

Granitoids, continents, life and puns A tribute to Hervé Martin

Abstract volume

Clermont-Ferrand
5th – 8th July 2023

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Laboratoire
Magmas &
Volcans



Hervé Martin

1951 - 2021

Foreword

When and how did the continents grow? When did lithospheric subduction begin? These scientific questions are also philosophical, because they raise questions about the Earth's ability, ultimately, about our own existence. Hervé Martin's scientific contribution to these questions is immense and decisive. Hervé Martin was a great petrologist who not only made a major national and international contribution to the scientific reputation of his laboratory, Magmas et Volcans (Université Clermont-Ferrand, CNRS, IRD), but also set an example by training some of the best specialists in the dynamics of the Archean Earth. Hervé Martin was also a man of great human qualities, always attentive and much appreciated by his students. An example for the French academic system, he was both a professor of University and a top-class researcher.

Stéphane Guillot

Deputy Director, National Institute of Universe Sciences

It is with great pleasure, but also with great emotion, that I write these few lines as an introduction to the workshop in tribute to Hervé Martin. Hervé came to Clermont-Ferrand in 1993 as a full professor, just a few years after I was recruited as a young CNRS researcher. So we worked side by side for almost thirty years. During all those years, I saw him invest himself passionately in his research and in the dissemination of knowledge, while at the same time taking part in tasks of collective interest, which he carried out with a great sense of responsibility. He was deputy director of the Laboratoire Magmas and Volcans (LMV), director of the LMV doctoral program for more than twenty years, and in charge of the Earth Sciences Master's program for more than ten years. As he was a geochemist and I was a petrologist, our respective scientific priorities at the time were not very conducive to collaboration, but that didn't stop us from starting to work together on two occasions: first on a project in exobiology, then on a project on the partial melting of a metasomatized mantle by an adakitic liquid as part of the supervision of a doctoral thesis (2008). It was during this thesis that we developed a new technique for extracting the first liquids in partial melting experiments of the mantle in the presence of volatiles.

Above all, I remember the coffee meetings at the Brasserie du Jardin (this was before the LMV moved to the Cézeaux university campus). Hervé and other geochemists and volcanologists would join petrology colleagues to talk about science and current events, or any other topic of interest. It was at such times that we could appreciate the full extent of Hervé's extensive knowledge, good humor and jokes.

Didier Laporte

Head of Department, Laboratoire Magmas & Volcans



Practical information

Dates and times

Wednesday 5th of July

- 17h Visit of the facilities at LMV: Experimental petrology, Geochemistry, Mineral collections
18h Icebreaker and buffet dinner

Thursday 6th of July

- 8h30 – 12h00 and 14h00 – 17h00 Scientific talks at IAE
17h45 Bus departs from Gare Routière to the Puy de Dôme
18h40 Train to Puy de Dôme departs from lower station
Conference dinner at Puy de Dôme summit restaurant
22h00 Train departs from summit of Puy de Dôme
22h30 Bus leaves from lower station
Ca. 23h00 Back in town

Friday 7th of July

- 8h30 – 12h00 and 14h00 – 17h00 Scientific talks at IAE
20h30 Open conference at IADT (see next page)

Saturday 8th of July

field trip to the Monts du Forez (leaders B. Barbarin & O. Laurent)

- 8h30 Bus leaves from Gare Routière
18h00 Bus in Roanne to drop of passengers
19h00 Bus returns to Clermont

Places

Icebreaker, welcome reception (Wednesday 5th):

Laboratoire Magmas et Volcans
Campus des Cézeaux
6 Avenue Bliaise Pascal
63170 Aubière
Tram A, stop **Cézeaux Pellez**

Scientific presentations (Thursday 6th and Friday 7th):

Amphithéâtre J. Olargier
IAE Clermont Auvergne - School of Management
11 Bd Charles de Gaulle
63000 Clermont-Ferrand
Tram A, stop **Lagarlaye**

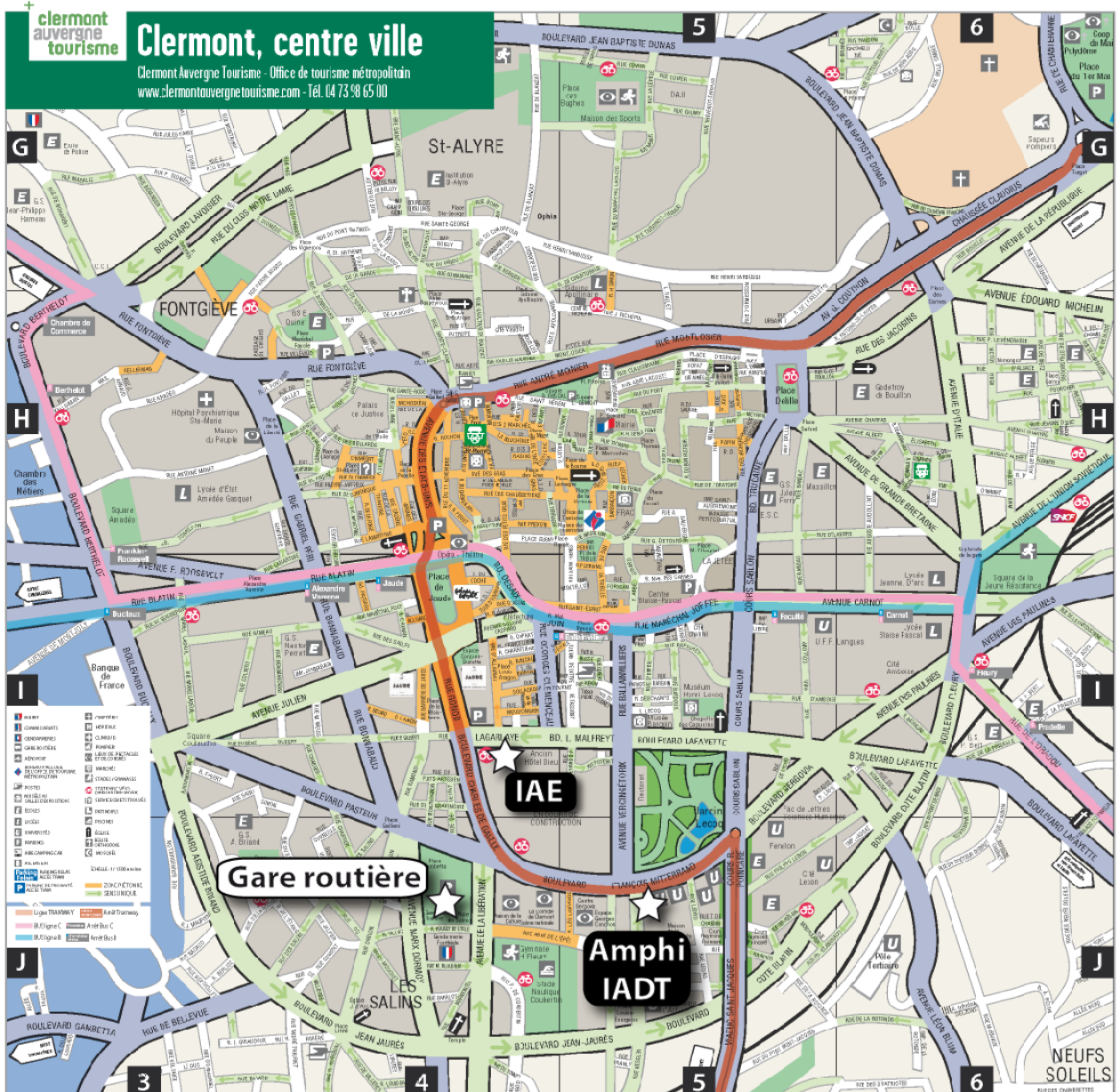
Public conference by N. Prantzou, Friday 7th evening

IADT (Institut d'Auvergne du Développement des Territoires)
51 Bd François Mitterrand
63000 Clermont-Ferrand
Tram A, stop **Universités**

Meeting point for bus (Thursday evening, Saturday morning)

Gare Routière de Clermont-Ferrand
Place des Salins
63000 Clermont-Ferrand
Tram A, stop **Lagarlaye** or **Maison de la Culture**

