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## Letter from the President

### Should we webcast from the Goldschmidt conference?



Marty Goldhaber  
GS President (2008-09)

The Goldschmidt Conference has become one of the top, if not the top, geochemical meetings in the world. As Alex Halliday, President of the EAG, stressed to the joint meeting of the GS and EAG Boards of Directors in Vancouver, assuring the future of this conference is a trust that we must take very seriously. The importance of the meeting, and its growing size and complexity requires us to plan further and further into the future. Preparations for the 2009 and 2010 conferences in Davos and Knoxville are at advanced stages and we are now seriously looking at 2011, 2012, and beyond. In that light, we need to take the long view of issues that may affect our meeting. Although there are several long-range concerns, in this note, I would like to look specifically at trends associated with the cost of travel.

The person-to-person exchange of ideas is a critical function of our conferences, so travel is a particularly important consideration. Yet travel, especially internationally, is becoming increasingly expensive. In recent months, increasing fuel costs have negatively influenced air travel. Although, as I write this, the per barrel price of oil has dropped to only \$50, the likelihood is that over the long term, rapidly increasing demand in industrializing countries and general population growth, together with the prospect of reaching peak oil production will drive oil prices higher once again. Some analyses predict the peak of world oil production will occur around 2020 (although the timing is controversial).

So what does this have to do with the future of the Goldschmidt meeting and 'webcasting' in the title of this piece? For many organizations around the world, the internet is starting to offer an alternative to travel for exchange of information. This was emphasized for me when one of our members sent an email suggesting we view live webcasts from the Division for Planetary Sciences of the American Astronomical Society meeting in Ithaca, New York, USA. The webcasts were of a very high quality, unlike the sketchy, jerky pictures that some may associate with webcasting. There were several viewing panes for each talk, so that the viewer could simultaneously see and hear the speaker and view the PowerPoint slides. The capability exists for those watching remotely to submit questions to the presenter. Three parallel sessions were streamed over five days. Based on talking with several folks both in leadership positions with the Planetary Sciences Division, and local meeting organizers, the overall feedback from the webcasting experiment was highly positive. There are issues about archiving talks that contain information embargoed pending publication, so these talks were not archived. Altogether, there were 6500 hits for their webcasts, although perhaps 40% were from attendees' onsite. Probably a number of the onsite hits were from people viewing a talk that they were interested in that they could not attend because of a scheduling conflict against a competing session. Based on the overall numbers, many scientists were able to view either in real time or as part of the archive, presentations that they would not have otherwise have seen.

Driven by some of the above considerations, the Board of Directors of the Geochemical Society exchanged ideas on webcasting from the Goldschmidt Conference. Most members were supportive. However, some raised concerns that the camera would inhibit presenters. Others suggested that archiving of the presentations should only occur for a limited period. Time limited archiving would allow viewing by those who could not attend the meeting or a given talk, but keep the more informal and potentially speculative nature of conference presentations (relative to publications) intact. There seemed to be some agreement that major talks given in plenary sessions and award ceremonies were potentially a useful focus for webcasting and archiving. This has been the strategy of the American Geophysical Union, which has webcast some featured lectures since 2003.

Of course, cost will be an important consideration. Some sense of the costs comes from The Geological Society of America (GSA), which webcast five major events from their recently completed annual meeting in Houston Texas. Based on discussions with the GSA meeting planning staff and the audiovisual subcontractor, the total cost was \$5700 plus some additional charges for the camera and labor. The Division for Planetary Sciences spent under \$40,000 to webcast their multiple sessions. These numbers are within reach for a conference whose overall budget tops well over a million dollars.

A key consideration that we will need to address in order to implement a webcasting strategy is the potential for a negative financial impact on the meeting. Although the overall budget for a Goldschmidt is subject to many uncertainties, projecting the overall attendance is one of the most important variables. In order to make the meeting financially successful, the meeting organizers must make financial projections far in advance of the meeting date. Adding an uncertain impact of webcasting on meeting attendance on top of other financial uncertainties is not feasible without detailed long range planning. For that reason, external webcasting will not be done from the Davos meeting in 2009.

