215 Ma and 955 Ma in response to the relative movements of the bounding Yilgarn and Pilbara Cratons. The Mesoproterozoic 1620-1456 Ma Edmund Basin comprises a sequence of sedimentary rocks formed in the later stages of the evolution of the Capricorn Orogen. Its sediments include the stratabound Pb–Zn–Fe–Ba–Cu Abra deposit. The c. 2.1 Ga Yerrida rift-

basin, on the north margin of the Yilgarn Craton, was deformed during the c. 2.0-1.9 Glenburgh Orogeny.

U-Pb ages of the detrital phases, measured by LASS-ICPMS, constrain the maximum and minimum depositional ages of the sedimentary packages, and vertical fluctuation on the sediment source. The detrital minerals ages, coupled with trace element compositions, are used to identify sediment source region and place temporal constraints on basement erosion. These results yield valuable information on near-surface tectonic evolution of the Capricorn region, which complements information from deeper, higher-temperature systems.

THE CHALLENGE OF AUTOMATING FISSION TRACK LENGTH MEASUREMENTS IN APATITE FOR LOW-TEMPERATURE THERMOCHRONOLOGY

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Fission track length data are a unique attribute of the fission track method, and are of crucial importance in modelling the thermal histories of rocks. Such length measurements are usually made on horizontal confined fission tracks, which give the best representation of the true underlying length distribution. However these are inherently rare features and many samples contain too few for adequate thermal history modelling. Other problems include very poor reproducibility between different observers in inter-laboratory comparisons, and currently insurmountable problems in the automated location of suitable confined tracks for measurement. We have now developed a variety of software and image analysis tools to assist in the measurement of track lengths and improving the quality and consistency of the results. These include manual 3D measurement tools to increase sample size, and a promising new approach to fully automated length measurement based on so-called ‘semi-tracks’ – the same surface-intersecting tracks used for counting.

DOES URANIUM INFLUENCE FISSION TRACK ANNEALING IN APATITE? EXAMPLES FROM VARIOUS STUDIES

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Hendriks and Redfield (2005) suggested that elevated concentrations of U in apatite influence fission track annealing. Their model of radiation-enhanced annealing was quickly contested by

the community and therefore mostly abandoned. The recent use of in-situ U concentration measurements into the apatite fission track age-equation, provides large quantities of precise U concentration estimates, spurring a re-evaluation of the influence of U on fission track annealing. AFT studies conducted on granitoids from northern Ghana, eastern Russia, northern Tajikistan and southern Australia, reveal typical open-jaw displays of single-grain AFT ages in radial plots. For those, higher U concentrations correlate with younger age estimates and vice versa, pointing towards the differential preservation of discrete thermal events. We compare our results with the more accepted use of Cl as discriminator (example from Russia) and present AFT length histograms associated with different AFT age populations (example from Ghana), suggesting that U indeed affects AFT annealing.

Hendriks, B.W.H., Redfield, T.F., 2005. Apatite fission track and (U-Th)/He data from Fennoscandia: An example of underestimation of fission track annealing in apatite. EPSL 236, 443-458.

AN APATITE U-Pb MAP FOR THE NORTHERN GAWLER CRATON: PRELIMINARY RESULTS

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Traditionally, the cooling history of rocks through ~550-300°C is constrained using ⁴⁰Ar/³⁹Ar analysis on micas and other minerals, which can be rather expensive and time-consuming if used on a regional scale. Recent advancements in the apatite U/Pb dating technique (Chew et al., 2011; 2014) allow for rapid and relatively cheap estimates of cooling ages in a similar temperature window. We present a map of new apatite U/Pb data collected for the northern Gawler Craton and compare the results with published ⁴⁰Ar/³⁹Ar data. The results compare well, displaying thermal events related with the Kimban (1730 – 1690 Ma), and Kararan (1570 – 1540 Ma) Orogenies as well as the Hiltaba event (1595 – 1575 Ma). The northernmost samples record apatite U/Pb ages that post-date the Kararan Orogeny and mimic Muscovite and Biotite ⁴⁰Ar/³⁹Ar data.

Chew, D.M., Petrus, J.A., Kamber, B.S., 2014. U–Pb LA–ICPMS dating using accessory mineral standards with variable common Pb. Chemical Geology 363, 185-199.

