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The oxidation state of uranium in basaltic melts

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Uranium can occur as U\textsuperscript{4+}, U\textsuperscript{5+} and U\textsuperscript{6+}, however, it is assumed that U\textsuperscript{4+} is the only important oxidation state under upper mantle conditions. This assumption is consistent with the similarity of the partitioning of U and Th (which occurs exclusively as Th\textsuperscript{4+}) between clinopyroxene and melt at mantle pressures. If, however, U\textsuperscript{5+} or U\textsuperscript{6+} were stable this would change the partitioning of U relative to Th and provide a mechanism for fractionation.

We have quantified the oxidation states of U in synthetic MORB glasses (0.5 wt\% U\textsubscript{3}O\textsubscript{8}), equilibrated as a function of oxygen fugacity at atmospheric pressure and 1400 °C, using both M- and L-edge X-ray absorption near edge structure (XANES) spectroscopy. At an oxygen fugacity typical of natural MORB (QFM) ~ 30% of the U is present as U\textsuperscript{5+}. Similar results were obtained for glasses of Fe-free anorthite-diopside eutectic composition and for melts recorded in situ, confirming that U\textsuperscript{5+} occurs at high temperatures. U\textsuperscript{5+}, however, was not found in glasses quenched from high pressures and similar oxygen fugacities. The concentration of U in natural samples is below the detection limit of the technique.

The XANES results are supported by new U and Th clinopyroxene-melt partitioning experiments. At atmospheric pressure and reduced conditions D\textsubscript{U}/D\textsubscript{Th} is approximately 1, whereas under oxidising conditions D\textsubscript{U}/D\textsubscript{Th} is <<1, indicating the presence of U\textsuperscript{5+} and/or U\textsuperscript{6+}, which are both more incompatible than U\textsuperscript{4+} and Th\textsuperscript{4+}. The relationship between D\textsubscript{U}/D\textsubscript{Th} and oxygen fugacity is similar to that found by XANES. Partitioning experiments at 1.0 GPa, however, only indicate U\textsuperscript{4+} at mantle oxygen fugacities, in agreement with earlier studies. It appears that U\textsuperscript{5+} is suppressed at high pressures.

Our results suggest that all U occurs as U\textsuperscript{4+} in MORB at pressures corresponding to the source, whereas at the surface ~ 65\% is U\textsuperscript{4+}, 30\% U\textsuperscript{5+}, and 5\% U\textsuperscript{6+}. Thus between the source and surface, at constant oxygen fugacity, there is a significant change in oxidation state. The behaviour of U, relative to Th, will hence vary during melt transport. It may also vary between MORB and arc basalts produced under oxidised conditions. The implications of the pressure-dependent-redox-variability of U for U-series disequilibrium is the subject of ongoing work.
The potential of U-series nuclides for investigating weathering, erosion and sediment transport processes has been recognized since the 1960s. It results from the property of the nuclides to be fractionated during water-rock interactions and to have radioactive periods of the same order of magnitude as the time constants of many weathering processes. The recent progression in this field of research was clearly related to the analytical developments made over the last decades in measuring the $^{238}$U series nuclides with intermediate half-lives (i.e., $^{234}$U-$^{230}$Th-$^{226}$Ra). These studies provided important theoretical elements for the determination of regolith production rates and soil formation rates as well as of sediment transport and deposition time scales.

The approaches for recovering such time information from both the U-Th-Ra methods and the U isotope comminution age shall be discussed here. The later is determined from the $^{234}$U/$^{238}$U ratio and reflects the timescale associated with the transformation of bedrock to sediment. It measures the amount of time elapsed since sediment generation by mechanical weathering and erosion and seems to give very promising information about the residence/transport time of sediments in a watershed. The U-Th-Ra methodology has been developed in two main directions. The first one concerns the determination of the regolith propagation rates from the analysis of U-series nuclides in a series of samples collected along a weathering profile. The second one is based on the analysis of the U-series nuclides in sediments collected along rivers for deriving the transfer time of sediments within alluvial plains. Both approaches interpret the variation of U-Th-Ra nuclides along the weathering profile and along rivers respectively, through simple modeling of U-series nuclides assuming a continuous gain and loss of the different U-series nuclides. These different approaches will be illustrated by the presentation of several case studies, which could open future directions in the use of U-series nuclides for constraining the rates of weathering and erosion processes.
Insights into magmatic processes in the crust from U-series disequilibria

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A temporal context is critical to developing an understanding the dynamics of magma systems in the crust, which in turn is critical to understanding the chemical and thermal evolution of magmas. In this presentation I will focus primarily on studies centered around U-series dating of crystals in volcanic rocks, with a secondary topic being whole-rock or glass analyses used to understand degassing histories of magmas. Crystals in volcanic rocks represent some combination of crystals grown in-situ from the host liquid with pre-existing crystals, and major and accessory phases may record different parts of a magma’s passage through a reservoir system. One of the frontiers of the field involves coupling U-series ages with other types of geochemical information at the crystal scale (trace elements or isotopic compositions) in order to constrain temporal changes in the differing chemical environments recorded by the crystals, and therefore the evolution of different parts of a magma reservoir over time and space.

For example, rhyolitic erupted products from South Sister, OR, Okataina Volcanic Center, New Zealand, and Yellowstone Caldera, WY, show surprisingly similar patterns when comparing ages and chemical compositions of major vs. accessory phases, despite orders of magnitude variation in eruption volumes. Commonalities are that: 1) eruptions have diverse zircon populations documenting that eruptions gather crystals that originated in coeval yet chemically distinct magma bodies that existed for tens of thousands of years, and 2) these same eruptions contain feldspar with significantly shorter pre-eruptive histories and less chemical diversity. These data suggest that zircon were physically separated from coeval feldspar, likely due to melt+zircon extraction from a locked crystal network containing the major phases, and the resulting magma bodies subsequently crystallized new feldspar during relatively brief periods of storage prior to eruption. Similar conditions of storage are implied using a novel approach combining time scales of crystal residence derived from time scales derived from U-series disequilibria, textural information, and trace-element zoning in crystals. For crystals derived from the silicic end-member at Mt. Hood, OR, we show that only a small fraction (likely < 1%) of the >21 kyr total storage duration has been spent at temperatures above the critical crystal fraction of 40-50%, where the magma body is easily mobilized. Thus, our results collectively imply that silicic magma bodies of diverse sizes and settings reside dominantly as locked mushes, with largely-liquid bodies present only for a short time prior to eruption.
Continental back-arc magmatic assessment using U-series

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The continental back-arc in central west Argentina is dominated by several Quaternary volcanic fields. The two fields of interest, Llancanelo (LLVF) and Payunia Volcanic Field (PVF), are approximately 35km apart and they present distinct trace elemental signatures. The LLVF has some arc signatures while the PVF is depleted of any arc signature and has enrichment of high field strength elements (HFSE), suggesting different magmatic sources for the two volcanic fields. Based on existing geochemical data the aim of this investigation is to assess the origin of the enrichment in high field strength elements (HFSE) in the PVF and to determine the dominating magmatic processes in the PVF.

