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Current and future projects

1. Large igneous provinces

About 200 Million years ago, the continents were assembled in a mega-continent named Pangaea. The progressive dislocation of the Pangaea was associated with major magmatic eruptions (Continental flood basalts; CFBs). These eruptions generally preceded the rifting processes (e.g. Karoo-Ferrar, Parana-Etendeka, CAMP) or were associated with aborted rifting (Siberia traps). Therefore, the study of continental disruption involves the study of CFBs and their correlation with the onset of ocean-formation. It has also been proposed that CFB eruptions may be associated with major mass extinction (e.g. Courtillot and Renne, 2003). Controversy still surrounds the origin of CFBs. For instance, models range from deep-seated mantle plumes to the upwelling of the enriched sub-continental lithospheric mantle in response to thermal accumulation under the mega-continent. In between models have been proposed, involving strong inherited characters of the lithosphere such as orogenic belts or pre-existing heterogeneities. Other crucial topics are: i) spatial and temporal evolution of the magmatism, ii) mantle sources and petrogenetic processes, iii) the role of structural inheritance in magmatism emplacement and dike swarm distributions, and iv) the transition between the last CFB magmas and first asthenospheric (MORB-type) magma related to oceanisation.
My previous research experience has focused on these problems and particularly on Karoo (southern Africa; 180 Ma) and CAMP (central Atlantic; 200 Ma) Phanerozoic provinces with some implications on the Umkondo (southern Africa; 1100 Ma) Proterozoic province.

1.1. $^{40}Ar/^{39}Ar$ results

The high-precision $^{40}Ar/^{39}Ar$ dating results that we obtained so far, show that the Karoo flood basalts (southern Africa) were emplaced on a significantly larger duration (~11 Myr; with 6-7 Myr for the main basaltic volume) compared to other large provinces (~1Myr for the main pulse). We also detected briefer distinctive pulses inside the province. Results on younger silicic and E-MORB-like magmatic products occurring close to the future rifted margin provided the first high-resolution picture of the transition between flood magmatism peak and ocean formation.
These results suggest that the Karoo province does not fit the general plume model invoked for most continental flood basalts (including the Karoo itself) and may explain the absence of important contemporaneous mass extinction. We also emphasized the role of the lithosphere architecture control on magma productions and plate boundary forces on continental breakup.

1.2. Dike swarms inheritance and structural characteristics

Large igneous provinces are quasi-systematically associated with giant dike swarms. The commonly radiating geometry of dike swarms is generally interpreted as the result of the stress regime that affected the lithosphere during the initial stage of continental break-up or as the result of plume impact. In order to test these models and the role of pre-dike structures on the four major putative Karoo-aged dike swarms, I developed a new concept of dating based on $^{40}Ar/^{39}Ar$ technique that I call speed step-heating experiments. It consists of compromising the precision on the age but allow investigating dozens of dikes in an extremely fast way and efficiently distinguishing between Jurassic and Precambrian dikes. Our results show that the apparent "triple junction" formed by radiating dike swarms is not a Jurassic structure; rather, it reflects weakened lithospheric pathways that have controlled dike orientations over hundreds of millions of years. One consequence is that the "triple-junction" geometry can no longer be unambiguously used as a mantle plume marker. Additionally, the analyses of the structural organization and absolute ages of the two largest dike swarms (Okavango and Save-Limpopo) suggest that they were synchronously emplaced as shear and pure extensional structures, respectively, in response to an inferred NNW-SSE extension.

1.3. Geochemistry

In order to study the petrogenesis and highly controversial origin of the mantle sources of the Karoo and CAMP provinces origin, I undertook systematical major and trace element and Sr-Nd-Pb-Hf isotope analyses on tholeiitic lava-flows, sills and dikes. Whole rock and mineral compositional variations can generally be accounted by fractional crystallization (MELTS algorithm) and partial polybaric melting modeling of substantially enriched mantle sources as will as a slight contribution from the lower crust in the case of the CAMP rocks. CAMP and Karoo mantle sources are suggested to be similar and both located in the metasomatically enriched sub-continental lithospheric mantle. The geochemical and isotopic signatures of hotspots related to these provinces (often assumed to be present day expression of the hypothetical mantle plumes?) are not recognized in our data set but we do not exclude that mantle plumes may have contributed to the lithospheric melting as a heating source.