Clermont-Ferrand downtown



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Scientific abstracts





The chemistry of the Archean oceans

Francis Albarède

ENS LYON

Element flux to the ocean increases with continental surface exposed to weathering and atmospheric P_{CO_2} . The phosphorus record in sediments, which has no significant source in the ocean, and radiogenic strontium isotopes in Archean carbonates indicate that, prior to the Great Oxidation Event (GOE), subaerial expanses represented only around 20% of the modern continental surface, i.e. 7% of the Earth's surface. These simple, first-order observations contrast with the low oxygen content of the pre-GOE atmosphere and have so far received little attention in the assessment of early Earth marine chemistry. A reassessment of pre-GOE ocean chemistry is therefore warranted. Here, we discuss some of the geochemical cycles of the Archean world, that of protons, alkalinity, electrons and other electrolytes, and attempt to construct a first conceptual framework for chemical Archeoceanography. The scarcity of emergent land that characterizes the Archean and the low abundance of Archean carbonates and mudstones imply that the flux of alkalinity to the ocean was much lower than today, and therefore that the capacity of runoff to neutralize high-temperature hydrothermal fluids was less important. This reduced flow in turn leads to a drop in seawater pH and an increase in chlorinity. The absence of atmospheric oxygen allowed iron to be in its soluble Fe(II) form, reducing HCO_3 to CH_4 and releasing large quantities of protons. The low pH of the pre-GOE ocean and reduced alkalinity input, reinforced by low phosphorus input, explain the reduction in carbonate precipitation. Ocean chemistry has evolved under the control of two changing factors: Ocean chemistry has evolved under the control of two changing factors: (i) the balance between chemical respiration and hydrothermal fluxes, and (ii) oxygen pressure in the ocean and atmosphere. Iron concentration in seawater was controlled by high $[Fe^{2+}]/[H^+]^2$ ratios. As the temperature of hydrothermal fluids at mid-ocean ridges and other active volcanic edifices is determined by the expansion properties of seawater, the chemistry of hydrothermal fluids is controlled by the chlorinity of the ocean. Of all the major element cycles in seawater, those of Na, Mg and P appear to be unbalanced when flow falls below the modern value. The very low phosphorus content of the banded iron formations is not compatible with a major role for biological activity in the oxidation of dissolved Fe^{2+} in the Archean ocean. Prior to the GOE, banded iron formations were the main sedimentary sink for seawater cations, a role now played by carbonates. The alkalinity of seawater, which today is controlled by the Ca^{2+} - $CaCO_3$ couple, was controlled by the Fe^{2+} -magnetite or Fe^{2+} -ferrihydrite (maghemite?) couple. In simple language: the chemistry of the atmosphere and seawater depends essentially on the land surface and the chlorinity of the ocean. The absence of oxygen in the atmosphere allowed iron to remain in solution and reduce atmospheric carbon dioxide to methane. The pH of the ancient oceans must have been lower because there was less river water to neutralize the high-temperature acidic submarine hydrothermal fluids emitted at mid-ocean ridges. The limited continental surface deprived the sedimentary column of clay. Low pH and scarce phosphorus drainage led to rare carbonate deposits. This new model for Archean marine chemistry and geochemical cycles explains the chemical and geological observations of Archean and early Proterozoic rocks.

How and when did the continental crust form?

Nicholas Arndt

Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, Univ. Gustave Eiffel, ISTerre, 38000 Grenoble, France.

There are two main hypotheses for the formation of continental crust. One school argues that through most of geological time, granitoids formed at convergent margins. The other argues that from the Hadean to at least 2.5-3.0 Ga, the continental crust grew in a stagnant or sporadically mobile lid. In one version of this model, the lower part of thick mafic crust partially melts to produce felsic magma. In another, the lower part of a thick pile of mafic rocks converts to eclogite, sinks into the mantle, and partially melts. I argue that the latter processes are implausible. The lower part of thick oceanic crust consists of mafic-ultramafic cumulates, not basalt, and these rocks are dry. Missing is the fertile basaltic material and the water which are both needed to form granitic melt. Hydrated volcanics never are deeply buried, and any water released during dehydration migrates upwards into cooler rocks where it cannot trigger partial melting.

Subduction probably operated on Earth from 3.8 Ga. Archean subduction zones were shallow, short-lived and transient but were capable of transporting hydrated oceanic crust to depths of 100km as is needed to form felsic magmas. The presence of subduction zones does not necessarily imply the operation of plate tectonics.

The changes said to signal a major change in geodynamic regime around 3 Ga are better explained as the nexus of several ongoing processes: progressive growth of felsic crust particularly during major pulses at 2.7 and 2.5 Ga; the emergence of land and a drop in sea-level; and falling temperatures in mantle and crust.

The Paleoproterozoic record of the São Francisco craton from zircon U-Pb and Hf isotope systematics

M. Botero¹, J. Vervoort¹ and V. Tieppo-Meira²

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² Institute of Geosciences, University of Campinas, Campinas, São Paulo, Brazil

The Paleoproterozoic (3.6-3.2 Ga) is a pivotal time in Earth's history. This time was marked by major events, including large-scale craton formation, important crustal growth episodes, and the likely transition in tectonic modes from hot-stagnant lid to active lid. Therefore, the Paleoproterozoic crustal record provide links to fundamental planetary processes in the evolving Earth. In this research we focus on the oldest known rocks in South America: Paleoproterozoic gneisses in the Mairi complex in the São Francisco craton (SFC) in Brazil. Here, we report new zircon U-Pb and Hf isotope data and whole-rock Hf and Nd isotopes from gray gneisses, granites, and a leucosome from the Mairi complex. The U-Pb data yield well-defined populations with ²⁰⁷Pb/²⁰⁶Pb ages spanning from 3.60 to 3.59 Ga. One gneiss yields a ²⁰⁷Pb/²⁰⁶Pb age of 3.4 Ga with presence of 3.6 Ga inherited zircons. The Hf isotopic compositions in all samples are consistently subchondritic with a narrow range of initial $\epsilon_{\text{Hf}(3.6\text{Ga})}$ between -1.7 and -3.7. The bulk-rock data, on the other hand, exhibit a large range in Hf and Nd isotope compositions with initial $\epsilon_{\text{Hf}(3.6-3.4\text{ Ga})}$ ranging generally from +2 to -5 with a couple of outliers with $\epsilon_{\text{Hf}(i)}$ of -8 and -14 and $\epsilon_{\text{Nd}(3.6-3.4\text{ Ga})}$ with mostly positive values from +7 to 0, with outliers at -4 and -17. Open-system behaviour due to post-crystallization tectono-thermal events and/or mixing of different components during analysis result in the isotopic variability in whole-rock data. Our interpretations rely on the robust zircon Hf isotope data with extremely homogeneous compositions in samples where age can be well-constrained. The subchondritic initial compositions of the ~3.6-3.4 Ga gneisses indicate derivation from a homogenous reservoir and are consistent with melting and/or reworking/assimilation of ~3.8 Ga pre-existing chondritic crust. Our interpretation contrasts with previous work that suggests Hadean-early Eoarchean precursors for these rocks based on the assumption of the derivation from a depleted mantle reservoir. Rather we suggest that the Hf isotope data reported in this study for the 3.6-3.4 Ga Mairi complex gneisses are consistent with derivation from melting of a ~3.8 Ga precursor of broadly chondritic composition, in agreement with the dominant Hf isotope composition of other 3.8-3.6 Ga gneisses worldwide.

Granitic magmatism in the South Armorican Domain

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Partial melting in the continental crust is widespread in the late stages of orogenic evolution, particularly during gravitational collapse stages. This is well documented in the Variscan crust of France, in both the Massif Central and South Armorican domains. In the latter, the late Variscan evolution is marked by exhumation of lower continental crust (migmatitic unit), the working of large crustal-scale strike-slip and extensional shear zones, which accommodate exhumation of the lower crust, and the emplacement of syntectonic granites along them. Migmatites and granites are cut by granitic aplites and pegmatites which, at first glance, could be seen as late magmatic emplacement related to final crystallisation stages of parental granites.