Chew, D.M., Sylvester, P.J., Tubrett, M.N., 2011. U–Pb and Th–Pb dating of apatite by LA–ICPMS. Chemical Geology 280, 200-216.

THERMOCHRONOLOGICAL HISTORY OF THE NORTHERN OLYMPIC DOMAIN

Hall, J.W.¹, Glorie, S.¹, Reid, A.², Collins, A.S.¹, Jourdan, F.³, Evans, N.J.^{3,4}

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Multi method thermochronology applied to shallow drill core samples from the northern Olympic Domain records multiple thermal events. Apatite U/Pb (450 – 550 °C) and Muscovite ⁴⁰Ar/³⁹Ar (350 – 400 °C) ages relate with the emplacement of the Donington Suite (~1850 Ma) and comagmatic Hiltaba Suite / Gawler Range Volcanics (~1590 Ma). K-feldspar ⁴⁰Ar/³⁹Ar (~150 – 300°C), Apatite fission track (60 – 120 °C), zircon (U-Th-Sm)/He (ZHe; 180 – 200 °C), and apatite (U-Th-Sm)/He (AHe; 45 – 75 °C) reveal regional low temperature thermal events during the late Stenian (~1050 Ma), Silurian-Devonian (~440-380 Ma), and Triassic-Jurassic (~240-170 Ma). Interestingly, the Precambrian low-temperature ages are only preserved away from the major mine sites, on either side of an apparent northwest-southeast younger corridor. Samples taken near Olympic Dam, Carrapateena and Emmie Bluff record the youngest AFT ages in the study area, suggesting a potential relation between these deposits and a localised Mesozoic thermal event.

NOBLE GAS MASS SPECTROMETRY – AN UPDATE

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In the last decade there has been a revolution in static vacuum mass spectrometry. The emergence of a variety of new instruments with advances in ion optics, electronic design and materials development have resulted in a range of high performance instruments that have enabled the scientific community to resolve a number of long standing analytical issues.

In my talk I will outline the status of these three systems, present some of the latest user data from the different platforms and give an insight into recent and possible future developments.

UNIQUE CHARACTERISTICS OF THE HELIX MC PLUS MASS SPECTROMETER AT ANU

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The Helix MC Plus noble gas mass spectrometer installed at ANU is equipped with three high mass resolution (>1,800) collectors. It provides the capability to measure isobaric interference free noble gas isotopes in multi-collector mode, particularly for Ne and Ar, and significantly improves the accuracy to determine isotopic ratios. We will review the current status of the mass spectrometer, and discuss research projects, utilising its unique characteristics.

A THERMOCHRONOLOGICAL TRANSECT THROUGH THE WESTERN TIEN SHAN (UZBEKISTAN AND TAJIKISTAN)

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A series of ~40 samples were collected in a north-south transect across the main structural architecture of the westernmost Tian Shan to elucidate its exhumation history. Results indicate preserved fast cooling events during the late Triassic – early Jurassic (~230-185 Ma) and mid Cretaceous (~125-100 Ma) in the western Tian Shan verges and Oligocene (~35-25 Ma) and late Miocene (~10 Ma) cooling along the Tian Shan – Pamir suture zone. The timing of these cooling events correlates with distal continental collisions, associated with the progressive closure of the Tethys Ocean, which drove the exhumation of the Tian Shan. The youngest events date the timing of more recent pulses of mountain building, associated with the growth of Tibet and ongoing India-Eurasia indentation.

SEAWATER CYCLED THROUGHOUT THE EARTH'S MANTLE IN PARTIALLY SERPENTINISED LITHOSPHERE

Kendrick, M.A.¹, Hemond, C., Rodemann, T., Kamenetsky, V.S., Danyushevsky, L., Jackson, M.G., Devey, C., Perfit, M.R.