Additional geochronological and geochemical analyses on the Proterozoic dikes included in the Okavango dike swarm strongly suggest that these dikes can be related to the Proterozoic Umkondo province. Our results suggest that these flood basalts could be related to a sub-continental lithospheric mantle enriched through injection of fluids and sediments during the 1.4-1.3 Ga Kibaran subduction. However, a slight depletion of the Karoo basalts relatively to Umkondo rocks suggest that the emission of the Umkondo province may have contribute to a small depletion of the lithospheric mantle at ~1.0 Ga.

1.4. Future Research

Generally, the proposed models are based upon an insufficient number of data that are often located in a restricted area of the province and mainly concern basaltic magmatism. The database is thus far from being complete and a lot of high quality work remains to be done.

I propose to use a multi-techniques approach including U/Pb and Ar/Ar geochronology and isotopic geochemistry (Sr, Nd, Pb, Hf, He, Os) on unstudied (but key) areas of selected large igneous provinces. More particularly I envisage to pursue my works on the Karoo province and in particular on some poorly studied areas (e.g. Malawi, Mozambique (close to the rift) and the field of sills in South Africa) in order to better constrain the total duration of the Karoo province and to identify a potential migration of the magmatism. This would also constrain the temporal, spatial and chemical evolutions of the Karoo magmas. I would also focus on silicic magmatism, probably related to crustal thinning and on E-MORB dykes associated with the onset of oceanisation in order to detail the relationship between CFB and continental breakup.

In collaboration with Dr Marzoli from Padova (Italy), we investigate the possibility of studying the Permian Penjal traps (India), based on a grant from Italy. This magmatic province is little studied with regard to elemental geochemistry and no geochronological and isotopic data are available despite a significant volume. The Penjal traps have been related to the opening of the neo-Tethys, between the northern Gondwana and outlying terrains.

I am also pursuing the geochemical and geochronological study of the CAMP magmatism with Dr Marzoli and Dr. Bertrand with emphasis on the relationship between CAMP and the Trias-Jurassic mass extinction; a field trip has been already carried out on the north-western US and Nova Scotia.

Additionally, recent geochronological studies seem to show similar characteristics between CAMP and Karoo provinces, both showing a long duration and a migration of the magmatic emission centers. A systematic sampling in the central and other understudied areas and the search for silicic and E-MORB magmatism would allow understanding the geodynamics of the province and its relation with the oceanisation.

I also plan to study the Parana-Etendeka province (South America). The magmatic stratigraphy is similar to that of the Karoo province (basalts, rhyolite, E-MORB dykes) but geochronological results are still insufficient in terms of quality and quantity to firmly detect a magmatism migration and to investigate the relation with the South Atlantic opening. Moreover, despite the occurrence of picrites, He isotopic data are crudely absent and would provide important constraints on mantle source processes.

Finally, in the long term, I would like to undertake a systematic "speedy step-heating" study on unstudied giant dyke swarms associated with the large igneous province in order to test the role of inheritance. It should be mentioned that this concerns every single large igneous provinces on earth, Karoo excepted.

2. The Independence (subduction-related) dike swarm

The Independence dike swarm (IDS) is a locally profuse, mostly NNW striking and ~700 km- long dike swarm occurring throughout southeastern California and possibly extending into northern Mexico. Dike compositions range from mafic to silicic (though strongly bimodal) and span the composition range of the coeval Sierran calc-alkaline arc plutons. To date, most of the geochronological and geochemical investigations available are strongly localized and part of the swarm lacks basic data preventing a high-resolution picture of the swarm emplacement and its petrogenesis. We are currently performing a detailed $^{40}Ar/^{39}Ar$ and U/Pb (using the recently developed technique of thermal annealing coupled to chemical abrasion) geochronological study on the Benton range dikes (northernmost IDS). Our preliminary results along with pre-existing data reveal that the Independence dike swarm is a poly-phased complex intruded in several major, magmatic episodes (>170-140 Ma; 115-120 Ma and 100-85 Ma). The dikes were intruded during a time span coinciding with major changes in the orientation of plate convergence (e.g. J2 cusp at ~150 Ma; May et al., 1989). Therefore, the orientation of the dikes is unlikely to be entirely controlled by stress induced by the converging plate. Rather, the data suggest that the dikes are preferentially associated with weakened lithospheric pathways (imposed by the orientation of the free margin?) that have controlled dike orientations over >90 Ma. Preliminary geochemical analyses suggest a lithospheric mantle origin for the mafic magma. Isotopic data (in progress) are required to test whether silicic dikes involve a pre-Mesozoic crustal component or are evolved directly from a mantle melt.
Results obtained so far, are still sparse and strongly localized to the north of the swarm (including our data). A more systematic geochronological and geochemical approach applied over the total extent of the swarm would allow a better understanding of the role of structural inheritance and lithosphere influence on emplacements and compositions of subduction-related magmas and dike swarms in general.