We have performed high-resolution geochronological dating of one of these granites (the Quiberon granite) and of the dykes that cut through. The Quiberon granite emplaced within a detachment zone accommodating east-west extension. We found three periods of magmatism separated by about 10 to 15 millions years. The three stages of granitic emplacements relates to three distinct episodes of partial melting in the deep, exhuming continental crust. The late magmas (aplites and pegmatites) likely formed through biotite-out dehydration-melting reactions during lower crust exhumation, whereas the former main granitic body formed through muscovite-out dehydration-melting reactions, comparable with the ones recorded in the migmatites units now exposed underneath the granites. This repeated magmatism provides clues to understand the genesis of late orogenic rare-metal granites.

In the underlying migmatites, vertical granitic dykes display orientations compatible with the regional horizontal east-west extension. The age of these dykes is similar to the age of one of the three episodes of the granitic magmatism in the overlying Quiberon granite. Thus, this system offers a unique opportunity to characterize differentiation of crustal granites during their migration towards the surface. Actually, fractional crystallisation occurs during vertical migration, *en route* to the surface.

Mineral-whole rock isotope fidelity? A comparative study of Hf-Nd-O from high Ba-Sr granites

Emilie Bruand¹, Craig Storey², Mike Fowler², Bruno Dhuime³, Regis Doucelance⁴

¹Geo-Ocean Lab., CNRS, Univ. Bretagne Occidentale, France

²University of Portsmouth, UK

³Geosciences Montpellier Lab., Univ. of Montpellier, France

⁴Magma and Volcanoes lab., UCA, France

It is well-established that lanthanide rare earth elements (REEs) have the potential to record the nature and source characteristics of their host magmas, in both whole-rock and their minerals. Accessory minerals that concentrate REEs are especially useful in crustal evolution studies, both for their elemental and isotopic information; the classic and unrivalled example being zircon. Approaches using a single radiogenic isotopic system, or one radiogenic and one stable isotope system (e.g., Hf and O) in one REE-bearing mineral (usually zircon) are common, but those involving multiple isotopes in several minerals remain scarce despite offering many advantages. Importantly, the latter approaches also allow comparing different techniques and provide evidence on whether isotopic systems were disturbed by secondary processes. This contribution documents several isotopic systems within the abundant accessory mineral of Caledonian high Ba-Sr granitoids from Northwest Scotland. We present a multi-isotope study of titanite, zircon and apatite from two localities (Strontian and Rogart), which were selected for their contrasting whole-rock isotopic signatures - the former deriving from a depleted mantle source, whereas the latter derived from a strongly enriched mantle source. New in-situ Sm-Nd in titanite and apatite and Hf in zircon isotope data are discussed and compared with in-situ oxygen isotope data previously published for the same samples. An internal consistency is observed for Nd isotopes in apatite and titanite. Nd isotopes values for both minerals strongly correlate with Hf isotopes in zircon. Isotopic data at the mineral scale confirm the Strontian and Rogart source characteristics previously defined from whole-rock isotope data, with the Rogart having a more enriched signature than the Strontian source along the "Caledonian Parental Magma Array" (CPMA). Importantly, the contribution of sediments in the CPMA source(s) can be estimated from a diagram combining Sm-Nd isotopic signatures and $(La/Sm)_N$ in apatite and titanite. Overall, we demonstrate that detailed petrogenetic records are not only available in zircons but also in magmatic titanite and apatite, and we suggest that integrated multi-mineral approaches have potential to maximise constraints from in-situ mineral isotope geochemistry.

Geochemical models for the origin of Li-F rare-metal granites

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Many hard-rock rare-metal deposits are spatially associated with highly peraluminous Li-F granites for which two competing but non-mutually exclusive genetic models exist: extreme fractionation of a less evolved peraluminous magma or low-degree partial melting of a common (or pre-enriched) crustal source. Several Li-F rare-metal granites have been described in the Variscan French Massif Central, including the economic grade Beauvoir leucogranite. In this study, we performed forward geochemical modelling to investigate the respective effects of P-T conditions of melting and protolith type on the Li-F endowment of crustal melts. The methodology couples the output of phase equilibrium calculations (performed using PerpleX) with a set of Li-F partition coefficients. Typical components of the Variscan crust were considered as source rocks: a fertile metapelite, a restitic metapelite and a peraluminous orthogneiss. Modelling results indicate that the melts produced at low pressure (< 5 kbar) are depleted in Li by a factor two compared to those formed at medium pressure (7 kbar) because of peritectic cordierite crystallization. Besides, Li and F are decoupled during metapelite melting: Li-richest melts (~200-400 ppm) are produced below 750°C (by muscovite breakdown) whereas F-richest ones (~0.15 wt%) are produced above 825°C (by biotite breakdown). Restitic metapelites produce melts with Li contents close to that of fertile metapelites (~175 ppm), richer in F (up to 0.4 wt%) but still far from the range exhibited by Li-F rare-metal granites. In contrast, muscovite and biotite breakdown in orthogneiss occurs within a narrow temperature range (690-730°C) allowing the production of melts concomitantly enriched in Li (~600-1350 ppm) and F (0.3-1 wt%) which, following 80-90 wt% fractional crystallization, generate liquids akin to rare-metal granites (~10000 ppm Li; ~2 wt% F). Hence, peraluminous granite re-melting and subsequent magmatic differentiation appears as a viable mechanism to form Li-F rare-metal granites. In this frame, their unusual abundance in the French Massif Central should be tied to its peculiar pre-orogenic evolution which featured multiple episodes of crust reworking and peraluminous felsic magmatism.

Formation of the Solar System and the Earth

Aurélien CRIDA¹

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In this presentation, I will briefly show the main steps between a cloud of gas in the interstellar medium (a nebula) and a planetary system, in particular our own Solar System. The main physical processes leading to the formation of a disk, the sedimentation and aggregation of dust, the growth of solids and the accretion of gas by the cores of the giant planets will be shown, with a special attention paid to the composition of the solids.

Dynamical processes are key to sculpt a planetary system. They allow solids to change orbit and therefore to alter, mix the compositional gradient which appears as the temperature decreases away from the central star. We will show how Jupiter may have brought in the main asteroid belt asteroids that were formed further in the solar system, and how a global instability among the giant planets was necessary to sculpt the present architecture of our planetary system.

Finally, we will show how the Earth formed after the gas disk dissipated, through giant impacts. The last of these impacts engendered the Moon, probably a hundred million years after the formation of the Solar System.

TTG generation by fluid-fluxed crustal melting: Direct evidence from the Proterozoic Georgetown Inlier, NE Australia

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Across the Archaean to Proterozoic transition, the composition of newly-formed felsic continental crust changed from tonalite–trondhjemite–granodiorite (TTG) to calc-alkaline granitoid, possibly coinciding with the emergence of plate tectonics. Nevertheless, TTG suites were sporadically produced in Proterozoic and Phanerozoic orogenic belts, and such occurrences may provide petrological and tectonic insights into the formation of ancient continents. Here we demonstrate that the ca 1560 Ma Forest Home TTG plutonic suite in the Georgetown Inlier, NE Australia, was derived from partial melting of spatially-associated mafic rocks in a post-collisional setting. The studied TTG rocks have a 'high-pressure' geochemical signature, with elevated Sr, low heavy rare earth element and low high field strength element contents. Established petrogenetic models suggest they were derived by partial melting either of hydrated basaltic crust at >70 km depth or enriched lithospheric mantle, or by fractionation of lower-pressure mafic magmas. Using phase equilibrium calculations and trace-element modelling, we show that the geochemical signature of the Georgetown TTG likely resulted from fluid-fluxed crustal melting at relatively shallow depths (25–35 km), consistent with field observations and the inferred metamorphic evolution of the inlier. Our results suggest that the chemical variability of TTGs can reflect the variable availability of fluids rather than depth of melting, which has implications for tectonic processes responsible for the formation of early continental crust.