In order to investigate the magmatic origin in the PVF, U-series were applied to one of the youngest basaltic flows from PVF, the Santa Maria Flow and Sr-isotopes were measured for samples from the two volcanic fields including the Santa Maria flow. This particular flow was chosen as its scoria cone and corresponding basaltic flow are isolated from the rest of the basaltic products in PVF, hence its magmatic chamber has likely also been isolated from the rest of the volcanic field. Preliminary results show that Santa Maria has a Ra-excess, with the 226Ra/230Th activity ratios ranging from 1.1 to 1.6. Despite using this young basaltic flow (<8 ka), accurate geochronology is not available for the Santa Maria flow, and which provides a source of uncertainty on the measured 226Ra.

The Ra excess measured is not associated with: (i) fluids released from the subducting slab due to its distant location with the subducting plate, (ii) hydrothermal alteration as it results in addition of U from fluids hence 238U/232Th increases while 230Th/238U decreases which is not observed among samples nor (iii) crustal contamination as the samples have mantle range Sr-isotopic composition. Furthermore, the Ra excess decreases with differentiation suggesting an association with fractional crystallization in the magmatic chamber. Finally the Ra excess could be associated with deeper processes such as a lithospheric mantle or melt released from the subducting slab. Nevertheless these processes need to be further examined in order to fully assess their possible contribution. The origin of the high enrichment in HFSE in the PVF has not been fully determined but it could be associated with intraplate volcanism suggesting an OIB type of mantle and possibly suggesting the presence of a hot magmatic body under this area.
Modeling magma replenishment in a steady-state magma chamber using U-series isotopes: Yasur Volcano, Vanuatu

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Use of uranium-series isotopes to investigate the timescales of magmatic processes has traditionally relied upon the assumption that following initial disequilibrium, radioactive decay occurs in a closed-system. This assumption does not apply at a number of persistently active volcanoes, where rates of magma replenishment are believed to be significantly faster than the half-life of isotopes such as $^{230}\text{Th}$ and $^{226}\text{Ra}$. Hughes and Hawkesworth (1999) modeled regular replenishment by magma with constant ($^{230}\text{Th}/^{232}\text{Th}$), showing that this can buffer the isotopic composition of the magma chamber, sustaining ($^{230}\text{Th}/^{232}\text{Th}$) out of secular equilibrium for periods in excess of the half-life of $^{230}\text{Th}$. Here, the model of Hughes and Hawkesworth (1999) is applied to investigate magma replenishment processes at Yasur volcano, a persistently active scoria cone in the Vanuatu Arc. Current activity at Yasur has continued for 630–850 years, with a time-averaged eruption flux of $\sim$470 m$^3$ d$^{-1}$. Tephra and lava bombs erupted during this period display a limited range in U-Th isotopes, with ($^{230}\text{Th}/^{232}\text{Th}$) ranging from 1.449–1.463 and ($^{238}\text{U}/^{232}\text{Th}$) varying between 1.749–1.787. Ratios of ($^{226}\text{Ra}/^{230}\text{Th}$) extend from $\sim$1.5 – 2. While apparently restricted, this data spread is too scattered to be reconciled with a model in which magma is replenished on timescales of years to tens of years: a process previously assumed due to the persistent output of this volcano. Instead the range of U-Th-Ra isotopes measured at Yasur require replenishment approximately every 5 kyr, with a magma for which ($^{230}\text{Th}/^{232}\text{Th}$) is $\sim$1.42. This implies that Yasur’s persistent eruptions are driven by gas overturn within a large, periodically refilled magma body, rather than by persistent magma recharge occurring at similar rates to that of eruptions.

Reference:
Variations in slab input revealed through along-arc geochemical variation in rear arc volcanoes of Ecuador

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Measurements of U-series isotopes and major and trace element concentrations from three rear-arc volcanoes in the Northern Volcanic Zone (NVZ) of Ecuador reveal significant along-arc variation. Of the three volcanoes analyzed in this study for \( ^{238}\text{U} / ^{230}\text{Th} \) disequilibria, the most variable \( ^{238}\text{U} / ^{230}\text{Th} \) values are related to Sumaco Volcano. Sumaco is the southernmost volcano in the rear-arc and has been inactive since at least 1933, although no historic eruptions or age constraints exist for the alkaline lava flows from this volcano. Sumaco samples have \( ^{238}\text{U} \) excesses of up to 70% with the exception of the most evolved phonolites, which have \( ^{230}\text{Th} \) excesses of 15%. All samples are strongly inversely correlated with SiO₂, La/Yb and P₂O₅, and have the highest Sr concentrations (4,000 ppm) of any volcano in Ecuador. The northernmost volcano in this study is El Reventador, which has erupted calc-alkaline lavas since a cycle of activity began in November 2002. Lavas from Reventador have lower \( ^{238}\text{U} \) excesses of 10% and \( ^{238}\text{U} / ^{230}\text{Th} \) values that range from 0.87 - 1.1. The \( ^{238}\text{U} / ^{230}\text{Th} \) values of the Reventador samples do not correlate with indices of differentiation, although Ba/Th values at El Reventador range from 180-250; higher than values of 80-150 at Sumaco. Located between these two rear-arc volcanoes is an extinct volcano called Pan de Azucar. Samples (n=4) from this volcano are borderline alkaline, and are geochemically more similar to El Reventador than to Sumaco. Equiline U-series values for these samples are consistent with an eruption age older than 350 ka. The high \( ^{238}\text{U} \) excesses and low Ba/Th at Sumaco volcano compared to the high Ba/Th and calc-alkaline signature of Reventador lavas is consistent with decreasing fluid input from north to south. This has produced highly alkaline, apatite-saturated lavas at Sumaco that have \( ^{238}\text{U} \) excesses related to accessory phase fractionation. Quantitative modeling shows that melting of metasomatized mantle wedge enriched with at least 300 ppm Sr is required to produce the Sr concentrations in the Sumaco lavas, and the low Ba/Th and U/Th at Sumaco are consistent with this component being sediment melt. Reventador samples show no correlation between \( ^{238}\text{U} / ^{230}\text{Th} \) and trace element values, and the U-series variation can be modeled using 3% melting of garnet peridotite mantle source. Finally, the range of \( ^{230}\text{Th} / ^{226}\text{Ra} \) disequilibrium and mineral isochrons.
Modern fossil bones and teeth are virtually free of uranium. During diagenesis, the fossils acquire uranium which can then be used for U-series dating. In order to account for the open system behaviour, several models have been developed for the calculation of U-series age estimates. The most recent diffusion-adsorption-decay (D-A-D) model accounts for the diffusion and decay of both $^{238}\text{U}$ and $^{234}\text{U}$. This allows the cross-checking of $^{234}\text{U}/^{238}\text{U}$ and $^{230}\text{Th}/^{234}\text{U}$ activity ratios in a given volume and whether the data set of a bone or enamel cross section conforms to the basic assumptions of the D-A-D model.