3. The Twaing impact crater

Tswaing is a 1.1 km in diameter-sized crater impacted in the ~2.1 Ga Nebo granite of the Bushveld complex, South Africa. So far, no published radiometric data are available on this relatively small, but regionally important, geological feature. Our $^{40}Ar/^{39}Ar$ data obtained on tektites clearly failed to provide a reliable age for this structure but instead showed a wide range of ages (ranging from 180 to 1.2 Ma). This suggests that part of the basement-derived $^{40}Ar^*$ was preserved during the impact and that even 0.03% of initial $^{40}Ar^*$ can bias the age. This study raises the importance of a better understanding of diffusion processes during impact-induced melting and role of the composition and structures of the impactor and impacted bodies. We also raise the potential problems of dating un-reset extraterrestrial material derived from asteroids impacts (e.g. lunar spherules; SNC Martian meteorites).

More generally, impact craters are poorly constrained with regard to their age of formation (e.g. www.unb.ca/passc/ImpactDatabase/). A systematic study of the age of impact craters would allow: i) better constraints on the flux of large meteorites that have impacted during Earth history, ii) an understanding of the relationship between undated impacts and biologic crises, and iii) a study of the behavior of the $^{40}Ar/^{39}Ar$ chronometer (clock resetting) depending of the impacted basement nature and asteroid composition.

4. $^{40}Ar/^{39}Ar$ methodological development

4.1. The intercalibration of standards

The $^{40}Ar/^{39}Ar$ dating technique is a relative technique based on the knowledge of the age of neutron fluence monitors (standards). Ideally, the age of the standards is determined by K/Ar dating or other methods such as astronomical calibration. However, some mineral not suitable for K/Ar dating due for instance to some incomplete degassing of $^{40}Ar^*$ (e.g. sanidine) are known to provide more precise and reproducible ages when measured by $^{40}Ar/^{39}Ar$ dating (e.g. Fish Canyon sanidine (FCs)). Use of these "secondary" standards is also often justified by the fact that their age and composition could be similar to the unknown and therefore minimize the range of isotopic ratios to be measured. One of the most studied and most used standard in $^{40}Ar/^{39}Ar$ geochronology is FCs, mainly because of its high homogeneity and typically superior reproducibility. However, different interlaboratory experiments based on different standards and different analytical conditions tend to provide ages for FCs varying from ~2% seriously undermining the precision (and credibility?) of $^{40}Ar/^{39}Ar$ dating technique.

I have reinvestigated the age of FCs on intercalibration with four robust primary standards that K concentration was determined by isotopic dilution and $^{40}Ar^*$ concentration was measured using the 'first principles'. So far I have shown that the age of FCs is 28.03 ± 0.05 Ma. This study is also an attempt to improve the knowledge of the Ca and Ar branching ratio of the ^{40}K decay constant which value have recently been strongly questioned. My early research on this field also lead me to carry a study and publish a paper about the age and reproducibility of the widely use Hb3gr standard.

Currently, too many uncalibrated standards and/or standards with insufficient reproducibility are still used in many Ar laboratories. I propose to perform a systematic calibration and filtering of currently used standards and to search, test and identify high quality standards with a given range of compositions and ages. This could be performed by a careful inspection of the existing $^{40}Ar/^{39}Ar$ database.