Nevertheless, as noted above, the likelihood is that transportation costs will increase over time, perhaps dramatically. Furthermore, environmental considerations may start to weigh more heavily in people's travel decisions (for example, see discussions at [Nature](#) and [Science](#)). I think it is time begin to plan for webcasting from future Goldschmidt Conferences in 2010 and beyond. Perhaps we can start with webcasting and archiving the major addresses from these future meetings. For the Knoxville meeting in 2010, we might look into limiting web access to scientists and students from economically disadvantaged countries who would not otherwise be able to attend. However, eventually we should develop a financially viable strategy for presenting the entire program on the web. There may well come a time when international travel becomes prohibitively expensive to scientists either financially or environmentally. We will need to have a plan in place for when that occurs.

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## Geochemical Highlights (#138)

"Geochemical Highlights" is a new feature at Geochemical News that we are hoping catches on in popularity. Here you will find short summaries of recent journal articles that the GN editors (in future issues, this hopefully will include guests too) found particularly interesting. Some scientific journals do this for a wide-range of research topics (e.g. Nature's [Research Highlights](#)) but we thought it would be nice to have this specifically for the geochemistry community. This first sampling admittedly lacks representation from all geochemical research areas, but we hope to address this in future installments. If you have a suggestion for a recent paper that you think should be highlighted (or would like to write one yourself), contact us at [gnews@geochemsoc.org](mailto:gnews@geochemsoc.org).

### Mineral nanostructures influence transport

Kerisit and Liu (2009) *Environ. Sci. Technol.* DOI: 10.1021/es8016045 (in press, available online)

The influence of porosity on the movement of water through rocks has been taught in introductory geoscience classrooms worldwide for decades, yet researchers are still revealing surprising natural phenomena that change how we view this fundamental concept.

Sebastien Kerisit and Chongxuan Liu from Pacific Northwest National Laboratory in Richland, WA recently used molecular dynamics simulations of nano-fractures in orthoclase (KAlSi<sub>3</sub>O<sub>8</sub>) to show that the diffusivity of water and transport of electrolyte ions are significantly lower when confined to spaces up to several tens of nanometers wide when compared to bulk water. The researchers note that such nano-fractures may be important pathways for the sequestration of environmental contaminants across many mineral-water interfaces. The results may also have implications for understanding the surface reactivity of mineral nanoparticle aggregates where confined spaces of just a few nanometers are likely abundant. --NW

### Some bugs like it hot

Takai et al. (2008) *PNAS* 105 (31), 10949-10954

One of the holy grails of geomicrobiology is to discover the microorganism that lives at the highest temperature. For a long time, the record holder has been *Pyrolobus fumarii* at 113°C. In 2003, Kashefi and Lovely reported in a *Brevia* article in *Science* the growth of an uncharacterized organism that grows at 121°C (the temperature at which steam sterilizers operate), which they dubbed Strain-121. Now, Takai et al. report the growth of a methanogen, *Methanopyrus kandleri* strain 116, at 122°C. Normally, *Methanopyrus* attains a maximum growth temperature of up to 110°C. The increase, according to Takai et al., results from culturing *Methanopyrus* under a pressure of 20 MPa instead of just enough pressure to keep water from boiling (or 0.4 MPa).

Perhaps more significantly, Takai et al. report that the isotope fractionation of carbon by *Methanopyrus* to methane at 122°C and 40 MPa (-9.4‰) is much smaller than previously reported for methanogens under conventional conditions (-34‰ to -27‰). The relatively heavy values have significant implications for interpreting Earth's carbon isotope record and the search for life outside Earth. --MS

### Removing oxygen to study isotope adsorption

Hu et al (2008) *Geochem. Trans.* 9(12).

The United States tested 828 nuclear weapons tests at the Nevada Test Site (NTS) between 1951 and 1992. Radiogenic isotopes in groundwater at the NTS include iodine, neptunium, technetium, and a number of plutonium and uranium isotopes. Sorption of aqueous complexes of the radiogenic nuclides has been characterized under aerobic conditions in groundwater, but few studies address sorption under anaerobic conditions.

New experiments by Hu et al. show that more Np and Tc adsorb on to devitrified tuff where redox conditions correspond to sulfate reduction (pe -5) than where aerobic conditions prevail (pe 10). Behaviors of the other tested isotopes were less clear suggesting we need more laboratory and field investigations to define how redox conditions affect the behavior of aqueous radionuclides in groundwater. --SK

### Nitrogen fixers on the shelf

Rees et al (2009) *MEPS* 374, 7-12

Researchers from the National Oceanography Centre in Southampton and the Plymouth Marine Laboratory appear to have found the first evidence of nitrogen fixation in a shelf environment, which might lead to some revisions with regard to nitrogen and carbon budgets.