In principle, slow diffusion into enamel could be used to extend the dating range of U-series dating by using the decay of $^{234}\text{U}$ during diffusion for age calculations. In practice, detailed micro-scale analyses using laser ablation multi-collector ICP-MS show that diffusion processes may be highly complex.
The U-series comminution approach: where to from here

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Quantifying the rates of landscape evolution in response to climate change is inhibited by the difficulty of dating the formation of continental detrital sediments. The ‘comminution age’ dating model of DePaolo et al. (2006) hypothesises that the measured disequilibria between U-series nuclides (²³⁴U and ²³⁸U) in fine-grained continental (detrital) sediments can be used to calculate the time elapsed since mechanical weathering of a grain to the threshold size (~50 µm). The comminution age includes the time that a particle has been mobilised in transport, held in temporary storage (e.g., soils and floodplains) and the time elapsed since final deposition to present day. Therefore, if the deposition age of sediment can be constrained independently, for example via optically stimulated luminescence (OSL) dating, the residence time of sediment (e.g., a palaeochannel deposit) can be determined.

Despite the significant potential of this approach, there is still much work to be done before meaningful absolute comminution ages can be obtained. The calculated recoil loss factor and comminution age are highly dependent on the method of recoil loss factor determination used and the inherent assumptions. We present new and recently published uranium isotope data for aeolian sediment deposits, leached and unleached palaeochannel sediments and bedrock samples from Australia to exemplify areas of current uncertainty in the comminution age approach.

In addition to the information gained from natural samples, Monte Carlo simulations have been conducted for a synthetic sediment sample to determine the individual and combined comminution age uncertainties associated to each input variable. Using a reasonable associated uncertainty for each input factor and including variations in the source rock and measured (²³⁴U/²³⁸U) ratios, the total combined uncertainty on comminution age in our simulation (for two methods of recoil loss factor estimation: weighted geometric and surface area measurement with an incorporated fractal correction) can amount to ± 220-280 ka. The modelling shows that small changes in assumed input values translate into large effects on absolute comminution age.

To improve the accuracy of the technique and provide meaningful absolute comminution ages, much tighter constraints are required on the assumptions for input factors such as the fraction of alpha-recoil lost ²³⁴Th and the initial (²³⁴U/²³⁸U) ratio of the source material. In order to be able to directly compare calculated comminution ages produced by different research groups, the standardisation of pre-treatment procedures, recoil loss factor estimation and assumed input parameter values are required. We suggest a set of input parameter values for such a purpose.
Uranium-series timescale constraints on recent changes in the eruptive behaviour of Merapi Volcano, Java, Indonesia

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The 2010 eruption Merapi volcano (Central Java, Indonesia) was the volcano’s largest eruption in 140 years and was much more violent than expected. Prior to 2010, for example in 2006, volcanic activity at Merapi was characterised by several months of slow dome growth punctuated by gravitational dome failures, generating small-volume pyroclastic density currents. We present new uranium-series (U-Th-Ra-Pb) isotope data for the volcanic products of both the 2006 and 2010 eruptions at Merapi to investigate the driving forces behind the recent unusual explosive behaviour and their timescales. The 2006 and 2010 volcanic rocks display $^{238}$U excess and suggest variable enrichment by a U-rich fluid or melt (e.g., subducted slab or crustal assimilant) within the last 380 kyr. The 2010 deposits display a slightly wider range in ($^{238}$U/$^{232}$Th) (0.671 to 0.723) compared to those of 2006 (0.702 to 0.720). A negative correlation is observed between ($^{226}$Ra/$^{230}$Th) and Th (as index of differentiation). Assuming that the degree of disequilibria in the sample with the highest ($^{226}$Ra/$^{230}$Th) (3.28) represents that at the onset of differentiation, $^{226}$Ra excesses implicate short timescales for magmatic differentiation at Merapi of < 750 years for the 2006 and < 300 years for the 2010 volcanic rocks, noting that apart from one 2006 sample, the volcanic rocks of both eruptions have similar ($^{226}$Ra/$^{230}$Th) activity ratios. However, it is unlikely that the U-series data at Merapi can be interpreted within the context of simple closed-system evolution due to the previous recognition of open-system processes, such as magma recharge, magma mixing and mingling processes and assimilation of crustal carbonates. The 2006 and 2010 volcanic rocks have initial ($^{210}$Pb) values of 2.66 to 3.04 dpm/g and 2.22 to 3.08 dpm/g and ($^{210}$Pb/$^{226}$Ra)₀ ratios of 0.81 to 0.95 and 0.72 to 0.96, respectively and may suggest persistent and complete $^{222}$Rn degassing over a few years to a decade prior to eruption possibly related to the time for magma ascent from a deeper crustal reservoir. The 2010 volcanic rocks show the largest $^{210}$Pb deficits suggesting longer timescales of degassing prior to eruption compared to the 2006 eruption. However, volcanic rocks of both eruptions display relatively similar range in ($^{210}$Pb/$^{226}$Ra)₀ ratios.
Slow, Slow, Quick, Slow: the rhythm of sediment transport in a large catchment