4.2. The ^{37}Ar and ^{39}Ar recoil due to fission-induced neutron flux.

This study concerns the direct measurement of ^{39}Ar and ^{37}Ar recoil ejection loss from individual, dimensionally characterized multi-grain aliquots due to neutron irradiation. Previous results on the GA1550 biotite show that thinner fraction (3 µm) could have as much as 26 % higher $^{40}Ar/^{39}Ar$ than thicker grains due to ^{39}Ar recoil. I used the well characterized Fish Canyon sanidine and plagioclase and Hb3gr hornblende known to be homogenous with size ranging from 500 to <5 µm.

In contrast to previous investigation, my results reveals that recoil effect on the $^{40}Ar/^{39}Ar$ of sanidine is much smaller (only 3 % higher for the <5 µm fraction) compared to biotite. I calculated that the thickness of the depletion layer in the sanidine is 0.034 ± 0.016 µm, in agreement (though slightly lower) with the commonly adopted value of 0.08 µm. For comparison my calculations show that the biotite depletion layer thickness is at least an order of magnitude higher with a value of 0.57 ± 0.16 µm. Part of this discrepancy might be due to the higher surface/volume ratio of the biotite, its mineral structure and/or be related to its composition as well, but this does not account for the entire difference.

More impressive is the recoil of ^{37}Ar affecting the minerals with high Ca/K such as plagioclase. Preliminary results suggest that the depletion thickness for ^{37}Ar might be as high as 3-4 µm. Because of the use of the ^{37}Ar in the age calculation (interference corrections), the recoil of the ^{37}Ar is able to decreases the age by as much as 20%. These preliminary results will be assessed with the study of the high Ca/K Hb3gr hornblende and pure fraction of the FC plagioclase.

Study of recoil in various minerals is important not only for routine age measurements, but also to investigate the role of recoil in multi-diffusion domain theory and other thermochronologic applications exploiting variable diffusion radii and/or grain size effects.

I would like to pursue the study of recoil effect on minerals of various compositions and widely used in $^{40}Ar/^{39}Ar$ dating. In addition and not necessarily related, I would like to contribute to refine the K decay constant by dating some carefully selected eruptive rocks using U/Pb and $^{40}Ar/^{39}Ar$ geochronometers.

5. $^{40}Ar/^{39}Ar$ and paleomagnetism investigation of lunar spherules

The origin of magnetic fields on the ancient Moon is one of the greatest remaining mysteries from the Apollo era. Paleomagnetic measurements on Apollo rocks and spacecraft magnetometry suggest that there were intense (1-20 microtesla) fields on the Moon between 3-4 Ga. There are two leading hypotheses for how these fields originated: (a) a dynamo in the lunar core, and (b) fields generated or amplified by impact-generated plasmas at the lunar surface. The verification of either of these mechanisms would have critical implications for our understanding of the lunar interior and for planetary magnetism in general. Equally importantly, it would also mean the discovery a fundamentally new process for generating magnetic fields in the solar system.
In this project, my role is to conduct $^{40}Ar/^{39}Ar$ dating on each spherule to obtain the history of the lunar magnetic field. The magnetism study will be undergone at the MIT (Dr. B. Weiss). This will be the first combined magnetic/radiometric measurement on lunar samples from 3.0 to 1.5 Ga. This project is submitted to NSF and analyses have not been fully initiated yet.

6. Cosmogenic Argon and surface exposure dating

Surface exposition or erosion rates can be investigated by using cosmo-nuclides. The $^{38}Ar_C$ can be produced and accumulated on material containing calcium and therefore used for the same purpose. Compare to other short-lived isotopes (e.g. Be, Al), ^{38}Ar is stable and can be used beyond the time range of other isotopes. It can be measured on the same instrument used for conventional $^{40}Ar/^{39}Ar$ dating. A method currently developed at the Berkeley Geochronology Center by colleagues consists in irradiating the sample before analysis. This technique allows measuring the $^{38}Ar/Ca$ ration and better constraining the $^{38}Ar_c/^{38}Ar_{atm}$ by step-heating experiment.
In the long term and in association with geomorphologists and cosmogenic specialists from the University of Seattle/Nice-Sophia Antipolis; I plan to apply this relatively new technique on quartz-poor mineral surface (i.e. preventing the use of ^{10}Be) such as young lava-flows or Ca-rich rocks such as carbonates. This project has not been initiated yet.