The granite basement of the Chicxulub impact structure peak ring: petrography and geochemistry

J-G. Feignon¹, S. J. De Graaff², L. Ferrière³, P. Kaskes^{1,4}, T. Déhais^{1,4}, S. Goderis¹, P. Claeys¹, and C. Koeberl⁵

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A unique feature of complex impact crater formation is to move target lithologies from depth to the surface in the form of central uplifts or peak rings, providing insights into the nature and composition of the subsurface in the impact area. For the first time, a large, nearly continuous crystalline basement unit (~600 m thick), was recovered within the Chicxulub impact structure (200-km-diameter, ~66.05 Ma) peak ring, which was drilled during the joint IODP-ICDP Expedition 364 in 2016. The bulk of the basement consists of pervasively deformed, fractured, and shocked granite. This offered a unique opportunity to constrain the chemistry and sources of the granite; how it was affected by the impact event; and to refine the Yucatán Peninsula basement geology. Detailed petrographic and geochemical investigations of 41 granite samples, including Sr-Nd isotopic analyses for 16 samples, were conducted. The granite is mainly equigranular, coarse-grained, and holocrystalline. The bulk mineral assemblage (grain size from ~0.5 to ~4 cm) consists of orange to brownish K-feldspar (orthoclase, ~25-50 vol%), plagioclase (~15-35 vol%), quartz (~15-35 vol%), and, to a lesser extent, biotite (~1-5 vol%, commonly chloritized). The granites are relatively homogeneous in terms of major (66.7-77.5 wt% SiO₂) and trace element compositions, and are different compared to felsic clasts recovered within other drill cores from the Chicxulub. The granites are part of the high-K, calc-alkaline metaluminous series, and have high Sr/Y and (La/Yb)_N ratios, which are typical for adakitic rocks. However, other criteria (such as Al₂O₃, MgO, and Ni contents, Mg#, K₂O/Na₂O ratio) do not match the adakite definition. These results are consistent with previous studies, supporting that the granite intruded the Maya block during the Carboniferous, in a volcanic arc setting with crustal melting of a minor Grenvillian component (according to initial (ε_{Nd})_{t=326Ma} (from -4.0 to +3.2) and the TNd_{DM(t=326Ma)} model ages of ~1.1 Ga), related to the closure of the Rheic Ocean during the assembly of Pangea. Then, the granite was altered/deformed by two distinct hydrothermal events: (1) a hydrothermal metasomatic event, possibly related to the first stages of Pangea breakup (~273±21 Ma, according to Rb-Sr errorchron and initial ⁸⁷Sr/⁸⁶Sr_{t=326Ma} compositions), and (2) the post-impact hydrothermal alteration linked to a long-lived (>1 Myr) hydrothermal system within the Chicxulub impact structure.

Textural and chemical constraints from polygenetic titanite: insight from Late-Archean Closepet batholith (Dharwar craton)

Wiktoria Gmochowska¹, Ewa Słaby², Robert Anczkiewicz³, Jiri Slama⁴, Jakub Ciężła¹, Gabriela Kozub-Budzyń⁵, Sourabh Bhattacharya⁶

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Accessory minerals are used to describe the path of igneous, metamorphic, and hydrothermal changes. The best for this purpose are minerals with a complex composition, where a complex scheme of substitutions of trace elements is observed. Here, titanite is used as a tool to discriminate the origin in the Late-Archean Closepet batholith (Dharwar craton, southern India), where post-magmatic processes were previously documented (Słaby et al. 2021).

The laser ablation ICP-MS data have been obtained on a few samples from the northern, central and southern parts of the batholith. Titanites in the Closepet granitoid occur in five generations which are distinguished by the differences in their composition and textures (visible on the BSE images): (1) an alteration product of biotite, forming fine-grained lenticular inclusions enclosed within biotite; (2) overgrowths harbouring Fe-Ti oxides; (3) hydrothermal titanite characterized as zoned to patchy textures with secondary fractures and veinlets; (4) homogeneous titanite, interstitial to other accessory minerals; (5) magmatic titanite with observed oscillatory zonation. The statistical bootstrap approach of Argue & van Haren (application description in Durand et al. (2015)) which quantifies the mass/concentration changes was chosen to illustrate the differences in trace element composition. Our preliminary results show that all types of titanites demonstrate the loss of Y and rare earth elements (REEs), however, in different magnitudes, compared to magmatic titanites. The loss of light REE is observed in types 2 and 4, whereas the loss of heavy REE is observed in type 3. Type 1 is characterized by the loss of all REE in almost similar manner. Other elements, such as Th, K, Rb, and Sr, show deviations of loss or gain depending on the type of titanite, indicating post-magmatic origin.

Textural subtypes and geochemical variations of titanite track the evolution of the Closepet granitoid from magmatic to post-magmatic stages and fluid-rock interaction event, indicating multistage processes.

The work was funded by the NCN Project UMO-2018/31/B/ST10/01060.

Why Are There No Low- $\delta^{18}\text{O}$ Magmas in the Andes?

Chris Harris and Connie Sigauke¹

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Globally, low- $\delta^{18}\text{O}$ (<5.7‰) magmas are rare, especially in subduction zone settings. Here, we report the variation in oxygen isotope composition of rocks across the Central Volcanic Zone (CVZ) of the Andes, ranging in age from about 12 Ma to recent. The analysed samples include rocks with compositions from andesite ($\text{SiO}_2 = 62$ wt.%) to dacite ($\text{SiO}_2 = 72$ wt.%) and ignimbrite sheet deposits, and lavas associated with younger volcanoes and lava domes. We actively targeted highly altered rocks ($n = 136$) for bulk-rock analysis. The $\delta^{18}\text{O}$ value of quartz phenocrysts range between 5.0 to 10.7‰, whereas the bulk rock of the same samples ranges from 5.0 to 22.3‰. The $\delta^{18}\text{O}$ values for quartz phenocrysts are consistent with a hybrid compositional character, that was 70% crustal and 30% mantle-derived basaltic andesite. The δD values of biotite phenocrysts are similar to those of bulk rock (-138 to -71‰). Therefore, there is little evidence for low- $\delta^{18}\text{O}$ magmas in the CVZ, and the lowest value (5.0‰) was found in one hydrothermally-altered sample. There is no evidence for high-temperature interaction between rocks and surface water.

Explanations for why low- $\delta^{18}\text{O}$ rocks and magmas are not observed in the Andes CVZ are as follows. (1) They are present but have not yet been found. (2) Easily fusible high- $\delta^{18}\text{O}$ material exists at depth and high-level contamination by hydrothermally-altered, low- $\delta^{18}\text{O}$ rock at shallow levels cannot lower the magma $\delta^{18}\text{O}$ sufficiently (Grunder, 1987; Feeley and Sharp, 1995). (3) The heat input was insufficient to melt and/or assimilate enough hydrothermally-altered material. Nearly all low- $\delta^{18}\text{O}$ magmas are associated with proposed mantle plumes (e.g. Bindeman, 2008). (4) The absence of significant extension did not allow the penetration of water to sufficient depths to interact with rock at high-temperatures. Folkes et al. (2013) suggested that the lack of low- $\delta^{18}\text{O}$ magmas in the CVZ was largely the result of climatic conditions of the central Andes, where low precipitation, combined with high evaporation rates and high elevation, limited the supply of meteoric waters, and all played significant roles in the lack of low- $\delta^{18}\text{O}$ magmas in the region. However, the CVZ and other arc volcanoes, e.g. Merapi (Darmawan et al., 2022) and Soufrière (Heap et al., 2022), share similar ranges of $\delta^{18}\text{O}$ and δD . This is consistent with a common process where fluid is dominated by subduction-related magmatic fluid that limits the influx of surface water.

Sanukitoid granitoids and related younger plutonic rocks in the Karelia Province

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The western and central parts of the Neoproterozoic Karelia Province contain compositionally variable late- to post-tectonic plutonic rocks with ages younger than those of the older dominant TTGs (tonalite-trondhjemite-granodiorites). The plutonic rocks can be divided into four groups: 1) 2.74-2.71 Ga sanukitoid granitoids, 2) 2.70 Ga quartz diorites, 3) 2.74-2.68 Ga alkaline-enriched quartz syenites and diorites, and 4) crust-derived granitoids. The first and most studied group of the sanukitoid granitoids shows a prominent geochemical signature of combined high Mg-Ni-Cr and high K-Ba-Sr contents. The second group, quartz diorites, overlap partly with the sanukitoid group, but shows lower Ba-K-LREE contents. The third group includes alkaline-enriched rocks that form a small group of intrusions from quartz syenites to quartz monzonites, diorites and gabbros. They are characterized by high contents of alkalis and show enriched K-Ba-Sr signatures. Their variable Mg-Ni-Cr contents could have been formed by the fractionation of olivine and clinopyroxene in the system. In general, a high K-Ba-Sr signature implies heterogeneous enriched mantle sources. Zircon O-isotope values indicate fractionation at low temperatures. The last group of plutonic rocks consists of crust-derived granitoids, mainly granodiorites and leucocratic granites. Their composition and heterogeneous zircon population points clearly to partial melting of the pre-existing crust. Overall, in the Karelian Province, TTG magmatism changed at 2.72-2.68 Ga to more variable plutonism derived from different sources from enriched mantle to crust.