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The uranium-series isotopic compositions of soils and sediments evolve in response to time and weathering conditions. Therefore, these isotopes can be used to constrain the timescales of river sediment transport. Mineralogical, elemental and isotopic data were determined for modern channel sediments, alluvial deposits and colluvial deposits from the Murrumbidgee River and three of its tributaries from the headwaters to the alluvial plain in its lower reaches. Low variability in alteration index (WIS) indicates that there is little chemical weathering occurring in the Murrumbidgee River. However, quartz content increases and plagioclase content decreases downstream, indicating progressive mineralogical sorting and/or physical comminution with increasing transport distance. No systematic downstream variation is observed in the behaviour of U-series isotopes in the Murrumbidgee River trunk stream sediments. The residence times of sediments within the catchment were determined using a loss-gain model of U-series isotopes. Modern sediments from a headwater tributary, the Bredbo River at Frogs Hollow, have a residence time of 76 ± 30 kyr but all other modern channel sediments from the length of the Murrumbidgee River and its main tributaries have residence times ~400 ± 180 kyr. The two headwater colluvial deposit samples have residence times 57 ± 13 and 47 ± 11 kyrs, respectively. All the alluvial deposits have residence times similar to the modern sediments. No downstream trend in residence time is observed. When considering the soil residence time of 30 kyr at Frogs Hollow in the upper catchment area of the Murrumbidgee River (Suresh et al., EPSL 2013), the current results indicate, for the first time, that sediment in the Murrumbidgee catchment spends longer in hill slope transport and storage than in alluvial transport or storage.
Application of U-series isotopes to quantify weathering rind formation rates along steep gradients of precipitation, bedrock ages, and topography in Guadeloupe Island

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Despite the fundamental importance of chemical weathering of volcanic rocks, we still lack effective tools to quantify their weathering rates and to understand how they respond to changes in climate, landscape, and tectonic regime. It is essential to develop and utilize new tools to directly quantify long-term chemical weathering rates. Here, our ongoing investigation combines a novel U-series isotopic technique with bulk chemical, petrographic, and electron microprobe analyses to study weathering rinds in multiple watersheds on the tropical island of Basse-Terre in French Guadeloupe.

Our previous study is focused on a basaltic andesite weathering clast collected from Basse-Terre Island in Guadeloupe. U, Th, and Ti elemental profiles reveal that Th and Ti behave conservatively during rind formation, and U is added from an external source to the rind. In the rind, weathering reactions include dissolution of primary minerals such as pyroxene, plagioclase, and glass matrix, as well as formation of Fe oxyhydroxides, gibbsite and minor kaolinite. Significant porosity forms in the rind mostly from plagioclase dissolution. The new porosity is inferred to allow an influx of soil water carrying externally derived, dissolved U. Due to this influx, U precipitates along with newly formed clay minerals and oxyhydroxides in the rind. The conservative behavior of Th and the continuous addition of U into the rind adequately explain the observed systematic trends of \(^{238}\text{U}/^{232}\text{Th}\) and \(^{230}\text{Th}/^{232}\text{Th}\) activity ratios in the rind. Rind formation rates, determined from the measured U-series activity ratios with an open system U addition model, increase by a factor of 1.3 (0.18–0.24 mm/kyr) from a low curvature to a high curvature section (0.018–0.12 mm\(^{-1}\)) of the core–rind boundary, revealing that curvature affects rates of rind formation as expected for diffusion-limited rind formation. U-series geochronometry thus provides the first direct evidence that the curvature of the interface controls the rate of regolith formation at the clast scale.

By comparing multiple weathering rinds collected from the Bras David watershed, our ongoing investigation will elucidate the controls and rates of weathering rind formation at the clast- through micro-scale processes such as dissolution, formation of new phases, and development of porosity. At a larger spatial scale, weathering rinds collected from seven watersheds on Basse-Terre will further allow us to study rind formation as a function of environmental variables including climate, relief, and age of protolith.
U-Th dating of vein calcite: preliminary results from geothermal systems in the Chilean Patagonia

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In actively deforming regions, high-pressure hydrothermal fluids play an important role in faulting and vein formation, and commonly fault rupture is followed by rapid sealing through mineral precipitation. Therefore, precise dating of vein growth is of special importance to our understanding of the complex interplay between seismic events and fluid flow in the upper crust, although precise age determination is difficult in young, <1 Ma old systems. Despite these difficulties, new applications of short-half life geochronometers such as the U-series disequilibrium series are providing new tools to assess the age of crack-seal events.

The measurement of U-series isotopes in precipitated minerals such as calcite holds various challenges, including low U concentrations (sometimes in the ppb range), and the presence of detrital $^{232}$Th which can lead to age overestimations. Additionally, as yet there does not exist a calcite standard reference material for inter-laboratory accuracy and precision comparison, with most laboratories using their own in-house standard material and focussing largely on application to paleoclimate studies (e.g. corals and speleothems).

We are developing the first U-Th measurements and ages of vein calcite from geothermal systems in southern Chile, using a Neptune Plus MC-ICP-MS coupled to an excimer 193nm Photon Machines laser. We will be comparing our results with the NIST612 glass standard, and an 189ka in-house calcite standard previously dated by TIMS. The ability to accurately date fault-filling calcite within such settings has the power to elucidate the complexities involved in the interplay between structure and fluid flow in the development of geothermal systems, and provide valuable information on the longevity of the heat/water source, in addition to the magmatic/volcanic history of an area.
Uranium series - size correlations in intraplate basaltic volcanic fields: a window to melt extraction

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Small-volume, near-primitive basaltic eruptions within volcanic fields have the potential to reveal subtle features of mantle melting and extraction processes which are overwhelmed and homogenised in larger systems. An important feature of geochemical analyses from monogenetic basaltic fields is their ability to show source heterogeneity both on whole-field and single-volcano scales. Additionally, because small-volume centres often display almost complete volcanic sequences within a range of sizes, opportunities are presented whereby correlations between physical features and chemical compositions can be investigated in detail.

The volcanoes comprising the Auckland Volcanic Field (AVF) of northern New Zealand show a spectrum of sizes and compositions from small-volume nephelinitic, through medium-sized alkalic, basanitic and basaltic, to larger-volume subalkalic basaltic eruptions. We focus on four eruptions which display a size and compositional spectrum: Purchas Hill (the smallest sampled volcanic centre in the AVF, nephelinitic in composition), Mt Wellington (medium sized, alkalic basalt) and the two eruptions of Rangitoto (Rangitoto 1: medium sized, alkalic basalt, and Rangitoto 2: the largest volcanic centre in the AVF, subalkalic basalt).