Until now, most marine research into nitrogen fixation had been dedicated to tropical and subtropical seas although it was known, for instance, that the Baltic Sea is a site where tremendous nitrogen fixation takes place every summer. Rees et al. took samples at two stations in the English Channel off Plymouth during a mixed phytoplankton bloom dominated by *Emiliania huxleyi* and *Karenia mikimotoi*. They incubated the samples with <sup>15</sup>N-N<sub>2</sub> and also carried out nifH identification in DNA and mRNA. The authors conclude that "there is clear evidence of nitrogen fixation in mesotrophic waters of the Western English Channel during summer conditions of thermal stratification and nutrient depletion." --AS

### A new look at ionic gold

Lintern et al (2009) *Geochim. Cosmochim. Acta* doi: 10.1016/j.gca.2008.12.019 (in press, available online)

Gold can cause obsession in man and nations, but, from a prosaic, geochemical viewpoint, gold could be conceived as less fascinating due to its inertness. However, Au does not only occur in nature in its metallic form but can also be incorporated in other minerals in the form of solid solutions. Incorporation of Au in pyrite or other chalcogenides has been reported and is not completely unexpected. However, a high correlation of Au with earth alkaline metals, as observed in some carbonate rich Australian soil profiles, is surprising. Elemental soil profiles suggest the concurrence of Au and earth alkaline metals relocation in these soils and point to the existence of an alternative binding form of non metallic Au. Analysing elemental distribution in these soils on micrometer scale reveals that the correlation of Au with earth alkaline metals breaks down at this scale and association of Au with Br indicates that immobilization of ionic Au in these soils is related to evapotranspiration processes. Local enrichment of

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Au in a root tubule suggests that Au mobility is influenced by the activity of living organisms and that Au might undergo biogeochemical cycling similar to less noble trace metals. --TB

*Note:* The study is a good example of the complimentary use of a variety of microanalysis techniques, including LA-ICP-MS, synchrotron micro-XRF, and electron microscopy. The potential of these techniques to provide new insight into biogeochemical processes becomes evident but also the limitation of the individual techniques can be recognized. Readers, who became interested in micro analysis techniques based on [the tabletop micro-XRF article in this issue](#), will find supplementary information on the above mentioned techniques in this article.

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## Goldschmidt bloggers needed

[*Nine bloggers have been chosen. Follow along at <http://geochemicalnews.wordpress.com/>*]

The Geochemical Society is looking for attendees of the 2009 Goldschmidt meeting in Davos, Switzerland to join GS President Martin Goldhaber in blogging about the meeting. All levels of experience--from undergraduates to emeriti--are encouraged to participate. No previous blogging experience required! The blog will appear on the GS homepage and will be an interactive tool for those on-site as well as those unable to attend. Please consider this unique opportunity to contribute to the society!

### Requirements

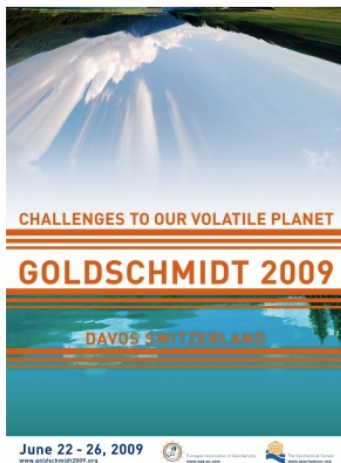
- Must be attending the [2009 Goldschmidt conference](#)
- Must have access to the internet while at Goldschmidt
- Must have command of English grammar
- Must have ability to write interesting and comprehensible blog entries
- Ability to attend the 'Earth's Future' panel discussion on Wednesday, June 24 is a plus
- Ability to attend the morning plenary talks is a plus

### Expectations

- Post at least one blog entry per day while at Goldschmidt
- If necessary, address questions related to posts

### Compensation

- 2009 (or 2010 if already a current member) Geochemical Society Membership
- Geochemical Society T-shirt
- Choice of one book (GS Special Publications or RIMG volumes)
- Ticket to the Conference dinner on Wednesday June 24



**The deadline for applications is May 27, 2009.**

All interested contributors should email the following information to Seth Davis ([seth.davis@geochemsoc.org](mailto:seth.davis@geochemsoc.org)), please write "Goldschmidt Blogger" in the subject line.