The R language: an ultimate recalculation, plotting and modelling environment in igneous geochemistry (GCDkit turns twenty!)

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Today, almost any project dealing with igneous petrogenesis brings a large body of geochemical data – bulk and/or mineral analyses. Their recalculation, plotting, statistical treatment, and numerical modelling require productive and freely available software tools. It is widely accepted that such packages should be written in an open-source, lucid, and platform-independent scientific programming language, e.g., R or Python. The *GCDkit* R package[1] has been proven a popular and powerful environment for the interpretation of the whole-rock elemental–isotopic data from magmatic rocks[2]. Furthermore, *R* and *GCDkit* provide a great environment for geochemical modelling, and numerous courses have been organised worldwide to explain the principles[3]. The current *GCDkit* 6.1 is a mature, platform-independent package that can be operated from a GUI or by external scripts. On its 20th birthday, we release *GCDkit.Mineral*, a package for treatment of mineral analyses acquired by microbeam techniques[4]. Apart from recalculation to apfu, analyses can be recast to structural formulae, end-member proportions, or classified by IMA rules. The calculation options are stored externally and can be easily tweaked. Available are assorted graphical and statistical tools, supplemented by the standard R. Ongoing *GCDkit*-related projects include integration of the MELTS thermodynamic package[5], using *GCDkit* for plotting and complementary trace-element computations. Similar interface is being developed for the *Rcrust*, a well-established package for thermodynamic modelling of crustal anatexis[6]. Our ultimate aim is a closer integration of most of the existing free software tools into a single *R/GCDkit* environment that can be programmed, *inter alia*, via Jupyter-style Python-driven *Jupyter* notebooks[7]. This would enable easier recalculation and visualization of the geochemical datasets, both real and modelled, and contribute to reproducibility of the research.

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Archean tectonics and crustal evolution in the Dharwar craton, southern India

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The Dharwar craton is a titled section of Archean crust that formed between 3600 and 2500 Ma and exhibit typical Archean tectonic features. This craton comprises grey gneisses, such as TTGs and transitional TTGs, volcano-sedimentary greenstone sequences, calc-alkaline to potassic gneissic plutons. Strain fabrics together with geophysical and petrological data, metamorphic records, geochronological, elemental and isotope tracers reveal that the Dharwar craton formed by assembly of three blocks (western, central, and eastern) with independent thermal and crustal histories.

The western block preserves the oldest cratonic nucleus. U-Pb zircon ages reveal that granitoids formed during three main stages (3430-3400, 3350-3280 and 3230-3150 Ma), with age inheritance up to 3600 Ma. Elemental and radiogenic isotope geochemistry suggest that granitoids formed by low- to high-pressure melting of juvenile mafic source with no or minor involvement of Eoarchean crust. The large variation in trace element contents and Nd isotope data for 3400-3200 Ma komatiites suggest that they originated from depleted to primitive mantle reservoirs with minor crustal contamination.

The central block contains greenstone sequences with gneisses of basaltic, boninitic, and adakitic affinity surrounded by minor granitoids of TTG, transitional TTG and sanukitoid affinity. The central block formed in three stages (3300-3000, 2700-2600 and 2560-2520 Ma). The 3300-3000 Ma TTGs are geochemically and mineralogically similar to those from the western block and their precursors probably formed by melting of juvenile mafic sources at different depths. The 2700-2600 Ma transitional TTGs geochemistry suggest derivation from sources involving mafic crust and sub-arc mantle. The 2560-2520 Ma sanukitoids very likely formed from a dominant juvenile enriched source with minor crustal input.

The eastern block comprises lithological assemblages of minor 2700-2570 Ma transitional TTGs, thin volcanic-dominated greenstone belts, 2560-2540 Ma sanukitoids and abundant 2530-2520 Ma diatexite. The transitional TTGs are similar to those of the central block but show more primitive Nd isotope signatures implying depleted juvenile sources. Sanukitoids show similar elemental compositions but less enriched in incompatible elements and show primitive Nd isotope signatures. Combined petrological and geochronological constraints together with tectonic fabrics analysis argue for three crustal blocks assembled into a cratonic framework during 2560-2500 Ma.

Slab melting in modern subduction zones: myth, oddity or widespread?

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Arc magmas are characterised by relative depletion in High Field Strength Elements (HFSE, such as Nb, Ta and Ti) relative to other similarly incompatible elements. A traditional view is that this geochemical signature is linked to the insolubility of HFSE in saline fluids released from the downgoing slab into the mantle source of arc basalts. Alternatively, such signatures can also be related to the melting of oceanic crustal lithologies (sediments and/or crust) in the presence of residual rutile (TiO₂). As such, discriminating between slab melts and saline fluid as the mechanism behind this signature with conventional trace elements and radiogenic isotopes tools is difficult.

The recent development of Ti stable isotopes as a tracer of oxide-melt equilibrium in magmatic studies provides an opportunity to test these models. Rutile hosts Ti in a different coordination to silicate melts (6- vs. 5-fold) and has been demonstrated to preferentially host lighter isotopes of Ti. As a result, modelling of experimental slab melts studies at sub-arc conditions show these display $\delta^{49/47}\text{Ti}$ of 0.2–0.3‰ higher than peridotite melts. If slab melting contributes to arc magmatism, primitive arc magmas are thus expected to show clearly elevated $\delta^{49/47}\text{Ti}$ compared to mid-ocean ridge basalts (MORB).

We test this hypothesis by measuring the Ti isotope composition of a suite of 37 primitive arc lavas ($\text{Mg}\# > 60$) from 8 global arcs covering the full range of subduction zone kinematic parameters. Primitive arc lavas show a large range in $\delta^{49/47}\text{Ti}$ that partially overlaps with MORB ($\delta^{49/47}\text{Ti}$ c. 0‰) but extends to notable heavier values, which we interpret as a slab melt signature that is present in all arcs investigated, suggesting that slab melting is a widespread feature of modern subduction zones. This indicates that, in extreme cases, silicic slab melts can traverse the mantle wedge with little modification and erupt at the surface. More commonly, hydrous slab melts can trigger additional partial melting of the mantle wedge to form arc magmas that are a blend of slab- and peridotite melt.

Phase equilibria constraints on the anatectic origin of peraluminous granites parental to tungsten deposits: a case study in NW India

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The majority of the tungsten deposits owe their origin to S-type peraluminous granites. Magma differentiation plays a key role in the generation of such fertile granites, further referred to as W-granites. However, recent studies highlight two additional key factors for generation of W-granites: *first*, participation of highly-weathered sediments in anatexis, and *second*, melt segregation at <750 °C. Investigations to testify these factors are clearly lacking and this study examines their relevance. In particular, we focus on the origin of Balda Granite (BG), a peraluminous, shallowly-emplaced (~7 km) intrusion, parental to W-rich ore bodies in the Sirohi region of NW India. Several prior studies speculate Sirohi Group Metapelites (SM) as the protolith for BG. Using open-system phase equilibria modelling, we explore the potential of SM as a protolith, and put constraints on the anatectic origin of BG.