U-series and other isotopic data for these case study volcanoes show strong correlations between eruptive volume and isotopic composition. The volcanic centres display a spectrum of compositions in U-Th isotopic, Pb-isotopic and SiO₂ vs. Total Alkali space, with the smallest centre (Purchas Hill) displaying the highest (²³⁰Th/²³²Th) (1.38), the lowest SiO₂ (39 wt%) and highest total alkalis (6 wt%). The largest centre displays the lowest (²³⁰Th/²³²Th) (1.14), the highest SiO₂ (49.5 wt%) and lowest total alkalis (3 wt%). The observed differences in the chemical parameters can be attributed to melting of a heterogeneous source, where the heterogeneity results in varying magmatic processes, and variations in the extent and efficiency of melt extraction. These results suggest that physical parameters of individual centres in intraplate volcanic fields – such as size – may be directly controlled by the melting process.
U-series isotopic constraints on mantle upwelling on the periphery of the Hawaiian plume; Isotope geochemistry of Haleakala crater basanites

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In order to understand the dynamics and structure of the Hawaiian plume, it is necessary to not only consider the predominant and well-studied main-stage tholeiitic volcanism, but also late-stage alkaline volcanism. These silica undersaturated lavas constitute an end-member in the compositional range of Hawaiian lavas and tap magma from the periphery of the plume as the Pacific lithosphere moves away from the plume center.

Here we present new major and trace element data, Nd, Sr, Hf, and Pb isotopic compositions, and ²³⁸U-²³⁰Th-²²⁶Ra and ²³⁵U-²³¹Pa-²²⁷Ac activities for 13 Haleakala crater basanites with ¹⁴C ages ranging from 870±40 to 4070±50 years (Sherrod and McGeehin, 1999). These lavas are nepheline normative and exhibit higher (²³⁰Th/²³⁸U) than main stage tholeiites, implying a small degree of partial melting in the presence of garnet. (²³⁰Th/²³⁸U) ranges from 1.181 to 1.315 with an average of 1.233 (n=13); (²²⁶Ra/²³⁰Th) ranges from 1.165 to 1.287 with an average of 1.248 (n=13); and (²³¹Pa/²³⁵U) ranges from 1.466 to 1.599 with an average of 1.525 (n=3). In addition, (²²⁷Ac/²³¹Pa) ratios are equal to 1, which is to be expected for lavas older than 100 years. In contrast, main-stage tholeiites from Kilauea and Mauna Loa exhibit average (²³⁰Th/²³⁸U), (²²⁶Ra/²³⁰Th), and (²³¹Pa/²³⁵U) of 1.019, 1.131, and 1.116, respectively (data from Pietruszka et al., 2001; Sims et al., 1999; Cohen et al., 1996; Cohen and O’Nions, 1993). Results of chromatographic porous flow modeling (Spiegelman, 2000) show that solid mantle upwelling rates and porosity of the melting zone are much lower for Haleakala crater basanites than for main-stage tholeiites from Kilauea and Mauna Loa as well as alkali basalts from Hualalai. Using a garnet peridotite starting composition, a 10 km melt column, and 3% melting, modeled solid mantle upwelling velocity for Haleakala crater basanites ranges from 0.007 to 0.025 m/yr, in good agreement with the conclusions of Sims et al. (1999) for basanites from the southwest rift zone of Haleakala. Sims et al. (1999) estimated the solid mantle upwelling velocity near the center of the Hawaiian plume to be as high as 1 m/yr. These conclusions are also consistent with the fluid mechanical models of the structure of the Hawaiian plume of Hauri et al. (1994) and Watson and McKenzie (1991). These U-series results, along with major and trace element and long-lived radiogenic isotope data, provide important insight into the processes of magma generation on the trailing edge of the Hawaiian plume.
PGE concentration and Os isotope constraints on the origin of $^{210}\text{Pb}$ - $^{226}\text{Ra}$ disequilibria in lavas from Kilauea volcano, Hawaii

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We report incompatible trace element, platinum-group element (PGE), Os isotope, and $^{210}\text{Pb}$-$^{226}\text{Ra}$-$^{230}\text{Th}$ data for lavas erupted from Kilauea volcano, Hawaii to investigate the mechanisms and timescales of magma-crystal-gas fractionation. Most samples analyzed here erupted from the Pu‘u ‘Ō‘ō vent between 1983 and 2008. Also analyzed were samples ejected during short-lived explosive eruptions including episode 54 at Nāpāpu crater in January 1997 (e.g. Garcia et al., 2000, J. Petrol.; Thornber et al., 2003, USGS Prof. Paper 1676). Our samples have ($^{210}\text{Pb}/^{226}\text{Ra}$) ratios ranging from near equilibrium for episode 54 magmas equilibrium to 0.75 for the most $^{210}\text{Pb}$ depleted lavas from Pu‘u ‘Ō‘ō. Deficits in $^{210}\text{Pb}$ compared to $^{226}\text{Ra}$ in lavas are commonly explained by $^{222}\text{Rn}$ degassing during magma ascent through the crust (e.g. Gauthier and Condomines, 1999, EPSL). Alternative explanations include mantle melting (Rubin et al., 2005, Nature) and sulfide phase fractionation from silicate magma (Sims et al., 2008, G³). Pb concentrations and ($^{210}\text{Pb}/^{226}\text{Ra}$) values correlate for the lavas from Kilauea, allowing control of ($^{210}\text{Pb}/^{226}\text{Ra}$) values by fractionation processes. However, other incompatible element concentrations also correlate with ($^{210}\text{Pb}/^{226}\text{Ra}$) values, and PGE element abundances decrease with increasing ($^{210}\text{Pb}/^{226}\text{Ra}$) values, indicating that although sulfides did fractionate from differentiating magmas, they did not play a significant role in lowering ($^{210}\text{Pb}/^{226}\text{Ra}$) values. The lack of correlation between ($^{210}\text{Pb}/^{226}\text{Ra}$) and ($^{226}\text{Ra}/^{230}\text{Th}$) values suggests that melting processes also did not play a role in fractionating Pb from Ra. Thus, the variations in ($^{210}\text{Pb}/^{226}\text{Ra}$) values for Kilauea probably resulted from year to decade scale Rn degassing. If Rn is completely and persistently degassed from Hawaiian magmas as they traverse the crust, then the rise time from initial CO$_2$ saturation to the surface is up to 7 years. Longer rise times are allowed if Rn degassing is incomplete or punctuated by periods without degassing. The near-equilibrium ($^{210}\text{Pb}/^{226}\text{Ra}$) values for the more differentiated episode 54 lavas can be explained by storage of magmas in the east rift for at least several decades before they erupted. During this period, these lavas underwent significant olivine and sulfide fractionation. They also must have assimilated lavas or fumarolic deposits with radiogenic Os, as their $^{187}\text{Os}/^{188}\text{Os}$ compositions are significantly higher than those of Pu‘u ‘Ō‘ō lavas analyzed here and primitive lavas from Kilauea in general (e.g. Ireland et al., 2009, Chem. Geol.).
Understanding geochemical and isotopic variations over time and space within a large silicic volcanic center, Taupo Volcanic Zone, NZ