1. Your name
2. Your email address
3. Position/experience level
4. If student, degree you are seeking and expected completion date along with your advisor's name and email address
5. Your field(s) of interest
6. Dates you will attend the Goldschmidt conference
7. Sessions you plan to attend
8. Do you plan to attend the Earth's Future panel discussion?
9. Do you plan to attend the the plenary talks?
10. Your T-shirt size (women-please indicate the equivalent men's size)
11. Book Preference - list either a [Special Publication](#) or [RIMG](#) title

All submissions will be acknowledge by email within 24 hours. If you do not receive an email then your submission was not received. Another email will be sent when the final selections are made.

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## Five Questions with Enriqueta Barrera

On scientific funding, the perfect proposal, and the future of research



Enriqueta Barrera

*Enriqueta Barrera is a Program Director at the U.S. National Science Foundation where she is responsible for the [Geobiology and Low-Temperature Geochemistry Program](#) as well as the [Critical Zone Observatories](#). She received her Ph.D. in Geology from Case Western Reserve University and was an Associate Professor at Akron University before joining NSF in 2000. She recently answered these questions for GN via email. She can be reached at [ebarrera@nsf.gov](mailto:ebarrera@nsf.gov).*

### 1) What is your primary role as Program Director at NSF?

The Program Director "gets to know" the community he/she represents and seeks to learn about new directions of scientific research within the scope of the program. In addition, the Program Director is responsible for implementing the proposal review and evaluation process for the program; conducting the final review of proposals and evaluations and recommending awards or declinations based on knowledge or resource availability, program goals and peer reviewer comments; evaluating projects and activities that are proposed or funded by conducting site visits and reviewing reports; negotiating interagency agreements with other Federal agencies for transfer of funds; and overseeing funded infrastructure including Centers and Facilities.

### 2) How did your earlier career as a geoscientist prepare you for the challenges you face as program manager?

Prior to my arrival at the NSF in 2000, I held positions as a research scientist and a tenured faculty member at several universities after graduating from Case Western Reserve University in 1987. At CWRU, my doctoral studies supervised by Sam Savin were in the areas of paleoclimates and isotope geochemistry.

I do not know if anyone can be fully prepared for the challenges one encounters at the NSF. My experience at the NSF started in the retired Geology and Paleontology program, a complex and large program covering several disciplines, and at the time when the Biocomplexity initiative was just beginning. My involvement in these two programs and other related initiatives at the NSF provided an excellent opportunity for exposure to the frontier of research ideas and to gain experience in the management of large competitions. Managing the program requires a) a willingness to embrace challenges and new ideas; b) common sense; 3) and the capacity to be a good listener and to argue on behalf of the community. NSF's working environment is very collegial and my fellow program directors have always provided advice or assistance when needed.

### 3) What are the most important things you look for in proposals, reviews, and/or committee evaluations?

A good proposal is a good idea, well expressed, with a clear indication of methods for pursuing the idea, evaluating the findings, and making them known to all who need to know. The proponent needs to have a clear idea of what he/she intends to do, why the work is important, what has already been done, and how the work will be performed.

A good proposal will convey clearly to the reader this information and will have well articulated hypotheses guiding the research.

Proposals are evaluated based on two criteria: the Intellectual Merit and quality of the proposed research, and the Broader Impacts of the activity. Considerations of the former include: the importance of the research in advancing knowledge and understanding within its own field or across different fields; the novelty of the research and its capacity to transform the field; the qualification of the investigator(s) to conduct the project; good organization and appropriate resources allocation. The Broader Impacts criterion deals with the promotion of teaching, training, and learning; the participation of underrepresented groups; the development of infrastructure for research and education; the benefits of the activity to society; and the dissemination of results to various groups.

### 4) a. What do you think have been the most exciting areas of research in low-temperature geochemistry and/or geobiology in the past decade? b. What areas of research do you think have the potential to be equally as exciting in the next ten years?