Geochemical data suggests that SM is a chemically mature, K-rich weathered residuum. SM exhibits compositional peculiarities compared to global average pelitic rocks and other metasediments in the terrane. Using two SM samples as starting compositions for phase equilibria modelling, the modelling results demonstrate that muscovite- and biotite-dehydration reactions produce approximately 9.5 and 13.2 wt% melt, respectively, during the prograde path at temperatures ranging from 676–742 °C and 754–868 °C. Si, K, Al, and Fe contents of the cumulative melt increased with progressive anatexis. The results suggest high-T (>800 °C) stability of the peritectic garnet, which is abundantly observed in the leucosome-dominated migmatitic patches. Cumulative melt extracted till 868 °C was chosen to model the crystal fractionation along three polybaric gradients of 30, 45, and 60 °C/kbar. As the modelled anatectic melt cools, the crystallization and extraction of high-T mafic phases, decrease the peraluminosity and maficity of the residual melt. With the intermediate cooling gradient of 45 °C/kbar, the melt achieves complete crystallization at ~7 km, the depth at which the BG had been emplaced, and evolves into a residual (fractionated) melt comparable to BG in terms of peraluminosity, and major and trace element (Lu, Sc, Dy, Y, Yb) chemistry. Thus, high-T anatexis of SM and anatectic melt cooling at the maximum gradient of 45 °C/kbar appear to promote BG generation. We contend that while the protolith and anatectic history undoubtedly affect the metal budget of S-type granites, the influence of anatectic temperature and W/Sn ratio of resulting melt on the formation of W-granites, still remains arguable.

Petrology of Cupim Pluton leucogranites: implications for Paleoproterozoic orogeny in the São Francisco Craton, Brazil

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S-Type granite magmatism commonly occurs in late stages of orogenies and between distinct crustal blocks. The Paleoproterozoic era witnessed the formation of early global-scale orogenic belts. In the São Francisco Craton (Eastern Brazil) ~2.1 Ga belts were developed and accreted as continental and island arcs to a foreland Archean nuclei. However, few recognized S-type granites within these terranes provide valuable insights into the collisional event and the last episode of magmatism before crust stabilization. S-type granites also reveal the dominant local sedimentary chemical and isotopic compositions, including distribution of detrital zircon ages when inherited cores are preserved. This study focuses on the mineral and whole-rock geochemistry, as well as zircon U-Pb geochronology, Lu-Hf, and Si isotope data for Cupim Pluton leucogranites, located in the Mineiro Belt — an orogenic belt developed during the Siderian-Orosirian period in the Southern São Francisco Craton.

The Cupim Pluton, covering an area of over 80 km², predominantly consists of two leucogranite lithotypes: (i) Mnz-bearing Ms-Bt-monzogranites and (ii) Grt-bearing Ms-Bt-monzogranites. These lithotypes exhibit peraluminous to strongly peraluminous compositions (ASI > 1.1), high-K, low-Mg#, low-CaO/Na₂O, and high SiO₂ content (71-75 wt.%). The pluton is characterized by elevated concentrations of incompatible trace elements (LILE, HFSE, LREE, and HREE), low Sr/Ba ratio (<0.4), and negative Eu/Eu* anomalies (0.22-0.11). These data are consistent with the derivation of the pluton from a metasedimentary source. Geochemical variations can be attributed to heterogeneities in the metasedimentary source and fractional crystallization of monazite and garnet. Zircons from this pluton indicate an emplacement age of 2000 Ma, with abundant inheritance of older events recorded in cores (>2.5 Ga). Cupim zircons (Th/U > 0.1) display a wide range of negative $\epsilon_{\text{Hf}(t)}$ values between -1 and -12, with an average of -8.1 ± 0.7 , suggesting a crust reworking origin for the parental magma. The Si isotope signatures confirm the S-type affinity as well as low-temperature crystallization in a highly silica-saturated magma.

From slab melts to crystal mushes: what are Archean TTGs?

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Meta-igneous rocks of the tonalite – trondhjemite – granodiorite (TTG) suite represent the dominant component of Archean grey gneiss units and are virtually absent from post-Archean crust. These rocks are, therefore, extensively studied to understand the mechanisms of continental crust nucleation and geodynamic settings of the early Earth.

Concepts and models about TTG significance and genesis have considerably evolved over the last decades. The pioneering work of Hervé Martin led to the idea that TTGs represent former melts of subducted Archean mafic crust. This interpretation has been extensively debated, in particular in the past 10 years during which a number of new models were introduced for TTG genesis. Some consider that the properties of TTG melts can be equally explained by source conditions (notably in terms of pressure and water activity) that can be met at the base of thick Archean mafic crust, not necessarily requiring subduction. Others entirely reconsidered the significance of TTGs, challenging the view that these represent melts compositionally unchanged from their source region to their final crystallization. This includes models considering TTGs as fractionated melts from a mantle-derived magma; or even mid- to upper crustal crystal mushes in which dynamics of crystal accumulation and melt extraction control bulk-rock geochemical compositions.

This diversity of interpretations largely results from the fact that TTGs have long been considered from a purely bulk-rock geochemical perspective. There are, however, several possible “geological pathways” for an igneous rock to acquire a certain chemical composition. These different possibilities are, in addition, not mutually exclusive and not necessarily tied to a specific geodynamic environment. Finally, it must be kept in mind that most TTGs are now part of complex grey gneiss units, such that polyphase deformation and metamorphism may have overprinted their original, magmatic characteristics. We, therefore, emphasize that TTGs should be considered in a more integrative way, by interpreting bulk-rock compositions within the perspective of their geological environment, crustal history and in combination with other petrological and geochemical tools, in particular accessory minerals (zircon, apatite, titanite).

Geochemical characterization of Tres Lagunas Granite, Ecuador

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A geochemical and mineralogical study has been carried out on samples of Triassic Granite Tres Lagunas, Ecuador, to determine the type of rock (granitoid), the tectonic setting of formation and possible geochemical anomalies of some critical elements (Li, REE, among others). According to the geochemical data (XRF and ICP-OES) and the mineralogical composition (XRD), the samples correspond to S-type granite, including: granites, monzogranites, and granodiorites. Mineralogically are mainly composed of quartz, plagioclase, orthoclase, biotite and muscovite.

Geochemical anomalies of La (> 115.50 mg/Kg), Rb (> 94.32 mg/Kg), Sr (> 61.06 mg/Kg) and Zr (> 128.78 mg/Kg) were detected, as well as sub-anomalies of Ce (> 483.26 mg/Kg), Co (> 65.43 mg/Kg), Fe₂O₃ (> 1.81 wt. %), Gd (> 7.62 mg/Kg), Li (> 64.84 mg/Kg), Mo (> 14.72 mg/Kg), Nd (> 245.36 mg/Kg), Th (> 67.80 mg/Kg) and Y (> 51.25 mg/Kg), applying geostatistics.

Using the geochemical data, the tectonic setting of the rock samples was determined, indicating active continental margin and passive continental margin, related to a rift.

Extensive N-fixation by volcanic lightning during large explosive eruptions

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This is the last scientific topic I discussed with Hervé, few weeks-months before he passed away. He was very supportive and enthusiastic about these preliminary results and I would like to show him today where we are on the subject.

Most of the nitrogen (N) accessible for life is trapped in dinitrogen (N₂), the most stable atmospheric molecule. In order to be metabolised by living organisms, N₂ has to be converted into

biologically assimilable forms, so-called fixed N. Nowadays, nearly all the N-fixation is achieved through biological and anthropogenic processes. However, in early prebiotic environments of the Earth, N-fixation must have occurred via natural abiotic processes. One of the most invoked processes is electrical discharges, including from thunderstorms and lightning associated with volcanic eruptions. Despite the frequent occurrence of volcanic lightning during explosive eruptions as well as convincing laboratory experimentation and theoretical modelling, no evidence of substantial N-fixation by volcanic lightning has been found in any geological archive.

Here we report on the discovery of significant amount of nitrate in volcanic deposits from large eruptions, which are well correlated with the concentrations of species directly emitted by volcanoes (sulphur, chlorine). The multi-isotopic composition ($\delta^{18}\text{O}$, $\Delta^{17}\text{O}$) of the nitrates reveals that they originate from the atmospheric oxidation of nitrogen oxides (Nox) formed by volcanic lightning. According to these first geological volcanic nitrate archive, we estimate that, on average, about 60 Tg of N could be fixed during a large explosive event. Our findings hint at a unique role potentially played by subaerial explosive eruptions in supplying essential ingredients for the emergence of life on Earth.