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The Taupo Volcanic Zone (TVZ) in New Zealand is one of the most active volcanic zones in the world, having erupted over 50 times in the past 45 ka. Rhyolites erupted from the Okataina Volcanic Center (OVC) within the TVZ vary in chemical composition over relatively small distances and within single eruptions, suggesting that multiple internally homogeneous melts are stored separately, albeit in close physical proximity to each other. Eruptive products record the mingling of chemically distinct melts; however, the timescales on which these melts are amalgamated prior to (or during) eruptions is not well understood. This study presents the results of new trace element, U-Th age, and hafnium isotopic data obtained from zircons of the 0.7 ka Kaharoa and 4.8 ka Whakatane eruptions, the most recent rhyolitic eruptions from the OVC; we also present U-Th-Ra ages of plagioclase crystals from the Kaharoa eruption. Zircons from both the Kaharoa and Whakatane eruptions display a wide range of trace element compositions and ages, with most grains yielding ages between ca. 0-50 ka but several displaying ages as old as secular equilibrium (>300 ka). There does not seem to be a coherent trend in trace element concentrations over time in either the Kaharoa or Whakatane zircons, suggesting that both eruptions sampled zircons from a variety of coeval yet geochemically distinct melts. Core-to-rim variations in Kaharoa zircons reveal significant variation in trace element compositions within older (28-56 ka) zircon cores, but more homogeneous populations present in younger (0-17 ka) zircon surface analyses. The chemically homogeneous rim data suggest that zircons derived from multiple sources underwent crystallization in the same melt just prior to eruption. Zircon εHf data were acquired from spots previously analyzed for trace element and U-Th age data in order to chemically fingerprint distinct melts that existed prior to amalgamation and eruption. εHf values within zircon range from approximately +2 to +9 at a given time, implying that discrete melts within the magma reservoir record the signature of an isotopically juvenile (basaltic) end-member component. U-Th-Ra disequilibrium ages of plagioclase crystals, when corrected for the addition of Th and Ra from additional phases within the plagioclase mineral separate (mainly glass, zircon, andapatite), are estimated to be younger than secular equilibrium (i.e., <8 ka), approximately 3-6 ka. Future work will link these age data with diffusion profiles to examine thermal histories of OVC eruptions.
Community need for more rational and uniform U-series age uncertainty estimates

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U-series disequilibria studies of rates, timescales, and absolute ages of geological processes has become a wide-ranging business, with practitioners using a range of isotope systems and analytical methods to address a wide range of earth science processes. In the best cases, analytical precision has gotten quite high due to analytical and instrumental advances, translating to analytical errors of just sub-annual to decadal time periods for isotope systems and applications that look at phenomena occurring within the last 20,000 years or so. This includes some applications of $^{210}$Po-$^{210}$Pb, $^{210}$Pb-$^{226}$Ra, $^{226}$Ra-$^{230}$Th and $^{230}$Th-$^{238}$U geochronology, and others as well. However, less progress has been made on “other” forms of error, such as sampling errors and biases, geological errors, initial condition estimates, and interpretation errors. Whereas in the old days (pre 1990s), when analytical errors were high enough to not worry so much about these “other” forms of error, the latter are now dominant since analytical precision has improved substantially (in some cases by better than 10×). The way in which these other sources of uncertainty are handled (or variably ignored) in the current literature has become problematic, particularly for non-U-series experts who wish to use our timescale constraints at maximum resolution (i.e., at human-relevant timescales of years to decades) and particularly when using results from multiple papers or labs. I will provide examples from my own work using short-lived isotopes in magmatic systems and $^{230}$Th-$^{238}$U dating of Holocene and deglacial corals for sea level studies to illustrate some of these challenges, and to discuss some possible steps forward for developing a more rational way of assessing uncertainties, and for tying our geochronologic results to absolute timescales. There is currently an effort underway by the good folks at IEDA to help bring about some standardization in how U-series data and resulting ages are reported and ingested into public-access databases, via their EarthChem and Geochron products, which I think our group could provide useful feedback to.
On the application of U-series disequilibria to the study of mantle melting and basalt petrogenesis

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The formation and transport of basaltic magma in the mantle by adiabatic decompression can be characterized in terms of the following parameters: the velocity of the solid upwelling mantle; the rate of melting; the melt velocity; the dispersivity associated with melt migration; and, the storage time of magma prior to eruption. The velocity of upwelling mantle and the corresponding melting rate can be estimated from models coupling thermodynamic data and geophysical observations. However, the melt velocity, dispersivity of the melt zone, and the magma storage times are difficult to estimate from first principles and require indirect geochemical methods to determine.

Since McKenzie (EPSL, 1985), departures from radioactive equilibrium observed for nuclides in the U-decay series have provided the geosciences community with a unique and fundamental geochemical method to determine the rate of melting, the melt migration velocity, and the extent of melting. In the ensuing three decades, numerous researchers have coupled theoretical constructs (Williams and Gill, GCA, 1989; Spiegelman and Elliott, EPSL, 1993; Jull et al., GCA, 2002) with measurements of U-series nuclides in basaltic lavas to: establish unequivocally the presence of residual garnet in the source of mid-ocean ridge basalt (Beattie, Nature, 1993; Landwehr et al., EPSL, 2001; Elkins et al., EPSL, 2008); map the upwelling structure of mantle plumes (Sims et al., GCA, 1999; Kokfelt et al., EPSL, 2004), determine the nature of melting and melt migration during the genesis of ocean island and mid-ocean ridge basalts (Sims et al., Science, 1995; Lundstrom et al., Science, 1995; Kelemen et al., Phil Trans. Roc Soc., 1997; Sims et al. GCA, 2002; Waters et al., J. Petrol. 2013); and, by contrast, demonstrate the importance of fluid and sediment components in arc magmas (Hawkesworth et al., Science, 1997; Elliott et al., CMP, 1997; Turner et al., Geology, 1999; Bourdon et al., Science, 1999; Peate et al., J. Petrol., 2001).