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Recent isotopic data suggest that ~90% of the non-radiogenic xenon in the Earth's mantle originated by subduction of atmospheric gases. However, the mechanisms for deep subduction of gases dissolved in seawater, and the extent to which subducted water and halogens might also dominate their mantle budgets remain unclear. We report the concentrations of halogens and water in magmatic glasses from globally distributed mid-ocean ridges and oceanic islands. We find that mantle abundances of halogens and water are broadly correlated with trace element signatures characteristic of subducted ocean crust and sediments, and that the reservoirs most enriched in water and halogens are depleted in other fluid-mobile trace elements. Additionally, the most incompatible halogens (Cl, Br, I) have abundance ratios that are both uniform throughout the mantle and different from calculated primitive mantle values. These observations imply that Earth's mantle is highly processed and that most of its water and halogens were introduced by subduction of incompletely dehydrated lithosphere.

CUTTING-EDGE SIMS CAPABILITIES AT UWA'S ION PROBE FACILITY

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UWA's Centre for Microscopy, Characterisation and Analysis (CMCA) houses three state-of-the-art ion probes: CAMECA IMS1280 large-geometry SIMS, for the isotopic analysis of minerals, and two CAMECA NanoSIMS 50 instruments for high-resolution imaging mass spectrometry. The new NanoSIMS 50L is equipped with the Hyperion RF plasma source, producing a high-brightness O⁻ primary ion beam which can generate a sub-50nm spot with a beam current of several pA. In 2017, the IMS1280 will be upgraded with the Hyperion source, with target specifications of <2µm spot with a 3nA beam. This presentation will showcase some of the cutting-edge analytical capabilities available at UWA to support the Australian geoscience community.

NOT SO COMMON, COMMON Pb

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The U-Pb system is a powerful chronometer and when applied across a range of different minerals, with different closure temperatures, can be used to produce informative thermal histories. A key consideration in such U-Pb chronometers, especially those with lower closure temperatures (e.g. titanite & apatite) is common Pb. Common Pb is frequently addressed by assuming a contemporaneous composition from a Pb model or adopting the common Pb value inferred from a coeval low U phase. However, we show intriguing results that suggest significantly different common Pb compositions for Proterozoic apatite and titanite across one study area. Specifically, all apatite (magmatic) indicates ancient common Pb incorporation during crystal growth. In stark contrast, all titanite (metamorphic) yields modern day values. Such differences suggest significantly different crystallographic sites hosting common Pb within these phases. Titanite appears to have the ability to permit recent common Pb exchange with ancient common Pb, whereas apatite appears to lock in its primary common Pb cargo within the crystal structure. These observations are of fundamental importance for the common Pb correction strategy applied and the resulting thermal model.

LOW TEMPERATURE THERMOCHRONOLOGY OF FRANCOLITE: INSIGHTS INTO TIMING OF DEAD SEA TRANSFORM MOVEMENT

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The Dead Sea transform (DST), separating the Sinai and Arabian plates, records sinistral displacement of ~105 km. Movement occurred during two phases; early Miocene and latest Miocene-Pliocene. In Cambrian strata on the western DST margin, apatite occurs as detrital grains [D-apatite] and as hexagonal plates of authigenic francolite (carbonate-fluorapatite) [A-apatite]. D-apatites yield fission track (FT) data reflecting Paleozoic-Mesozoic sedimentary cycles related to epeirogenic movements and a range of (U-Th)/He (AHe) ages. A-apatites yield mid-Miocene FT ages and AHe Pliocene ages. A-apatites first formed during early DST movement due to fracturing and hydrothermal alteration leading to partial or total dissolution of D-apatites and re-precipitation. Helium diffusion measurements on A-apatite are consistent with thermally activated volume diffusion and indicate a closure temperature of ~56°C (cooling rate 10°C/Myr). A-apatite AHe data suggest Pliocene cooling of ~35-40°C during the second phase of DST movement resulting from unroofing following initiation of the Dead Sea graben.

INDIA-ASIA CONVERGENCE: INSIGHTS FROM BURIAL AND EXHUMATION OF THE XIGAZE FOREARC BASIN (SOUTH TIBET), SOUTHERN ASIA MARGIN

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The composite forearc-foreland Xigaze basin in south Tibet preserves a key record of India-Asia collision. New zircon (U-Th)/He and apatite fission track data from a N-S transect across the preserved fore-arc basin sequence near Xigaze show a consistent northward younging trend between the Late Cretaceous to Middle Miocene, while coexisting apatite (U-Th-Sm)/He ages are all Miocene. Thermal history modelling indicates that the basin experienced northward propagating episodic exhumation, along with a northward migration of the depocenter and had pre-existed Cenozoic foreland sequences which had been removed. Importantly, these cooling/exhumation episodes of the Xigaze basin are associated with independently constrained changes in India-Asia convergence rates, which probably relate to the activity of corresponding large plumes and various subduction patterns (high angle – break off and flat of Indian and Neo-Tethyan slabs). These temporal and spatial relationships indicate that surface processes within the orogenic belt well are strongly coupled with dynamic activity of the deep crust.