The Earth's latest TTG-sanukitoid magmatism: implications for mantle oxygenation and the onset of plate tectonics

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Most of the continental crust was generated in the Archaean before 3 Ga. Destruction rates dramatically increased after that point and 40% of what had been generated was recycled back into the mantle in the following c. 500 Ma. The pre-3 Ga continental crust was dominantly composed of the tonalite-thronthjemite-granodiorite (TTG) series, formed by partial melting of altered mafic sources. Eclogites were formed as the restite products of the TTG magmatism and increased the density of shallowly subducting mafic plates, which likely caused the opening of mantle wedges and triggered vigorous recycling. Similar TTG-like melts, once interacting with an overlying metasomatised mantle wedge, generated high Ba-Sr magmas with elevated Mg#, Cr and Ni: the sanukitoid series. This type of magmatism marks deep penetration of the mantle and assimilation of evolved material from the subcretion zone. The majority of this transitional magmatism occurred from 3.2 to 2.5 Ga and represents a diachronous failed attempt to initiate global modern-style subduction-driven plate tectonics. The latest occurrence of a TTG-sanukitoid transition is reported in the Mineiro Belt, Brazil. High-Al garnet-bearing 2.35 Ga TTGs evolved to 2.13 Ga sanukitoids across the Great Oxidation Event (GOE), being geochemically and isotopically similar to the Archaean record. We explore this out-of-sequence magmatic transition to understand the evolution of the atmosphere-crust-mantle system by analysing Sulphur speciation via μ -XANES in apatite inclusions hosted by zircon grains. This new information is then interpreted in the light of U-Pb, Lu-Hf, trace elements and oxygen isotope analyses of the host zircon grains. Apatite inclusions reveal a change from reduced to more oxidised magmas from pre- to post-GOE during the early Proterozoic. This change is interpreted as the result of recycling of atmospherically-altered sediments into the mantle.

Mantle or crust? The dual origin of granitoids

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Granitoids are a major component of the continental crust. They play a pivotal role in its evolution, either by adding new material (continental growth), or by reworking older continental crust. These two roles correspond to two main ways of forming granitic magmas, either by partial melting of pre-existing crustal rocks yielding granitic melts directly, or by fractionation of mantle-derived mafic to intermediate magmas. Both models represent endmembers, or paradigms that have shaped the way the geological community envisions granitoids, their occurrence, features, formation and meaning for crustal evolution and differentiation of the whole planet. Here we expose the two competing paradigms and their implications. We explore the evidence on which each model is based, and how each school of thought articulates a comprehensive view of granitic magmatism based on field geological, petrological, geochemical (including isotopes) and physical constraints; and how, in turn, each view shapes the thinking on crustal growth and evolution, and the interpretation of proxies such as age and Hf isotopic patterns in detrital zircon databases. We emphasize that both schools of thought build a different, but internally consistent view based on a large body of evidence, and we propose that each of them is, or has been, relevant to some portions of the Earth. Thus, the key question is not so much “which” model applies, but “where, when and to which extent”.

The Hadean-Archaean transition

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Little is known about the Hadean crust, because of the lack of outcrop. Nevertheless detrital Hadean zircons yield informations due to their O and Hf isotopic signatures, trace element contents and mineral inclusions. Their parental magmas appear to derive from a protolith that interacted with liquid water. In addition, the Hadean crust seems to have known only recycling processes. By contrast, juvenile sources predominate at the beginning of the Archaean.

Was the Hadean protocrust mafic or ultramafic? A thick serpentinized protocrust is buoyant enough to survive for 1 Gyr after Reynard *et al.* (2022). The experiments and geochemical modelling of Borisova *et al.* (2021) show that an intermediate to felsic crust can be generated by melting of a serpentine (hydrated peridotite) protocrust in contact with basaltic magma at low pressure (< 0.2 GPa).

Besides, Lee *et al.* (2010) had shown that, for $T_p(\text{mantle}) > 1870^\circ\text{C}$, partial melts formed at > 330 km (> 11 GPa) are denser than their mantle protolith. Nédélec *et al.* (2017) suggested that the lack of juvenile addition during the Hadean can be explained by this density trap between 410 and 330 km. With secular cooling, the onset of mantle melting migrated above the density trap. Therefore, a burst of mafic-ultramafic magmas occurred at 3.9-3.8 Ga. This extensive volcanism triggered gravitational instabilities, thus inducing sinking of the Hadean crust in the mantle. After this resurfacing of the Earth, the Archaean history continued with its well-known greenstone belts and TTGs.

Water, rocks and life in a very cool early Earth: a tribute to Hervé Martin

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When did early Earth become a very cool environment to stabilize organic molecules and allowing life to colonize the planet? After 60 years of discoveries, from extinct radionuclides to weathered zircons, from noble gas systematics in asteroids to space missions in prebiotic worlds (read Titan and may soon the Jupiter moons) this fundamental question is still open. Hervé participated to this quest, bringing with his and his student's work some important element on how a very peculiar rock assemblage – the TTG or Tonalite–trondhjemite–granodiorite - formed to make the core of Archaean, and possibly Hadean first continents. In this brief review, I will present the latest hypotheses to picture how the planet was likely in the Archaean and possibly in the Hadean in term of liquid water, crustal differentiation, atmosphere composition and how the expected physical (T,P) and chemical compositions of these terrestrial reservoirs could have favored or hampered life. It is likely that water was stable since 4.4-4.3 Ga, which doesn't mean necessarily oceans. Yet liquid water is still the most important solvent for many biochemical reactions, and one of the fundamental parameters to be settled to define the habitability of a world. Hadean continents were little, possibly less than 3% of the present volume, yet possibly differentiated with small felsic bodies (possibly of TTG composition) produced locally at depth in a thick and hot mafic primitive crust. Continents will not rise up to the present volumes until 2.5 Ga or later when a modern plate tectonics shaped them, accreting new material at their margins. Small continents (read Earth as an Aquaplanet) had influence on the chemistry of oceans. Oceans were also hot (60-80°C) and last triple Si-isotope systematics seems to confirm that. Yet, these temperatures are difficult to survive for metazoans but not for, i.e. thermophilic cyanobacteria. Atmosphere may have been CO₂-dominated since the beginning, likely a CO₂-N₂ atmosphere as the ones which lasted in the two "sisters" of the Earth, Venus and Mars. Alternative models suggest CH₄ as dominant gas to mimic a prebiotic ooze as on Titan, where fundamental organic molecules such as HCN could have been produced.

Origin and evolution of the chemical elements in the Galaxy

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The theory of nucleosynthesis emerged around the middle of the 20th century as a result of rapid progress in our understanding of three different fields: (1) the composition of the Sun and the solar system, (2) the physical conditions prevailing in the interiors of stars during their various evolutionary stages, and (3) the systematic properties of nuclei and nuclear reactions.

I will present a brief - and largely historical - account of the basic ideas underlying nucleosynthesis, starting with a description of the cosmic abundances and the nuclear stability of the nuclei. I will then proceed with the primordial nucleosynthesis (producing in the hot, early universe the lightest nuclides), the early and advanced stages of stellar evolution (synthesizing nuclei up to the Fe peak) and finally the synthesis of heavier than Fe elements (through neutron captures in quiescent and explosive environments).

The success of the theory lies mainly in its ability to reproduce (within reasonable assumptions) the solar distribution of the elements and most of their abundance ratios observed on the surfaces of stars of various ages in the Milky Way.

Solar System formation in the context of exoplanets

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The past decade of exoplanet observations has confirmed one of humanity's (and all teenagers') worst fears: we are *weird*. Even though Jupiter is the only Solar System planet likely to be detected with present-day technology, the Solar System is quantifiably unusual among exoplanet systems at the ~1% level. Instead, roughly half of main sequence stars host close-in "super-Earths", and ~10% have Jupiters or non-Jupiter-like, eccentric or close-in orbits. In this talk I will explore how the Solar System fits in a larger context by addressing key steps in planetary system formation. I will present models to explain the diversity of observed planetary systems (including super-Earth systems and giant exoplanets) and the mechanisms that create that diversity. While there is as yet no consensus on exactly how the Solar System formed, Jupiter is likely to have played a decisive role.

Chemistry of life in space: Astrochemistry and exobiology

Vassilissa Vinogradoff

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The origin of life is central in the field of Exobiology and can be approached from different aspects. Our researches focus on the origin of the organic matter, on the key element for life, that could have been inherited from space. By reproducing the conditions in space (molecular clouds, comets, asteroids), we simulate the organic matter evolution and highlight the huge diversity of abiotic organic compounds that can be produced in extraterrestrial settings. We show that the building blocks of life (amino acids, sugars) can be easily formed there and could have been brought to the early Earth by meteorites. However, this is not enough for the emergence of life and other processes have occurred on the early Earth.