In this talk I will give a brief overview of the fundamental concepts behind the application of U-series measurements to understand melting processes. I will then discuss some of the above listed historical examples of how measurements of U-series disequilibria have enabled the community to determine fundamental, but previously intractable, parameters of melting. Finally, looking forward, I will discuss the measurement of the volatile U-series nuclides in volcanic gases to determine magma storage times, magma recharge rates and the kinetics of gas extraction.
$^{238}\text{U}/^{235}\text{U}$ isotopic fractionation in terrestrial environments: Implications for U-series geochemistry

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For several decades, the uranium isotopic composition of $^{238}\text{U}/^{235}\text{U}$ was considered to be invariant and equal to 137.88 throughout the Earth and solar system. Historically, this assumption was based on uranium’s heavy mass and the expectation that mass-dependent ‘stable’ isotope fractionation between lattice-bound $^{238}\text{U}$ and $^{235}\text{U}$ would not be observable. However, contrary to expectations, significant, permil-level variations in $^{238}\text{U}/^{235}\text{U}$ have been observed in both terrestrial and extra-terrestrial settings. Importantly, the $^{238}\text{U}/^{235}\text{U}$ observations available to date show some apparently conflicting results, and additional efforts are required to help reconcile these findings.

Using multiple-collector ICPMS (MC-ICPMS), we present $^{238}\text{U}/^{235}\text{U}$ observations for samples collected from a wide range of low- and high-temperature environments. A $^{233}\text{U}/^{236}\text{U}$ double spike was employed to monitor instrumental mass fractionation, allowing variations in $^{238}\text{U}/^{235}\text{U}$ to be resolved at the 0.005 % level (2σ). Our results provide further insight into the magnitude and direction of $^{238}\text{U}/^{235}\text{U}$ fractionation, the underlying mechanisms controlling these isotopic shifts, and the environments in which such fractionations occur. Specifically, these datasets show that in Earth’s surface environments, by far the largest U isotope fractionation effects occur during U(VI) reduction whereby isotopic shifts of up to 0.5 % are observed. In redox settings, $^{238}\text{U}/^{235}\text{U}$ fractionation appears to be exclusively governed by volume-dependent ‘nuclear field shift effects’, due to varying nuclear volumes and electron density distributions between different isotopes of the same element, rather than traditional mass-dependent thermodynamic effects. Opposing, but smaller isotope shifts consistent with mass-dependent fractionation are observed in other environments involving the leaching of U during silicate weathering and the adsorption of U onto mineral surfaces.

These datasets have a direct bearing on the suitability of the $^{238}\text{U}/^{235}\text{U}$ system for monitoring the bioremediation of contaminated groundwater following U mining, as a tool in mineral and oil exploration studies for economic geology, and as a paleo-redox tracer for quantifying the extent of anoxia in the ancient oceans for studies in paleoceanography. Variability in $^{238}\text{U}/^{235}\text{U}$ also has a direct impact on the accuracy of the U decay series chronometers, requiring the $^{238}\text{U}/^{235}\text{U}$ of every sample to be characterized, and the revision of important cosmo- and geo-chronological models when previous U-Pb and U-series ages, derived using a $^{238}\text{U}/^{235}\text{U}$ value of 137.88, have been inaccurate.
Uranium-thorium disequilibria in basement rocks from the Flinders Ranges, South Australia: implications for calculated sediment residence timescales

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Estimation of sediment U-series comminution ages and hence, residence times, requires knowledge of the initial \(^{234}\text{U}/^{238}\text{U}\) activity ratio of the sediment source, i.e. bedrock. However, few published studies to date have provided direct measurements of the U-series activity ratios of the source material. Most comminution studies have assumed that prior to physical weathering, fractionation of \(^{234}\text{U}-^{238}\text{U}\) is negligible and therefore, the \(^{234}\text{U}/^{238}\text{U}\) ratio of the source will be in secular equilibrium (equal to 1). While \(^{234}\text{U}/^{238}\text{U}\) activity ratios in fresh volcanic rocks are often reported to be within secular equilibrium, a number of crystalline rocks (fractured and unfractured plutonic rocks and quartzite) and sedimentary rocks (siltstone) have been shown to be out of secular equilibrium. We present uranium-series isotope ratios for six bedrock samples of variable sedimentary lithology from the Flinders Ranges in South Australia to: 1) test whether the source material is in \(^{234}\text{U}/^{238}\text{U}\) secular equilibrium prior to the onset of physical weathering and, 2) use U-Th isotope systematics to constrain the timing of any u-series disequilibrium observed in the source material.

Similar to the findings of Handley et al. (Chem. Geol. 2013), our results show that > 1 Ma-old bedrock from the Flinders Ranges has \(^{234}\text{U}/^{238}\text{U}\) ratios that are out of secular equilibrium (0.89 to unity). The siltstone rocks display the largest disequilibrium. The single limestone sample analysed is in \(^{234}\text{U}/^{238}\text{U}\) secular equilibrium. These results show and confirm that the starting \(^{234}\text{U}/^{238}\text{U}\) ratio \((A_0)\) within the comminution age equation cannot always be assumed to be in unity. We attribute the loss of \(^{234}\text{U}\) relative to \(^{238}\text{U}\) to preferential removal of \(^{234}\text{U}\) from the source material via leaching from recoil-damaged sites.

Thorium isotopes have also been determined for these bedrock samples. All samples have \(^{230}\text{Th}\) excesses relative to \(^{238}\text{U}\). The siltstone samples have relatively lower \(^{230}\text{Th}/^{238}\text{U}\) ratios than the quartzite samples (−0.84 compared to −0.91), whereas the limestone sample shows the smallest Th-excess \((^{230}\text{Th}/^{238}\text{U}) = 0.99\). The U-Th data form a relatively straight, positive sloping line in \(^{234}\text{U}/^{238}\text{U}\) versus \(^{230}\text{Th}/^{238}\text{U}\) space. This trend may be interpreted to represent the time since the bedrock underwent a single, uranium-leaching event. Using the U redistribution model of Thiel et al. (EPSL, 1983) this leaching event is estimated to have occurred on the order of hundreds of thousands of years ago. To test the single-event, uranium-leaching model, we will determine the \(^{226}\text{Ra}\) activities of the Flinders bedrock material. The half-life of \(^{226}\text{Ra}\) is 1600 years and so if the \(^{226}\text{Ra}/^{230}\text{Th}\) ratios of the bedrock samples are in unity, it supports an old, \((10^5 \text{ yr})\) single, U-leaching event. If Ra disequilibria are measured in the samples then a more complex, continuous leaching model is required.
Origin of $^{210}$Pb-$^{226}$Ra disequilibria in basalts – new insights from the 1978 Asal Rift eruption