INVESTIGATIONS INTO THE HIGHEST REPORTED HE CONCENTRATIONS IN NATURAL GAS SAMPLES: MT KITTY, AMADEUS BASIN, NORTHERN TERRITORY

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In 2014, Central Petroleum Ltd announced a natural gas discovery of unique composition (61% N₂, 13% CH₄, 4% C₂H₆, 11% H₂ and 9% He) from the Mount Kitty #1 well in the southern Amadeus Basin in the Northern Territory. The mineralogical analysis of the well cuttings, combined with isotopic analysis of the gas, provides insights into the origin of the high helium concentrations (~9% He), which is amongst the highest yet reported on Earth. The lithology of the cuttings shows a downhole transition from evaporitic mudstone to granite gneiss, suggesting that the well penetrated a gas reservoir consisting of granitoid basement rocks. U- and Th-bearing minerals (apatite, allanite, thorite, titanite and zircon) are present in trace amounts in all basement fragments, and the low ³He/⁴He ratio of 0.031 ± 0.001 RA indicates that almost all of the helium in the sample is the product of long-term release of radiogenic ⁴He from these minerals over geological time. The high He concentrations in the basement reservoir presumably indicate that the evaporitic mudstones have produced a highly efficient stratigraphic seal. The low CO₂/³He ratio of 4.46 x 10⁷ is two orders of magnitude lower than He-bearing gases from other sedimentary basins, indicating that the precipitation of carbonate

minerals is likely buffering the CO₂ content of the gases. The peculiarly high H₂ content has only been reported in gases collected from boreholes in the Canadian Shield, and may be linked to the abiogenic breakdown of hydrocarbons in a fractured granite reservoir.

MINIMISING U-Pb FRACTIONATION EFFECTS FOR LA-ICPMS ZIRCON GEOCHRONOLOGY

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Numerous studies have demonstrated that the differences between LA-ICPMS and TIMS U-Pb geochronology on zircons arise from the way the lasers interact with zircons crystals with variable extents of radiation damage. In this study, we explore other analytical effects that may affect the accuracy and precision of LA-ICPMS U-Pb zircon ages. The effects investigated include varying the air around the samples, the degassing of the mounting material, the fluence of the laser beam, and the homogeneity of the gas flow within the sample cell.

PROGRESS TOWARD TERRESTRIAL COSMOGENIC ³⁸Ar EXPOSURE DATING

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Cosmogenic exposure dating includes many techniques (e.g. ¹⁰Be; ³⁶Cl, ²¹Ne) that allow estimating how long a rock has been exposed to the bombardment of cosmic rays. Cosmogenic ³⁸Ar is produced by spallation reactions on Ca and K and has been particularly used in exposure dating of extra-terrestrial material for decades. However, this technique has not been applied to terrestrial rocks due to the difficulties of decoupling cosmogenic ³⁸Ar from atmospheric ³⁸Ar. We will show that modern multicollection noble gas instruments allow precisely measuring ³⁸Ar/³⁶Ar which, when combined with ³⁷Ar(Ca) neutron activation, open new avenues for dating terrestrial surfaces older than few hundred ka.

ASTRONOMICAL CALIBRATION OF $^{40}\text{Ar}/^{39}\text{Ar}$ REFERENCE MINERALS

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The new generation of multi-collector mass spectrometers for noble gas geochronology and geochemistry (e.g., Noblesse, ARGUSVI, HELIX-MC, Isotopx NGX) provide significantly enhanced levels of analytical precision (>10x) and greatly expanded capabilities compared to older instruments. In this presentation, I will discuss recent $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology results obtained on selected $^{40}\text{Ar}/^{39}\text{Ar}$ reference minerals using an ARGUSVI system.