Europium anomalies in zircon: a signal of crustal depth?

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Trace element concentrations and ratios in zircon provide important indicators of the petrological processes that operate in igneous and metamorphic systems. In granitoids, the compositions of zircon have been linked to the behaviour of garnet and plagioclase—pressure-sensitive minerals—in the source during partial melting. This has led to the proposal that Europium anomalies in detrital zircon are linked to the depth of crustal melting or magmatic differentiation and are a proxy for average crustal thickness. In addition to the mineral assemblage present during partial melting, Eu anomalies in zircon are also sensitive to redox conditions as well as magma evolution during extraction, ascent, and emplacement. Here we quantitatively model how rock type, mineral assemblages, redox changes, and reaction sequences influence Eu anomalies of zircon in equilibrium with silicate melt. Partial melting of metasedimentary rocks and metabasites yields felsic to intermediate melts with a large range of Eu anomalies, which do not correlate simply with pressure (i.e. depth) of melting. Europium anomalies of zircon associated with partial melting of metasedimentary rocks are most sensitive to temperature whereas Eu anomalies associated with metabasite melting are controlled by plagioclase proportion—a function of pressure, temperature, and rock composition—as well as changes in oxygen fugacity. Furthermore, magmatic crystallization of granitoids can increase or decrease Eu anomalies in zircon from those of the initial (anatectic) melt. Therefore, Eu anomalies in zircon should not be used as a proxy for the crustal thickness or depth of melting but can be used to track the complex processes of metamorphism, partial melting, and magmatic differentiation in modern and ancient systems. Secular changes of Eu/Eu* from the zircon archive may reflect a change in thermal gradients of crustal melting or an increase in the reworking of sedimentary rocks over time.

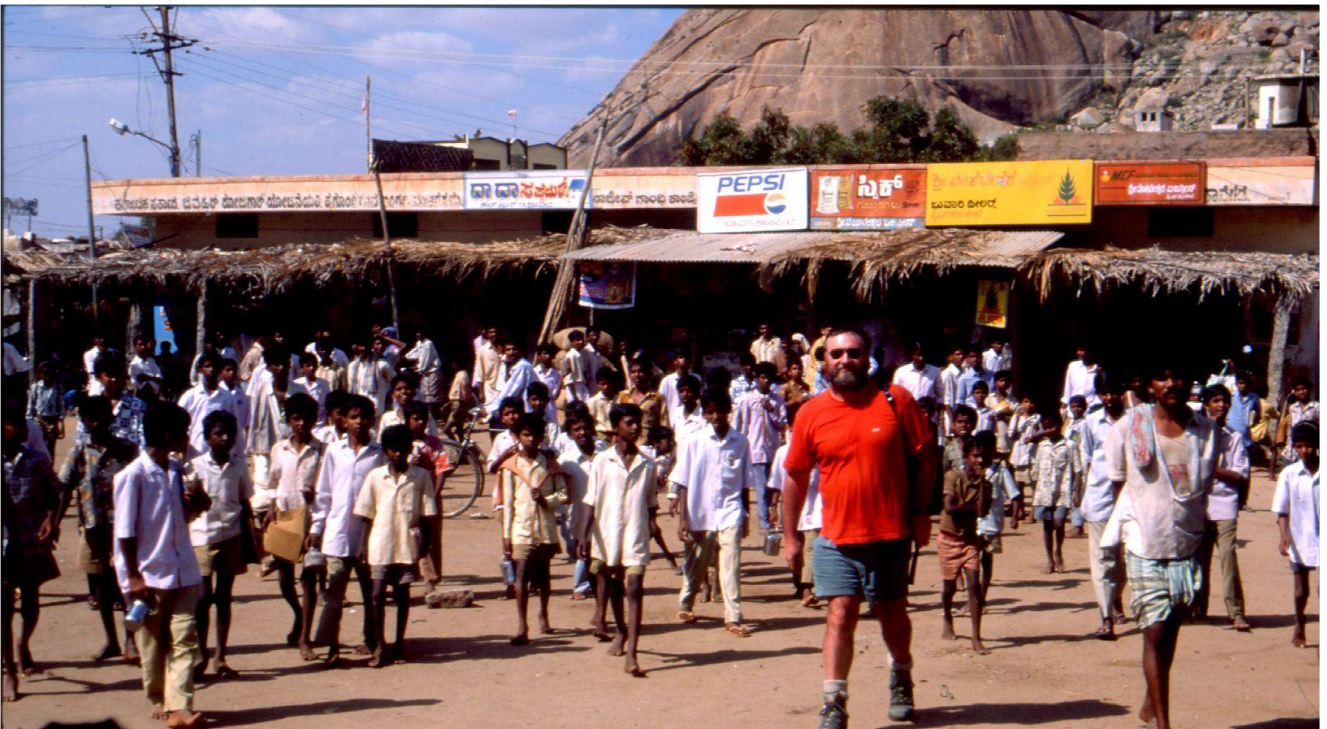
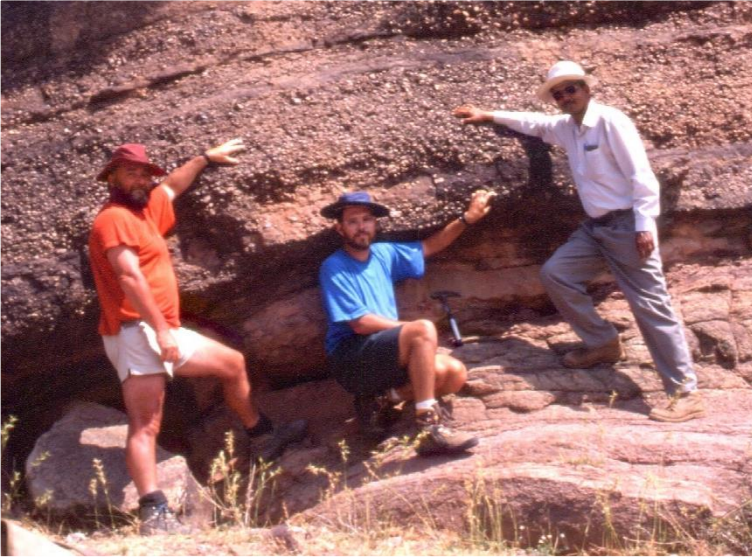
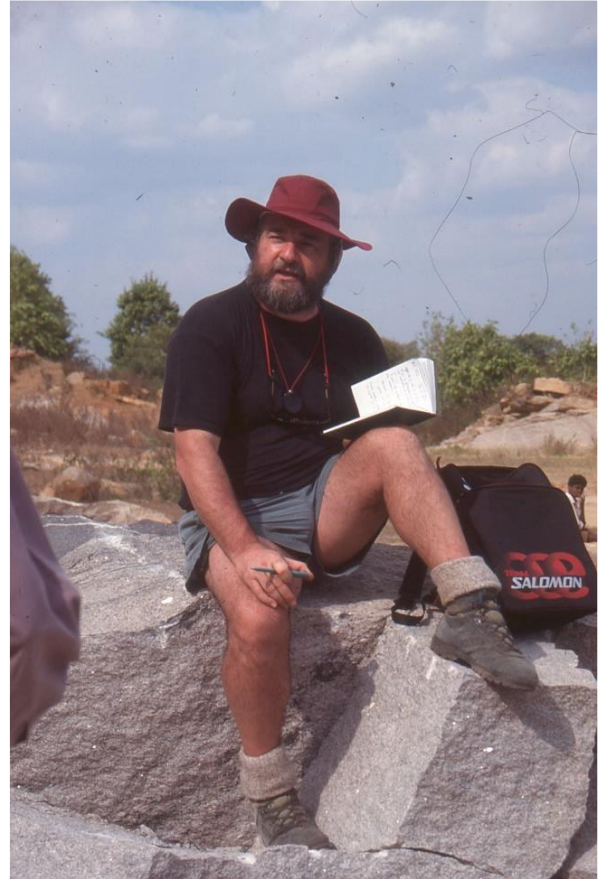
Memories



*Granitoids, continents, life and puns
A tribute to Hervé Martin - Clermont-Fd 5-8th 2023*



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