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There has been much debate as to whether $^{210}$Pb-$^{226}$Ra disequilibria in young volcanic rocks result from partial melting, cumulate interaction or magma degassing. Here we present new data from basalts erupted in 1978 from Ardoukoba volcano in the Asal Rift. The ($^{210}$Pb/$^{226}$Ra) ratios are very low (0.2 to 0.6) and appear to correlate negatively with ($^{226}$Ra/$^{230}$Th). Invariant ($^{230}$Th/$^{238}$U) and ($^{231}$Pa/$^{235}$U) ratios require similar melting rates, porosities, and extents for all parental magmas. Thus, the range in ($^{226}$Ra/$^{230}$Th), which is negatively correlated with Th concentration, reflects fractional crystallization over millennia after the magmas were emplaced into the crust. This precludes the $^{210}$Pb deficits from resulting from partial melting. Instead, the $^{210}$Pb deficits must have formed subsequent to magma differentiation and are interpreted to reflect several decades of magma degassing. Many young basalts erupted in a variety of tectonic settings are similarly depleted in $^{210}$Pb with respect to $^{226}$Ra, suggesting that they continuously degas over a period of a few to several decades, perhaps reflecting the time required to rise to the surface from deeper reservoirs. In some of these basalts, gas accumulation leads to the shallowest, most evolved, and earliest erupting magmas having the highest ($^{210}$Pb/$^{226}$Ra) ratios and sometimes $^{210}$Pb excesses.
Altered mineral uptake into fresh arc magmas: insights from U-Th isotopes

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Uranium–thorium isotope compositions of whole rocks, groundmasses and minerals from mafic to intermediate Andean arc magmas were determined to assess the influence of crustal stress on rates of pre-eruptive crystallization and the significance of crystal uptake. Volcanoes investigated include Lascar in the central Andes, situated in a compressional regime, and Callaqui and Lonquimay in the southern Andes, situated in a transtensional regime. In the southern Andes, Calbuco volcano, which experienced variations in the local stress field due to volcano unloading triggered by large debris avalanches, was also targeted. In U–Th equiline space, whole rock and groundmass coincide in each studied sample, and are close to secular equilibrium or in slight U-excess. No isochronal relationships are displayed by the mineral separates, although many are out of secular equilibrium. Further, (234U/238U) activity ratios of some mineral separates from the southern Andes are in disequilibrium and vary significantly between different phases of individual rock samples. With (234U/238U) > 1 in most separates, a case may be made for uranium assimilation by precipitation of uranium from hydrothermal fluids that are variably enriched in 234U. This process may also explain the high U/Th ratios of up to 2.4 of some of the mineral separates studied here. The combined data indicate that many crystals are foreign to the melts they are carried in, and that some mineral phases have experienced incipient weathering before their incorporation into the melt. The absence of 234U–238U disequilibria in Lascar suggest that incipient weathering is ineffective in the dry environment of the Altiplano, compared to the wet conditions of southern Chile. Using Calbuco as an example, we speculate that volcano loading may affect secondary alteration processes at depth, with alteration by a 230Th predominant recoil gain process prior to volcano unloading through large debris avalanche events. Future U–Th mineral isochron studies need to include 234U–238U data and provide sound evidence to show unequivocally that all minerals have grown from their host melt, for example through detailed petrographic and mineral chemical and/or isotopic analyses. The tightness of internal U–Th isochrons yielding precise crystallization ages is not sufficient in ensuring the reliability of the obtained ages. Extreme caution is warranted when U-series isotope data are employed to provide age constraints on preconceived ideas of magmatic evolution. Procuring abundant constraints on the petrogenetic processes operating beneath active arc volcanoes, independent from U-series constraints, is paramount.
High-resolution reconstruction of climate and environmental archives covering the last millennium is essential for understanding natural climate variability and superimposed anthropogenic effects on recent global warming. Precise dating of such archives is fundamental to their reliable correlation on global scales, especially between high-latitude annual-resolution archives such as ice cores, tree-rings and varved sediments and their lower-latitude counterparts such as speleothems and corals. In addition, recent accelerated climate change and dramatically intensified human activity have had severe impacts on coral reef ecosystems worldwide, resulting in bleaching, mortality, diversity loss and habitat deterioration. However, the exact timing of such events is poorly defined, and unresolved issues exist regarding their extent and significance, notably, what state and dynamics should be considered “natural”. In order to accurately determine the timing of past changes to precisions of a few years, a robust dating technique is required. Following the installation of a Nu Plasma multi-collector ICP-MS in our laboratory in 2010, we have specifically modified the instrumental configurations and developed a strict sample preparation protocol to enable rapid U-Th dating of young speleothem and corals of several to several hundred years of age, with precisions of ±1-10 years. This analytical protocol is capable of fully-automatic U-Th isotopic analyses of carbonate materials regardless of the dynamic range of $^{232}$Th/$^{230}$Th, or the age and purity of the sample. It takes advantage of the purpose-driven detector configuration characterized by two deceleration lens-filtered secondary-electron multipliers (SEMs) separated by four mass units, allowing for simultaneous static measurements of both U and Th isotopes in two sequential cycles (cycle #1: $^{229}$Th, $^{230}$Th, $^{233}$U, $^{234}$U, $^{235}$U and $^{238}$U with $^{230}$Th and $^{234}$U on SEMs; cycle #2: $^{229}$Th, $^{232}$Th, $^{233}$U, $^{235}$U and $^{238}$U with $^{229}$Th and $^{233}$U on SEMs). Sample and standard solutions as well as carry-over memories are measured using a modified auto-sampling system capable of handling a large number of samples on one rack. This protocol does not require U and Th to be measured separately, and the measurement is carried out fully automatically on 24/7 basis, and can be monitored by the operator remotely through Internet. Since its installation, the new MC-ICP-MS has dated several thousand young coral and speleothem samples for palaeoclimatic, palaeoenvironmental and archaeological applications, in addition to routine analysis of many other isotopes (such as Sr, Nd, Pb, Hf, and Cd).