The ARGUSVI system has enabled ultra-precise, calibration of $^{40}\text{Ar}/^{39}\text{Ar}$ standards against the astronomically tuned A1 Tephra unit from the Faneromeni section, Crete (6.943 ± 0.005 Ma [1]). These analyses have yielded highly precise (and arguably accurate) determinations of key reference mineral ages: Fish Canyon Tuff sanidine – 28.126 ± 0.019 (2σ) Ma; Alder Creek Rhyolite sanidine – 1.18404 ± 0.00068 Ma; Mount Dromedary biotite – 99.204 ± 0.076 Ma [2].

[1] Phillips D et al (2017) *Geochim Cosmochim Acta* 196: 351-369.

[2] Rivera T et al (2011) *Earth Planet Sci Lett* 311: 420-426.

TIMING SHEAR DEFORMATION ON A HIMALAYAN THRUST USING Ar/Ar GEOCHRONOLOGY AND DIFFUSION EXPERIMENTS

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The timing of movement on the Main Central Thrust of the Himalaya (MCT) has so-far been inferred solely on the basis of indirect arguments and models. Here, we applied $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology to directly date the highly strained muscovite in the MCT, showing that the timing of the shear movement lasted from 15–9 Ma. This age has been preserved because syn-deformation recrystallisation in retentive muscovite bands overprinted an earlier decussate mica growth that had taken place earlier than ~18 Ma.

Arrhenius data from ultra-high vacuum diffusion experiments show that our results directly date the age of the muscovite of the shear bands, thus providing for the first time an independent constraint for the actual timing of the shear movement on the MCT.

RESOLUTION OF NANOSCALE, ISOTOPICALLY-DISTINCT Pb RESERVOIRS IN DISCORDANT ZIRCON

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Discordant Pb isotopic data from zircon is commonly interpreted to represent isotopic disturbance of Pb by a younger thermal event. The data that plot on Pb discordia are often ignored, yet such data potentially record useful geological information that may constrain the temporal framework of geological events. Here we use atom probe microscopy to show that discordant data from the core of a 2.1 Ga zircon, metamorphosed at granulite facies conditions 150 Myr ago, contains distinct Pb reservoirs that represent both the crystallisation and metamorphic ²⁰⁷Pb/²⁰⁶Pb ages. Crystallisation ages are preserved within ~10 nm diameter dislocation loops that formed during annealing of radiation-damaged zircon during the prograde path of the metamorphic event. The results highlight the potential for resolving the chronology of multiple, distinct Pb reservoirs within isotopically complex zircon.

STRATEGIES TOWARDS STATISTICALLY ROBUST INTERPRETATIONS OF IN SITU U-Pb ZIRCON GEOCHRONOLOGY

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Zircon UePb geochronology has become a keystone tool across Earth science, arguably providing the gold standard in resolving deep geological time. The development of rapid in situ analysis of zircon (via laser ablation and secondary ionization mass spectrometry) has allowed for large amounts of data to be generated in a relatively short amount of time and such large volume datasets offer the ability to address a range of geological questions that would otherwise remain intractable (e.g. detrital zircons as a sediment fingerprinting method). The ease of acquisition, while bringing benefit to the Earth science community, has also led to diverse interpretations of geochronological data. In this work we seek to refocus UePb zircon geochronology toward best practice by providing a robust statistically coherent workflow. We discuss a range of data filtering approaches and their inherent limitations (e.g. discordance and the reduced chi-squared; MSWD). We evaluate appropriate mechanisms to calculate the most geologically appropriate age from both ²³⁸U/²⁰⁶Pb and ²⁰⁷Pb/²⁰⁶Pb ratios and demonstrate the cross over position when chronometric power swaps between these ratios. As our in situ analytical techniques become progressively more precise, appropriate statistical handling of UePb datasets will become increasingly pertinent.

VISUALISING DATA DISTRIBUTIONS WITH KERNEL DENSITY ESTIMATION AND REDUCED CHI-SQUARED STATISTIC

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The application of frequency distribution statistics to data provides objective means to assess the nature of the data distribution and viability of numerical models that are used to visualize and interpret data. Two commonly used tools are the kernel density estimation and reduced chi-squared statistic used in combination with a weighted mean. Due to the wide applicability of these tools, we produced a Java-based computer program called KDX to facilitate the visualization of data and utilizing these numerical tools.

RECENT DEVELOPMENTS IN THE NOBLE GAS GROUP OF CSIRO AT WAITE: FAILS AND SUCCESSES IN LABORATORY TECHNIQUES AND FIRST APPLICATION PROJECTS

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The noble gas group at Waite is the only laboratory in Australia and on the southern hemisphere dedicated to measure the concentrations of all noble gases and the activities of the radioactive noble gas isotopes ²²²Rn, ⁸⁵Kr, ³⁹Ar and ⁸¹Kr in water samples.

The talk will show the first data of the fully automated system for groundwater measurements of stable noble gases at Waite. It demonstrates the available precision using most recent results on internal standards and the first measurements on water samples. It also demonstrates new technical difficulties that have to do with the design of one of the cryo systems and how we will solve these difficulties.

The first application study of ⁸⁵Kr and ³⁹Ar on Rottneest Island is introduced and an outlook is given on the next application of ⁸¹Kr in the coal seam gas area of the Surat Basin.

SHRIMP Th/Pb DATING IN CARBONATITIC ZIRCONS

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Carbonatitic zircons are characterised by low U (<1 ppm up to 100s ppm) and high Th (up to 1000s ppm) contents. The best approach to date carbonatites, therefore, seems to be the Th/Pb dating rather than U/Pb dating. Our preliminary SHRIMP results on carbonatitic zircon grains indicate that the $^{208}\text{Pb}/^{232}\text{Th}$ ages are more precise and reliable than the $^{206}\text{Pb}/^{238}\text{U}$ ages. Moreover, zircons with the highest Th contents appear to show a relevant matrix effect on the $^{206}\text{Pb}/^{238}\text{U}$ ages. No matrix effect has been observed on the $^{208}\text{Pb}/^{232}\text{Th}$ ages.

LA-TOF-ICPMS Pb/U GEOCHRONOLOGY OF ZIRCON: SOME ADVANTAGES AND LIMITATIONS

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Laser ablation analyses of zircon for Pb/U ages using conventional quadrupole ICP-MS and a newly installed time of flight (TOF) ICP-MS are compared. Quadrupole ICP-MS measures masses sequentially which causes spectral skew leading to increased analytical error, particularly for transient signals (laser ablation). Additionally the more masses the quad has to scan the worse the spectral skew so that for analyses requiring high precision, like Pb/U dating, the list of masses must be short; losing information on mineral chemistry, age zoning, and inclusion compositions.

TOF-ICP-MS has three main advantages over quadrupole ICP-MS, 1) approximately simultaneous detection, 2) the ability to collect a spectrum that contains all masses, and 3) higher resolution ($r = 3000$ vs. 300 for quadrupole). One disadvantage of TOF-ICP-MS is 10x lower sensitivity compared to most quadrupole ICP-MS. Presented are preliminary data on zircon analysed with a TOF-ICP-MS showing some advantages and disadvantages over quadrupole ICP-MS.

U/HE DATING OF DIAMONDS

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Reliable and precise ages for diamond formation can be determined by Sm-Nd or Re-Os dating of large mineral inclusions. Successful dating of diamond by U/He will open up the possibility

to date diamonds that do not contain large mineral inclusions. As diffusion of helium in diamond lattice is negligible on a billion-year time scale, it could be an ideal mineral for U/He dating. In this study I will present the nitrogen, trace element and noble gas data of ten fibrous cubic diamonds from Congo and Botswana. These data show that the U/He ages are consistent with the nitrogen aggregation and that some fibrous diamonds can be formed several tens-hundreds of million years before the kimberlite eruption age. Further, the precision of the U/He ages of diamond will be discussed as they can be significantly compromised by the presence of cosmogenic ^3He and radiogenic ^4He implantation.

SETTING UP THE ARGUS AND EXTRACTION LINE FOR DIFFUSION EXPERIMENTS

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Setting up and automation of Argus mass spectrometer for the Ar/Ar geochronology laboratory at ANU presented multiple challenging steps.

Various parts of the UHV-extraction line were specifically custom-designed to meet the criteria required for the complex step-heating and diffusion experiments that the Structure and Tectonics Team exercise. Precise tuning of the furnace power controller and calibration of its thermal behaviour was undertaken to achieve the highest temperature stability and accuracy which is of great importance in diffusion experiments. The procedures associated with sample analysis were fully automated using an integrated application that was specifically developed for the lab to control all the hardware and data collection processes. Two new applications (for MS Windows and Mac) were also developed for data processing that benefit from modern framework.

$^{40}\text{Ar}/^{39}\text{Ar}$ GEOCHRONOLOGY OF PYROXENE

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With the advancement of machinery taking leaps and bounds the limit of geochronology is now the available minerals within the desired rock type. Felsic rocks have a plethora of minerals available and developed for geochronologic analyses. Mafic rocks and in particular ultramafic rocks, suffer from a lack of mineral types available for geochronology. Currently plagioclase is the common mineral utilized for crystallization ages for continental flood basalts. Plagioclase

unfortunately alters into a high K micaceous mineral (sericite) as well as being completely lacking in ultramafic rocks. Pyroxene is an abundant and essential mineral found in all mafic and ultramafic rocks that is more resilient from alteration than plagioclase. This study presents the first robust $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages from two different large igneous provinces (LIPs) located in Australia. These results open up unprecedented geochronological opportunities to all LIPs, ultramafic rocks, drudge rocks, as well as various metamorphic geochronology and thermochronology applications.

HIGH PRECISION $^{40}\text{Ar}/^{39}\text{Ar}$ GEOCHRONOLOGY OF LARGE IGNEOUS PROVINCES: THE TASMANIAN DOLERITES OF THE FERRAR LIP.

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The Ferrar large igneous province is exposed over 3000 km along the Transantarctic Mountains in Antarctica, terminating in the Australian state of Tasmania and in New Zealand. New high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages obtained on plagioclase separates extracted from doleritic sills of Tasmania were generated using an ARGUS VI multicollector mass spectrometer. These results are unprecedented in precision (≤ 0.5 Ma) for plagioclase dating. As a comparison, analyses on (larger) aliquots of plagioclase with a similar Ca/K ratio of ~ 30 , usually returns a precision of ± 1.5 to ± 2 Ma when analyzed using a single collector machine. This contrast in uncertainty illustrates the advantage of the ARGUS VI instrument. This gain of precision will be particularly useful for dating volcanic flows which, although constituting the bulk of large igneous provinces, are naturally devoid of zircon and were inaccessible to high precision geochronology ... until now.

AUTOMATION OF MOVEMENT OF THE MULTI-COLLECTORS ON THE HELIX MC PLUS MASS SPECTROMETER AT ANU

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For measuring different noble gas elements in a multi-collector mode, detectors are required to be set to different positions. The Helix MC Plus mass spectrometer is equipped with four movable detector holders, allowing detector positions to be adjusted. In order to measure a full suite of noble gases sequentially, starting from He to Xe, it is necessary to implement a device for automation of detector movement. This presentation provides the details of the project

currently carried out at ANU, in collaboration with Thermo Fisher Scientific, for the cup automation.

NON-MONOTONIC COOLING HISTORY IN THE SOUTHERN CENTRAL ANDES RECORDED BY MULTISYSTEM LOW-TEMPERATURE THERMOCHRONOLOGY

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Three low-temperature thermochronometers are used to study the temperature and exhumation history of the Sierra Laguna Blanca, a major basement range that rises over 6 km in the back-arc region of the Central Andes. Five samples analyzed with zircon (U-Th-Sm)/He thermochronology yield early Carboniferous to early Triassic dates. Ten apatite fission-track samples provide ~50 to 70 Ma ages with shortened, ~11-12 μm track lengths. Ten apatite (U-Th-Sm)/He samples yield highly dispersed dates ranging from ~30 Ma to 120 Ma, with eU values ranging from ~50 to 500 ppm. Time-temperature inverse and forward models reveal three major cooling events at the late Paleozoic, late Cretaceous and mid-late Miocene, and a heating event during late Eocene to early Oligocene. This study demonstrates that accumulated radiation damage, in this case caused by very high eU instead of a prolonged low-temperature history, may lead to significant apatite (U-Th-Sm)/He date dispersion.