Taking the proposal submissions to the program as a point of reference, some areas of research have flourished in the past decade. Geomicrobiology, the microbial interaction/transformations of Earth's material, has become well established and mature. New techniques and tools have added to the sophistication of this research. Future transformational research in this area is likely in environmental genomics, where genomics-enabled methods are used to understand organisms' impact on their environment.

Multidisciplinary/interdisciplinary research on processes occurring in the 'Critical Zone' is an emphasis area, as an era of observatory research is established nationally and internationally. The Critical Zone is the external terrestrial layer extending from the top of the canopy to the base of the weathering zone. There is fundamental understanding of the coupling of physical, chemical and biological processes in this zone, but there is still much more to be learned. In particular, studies that integrate biologic and geologic processes have great promise.

### 5) According to [this site](#), the funding rate for the Geobiology and Low-Temperature Geochemistry program was 17% in 2007 and 20% in 2008 (by contrast, over the same two-year period, the NSF as a whole was slightly higher at ~25%). Do you have any advice for young scientists starting their own research program in such a competitive field?

In reality, the funding rate for the program was slightly lower than 17% in 2007 and 20% in 2008, based upon the figures appearing in the NSF web site. Other factors are reflected in these percentages. NSF would like to achieve an average funding rate of 30%. The program does not have the resources to achieve this. Our more recent Committee of Visitors evaluating the program recommended increasing the program's budget. The slight increase in the 2008 funding rate is due to the successful competition of some of our proposals for funds of the Emerging Topics in Biogeochemical Cycles (ETBC) Opportunity, advertised at the Web site: <http://www.nsf.gov/nibs/2007/nsf07049/nsf07049.isn>. Another opportunity

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to be announced shortly, also in a "dear colleague letter", focuses on the development and/or integration of environmental models that link local, regional and global scales.

We worry about the impact that the limited support has on the disciplines covered by the program, and especially on early career researchers. This is taken into consideration when making funding decisions. My advice to early career researchers is not to get easily discouraged and to continue to submit revised proposals addressing the comments of reviewers, and in particular the panel. Talk to your program director and visit the NSF, if possible, to learn about the different programs and opportunities. The Directorate for Geosciences supports numerous workshops for early career scientists, including faculty and post-docs. Information is available at the following Web site:  
<http://serc.carleton.edu/NAGTWorkshops/index.html>.

--NSW

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# Bench-top micro-XRF - a useful apparatus for geochemists?

Thilo Behrends<sup>†</sup> and Pieter Kleingeld

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Analyzing heterogeneous samples from earth and environmental sciences with high spatial resolution became an indispensable approach for unraveling geochemical and biogeochemical processes controlling the speciation, coordination environment, and redox state of elements in these samples. A large variety of high-resolution techniques are nowadays available and their potential to provide valuable information about (bio)geochemical processes has been demonstrated in numerous applications. The list of techniques includes electron microscopy, electron microprobe analysis, ion microprobe analysis (secondary ion mass spectrometry, SIMS), as well as laser ablation - inductively coupled plasma - mass spectrometry (LA-ICP-MS), and synchrotron radiation based microanalysis as, for example, synchrotron micro X-ray fluorescence (S- $\mu$ -XRF). All these techniques are used for determining elemental compositions in samples from earth and environmental sciences with high spatial resolution. Several of these techniques can provide additional information such as coordination environment, crystal structure, redox state, or isotopic composition depending on configuration. They all have specific advantages and limitations whereas spatial resolution, range of detectable elements, feasibility of quantitative analysis, detection limit, dynamic range, and required sample preparation are relevant criteria regarding the analysis of elemental compositions. But also accessibility and costs often decide whether microanalysis is performed on a set of samples or not.

Compact  $\mu$ -XRF instruments were launched into market just a few years ago. These instruments are attractive alternatives to other microanalysis instruments due to the relatively low price and relatively low demands regarding infrastructure, sample preparation, costs, and expertise required for operation. Recently, we decided to order a bench-top  $\mu$ -XRF and in this article we want to share our experiences in the attempt to evaluate the possibilities and limitations of commercially available  $\mu$ -XRF instruments, especially in view of other microanalytical techniques.

**"Accessibility and costs often decide whether microanalysis is performed on a set of samples"**

Micro-XRF has been applied to geochemical samples since years but the usage of  $\mu$ -XRF analysis was only possible at a relatively small number of synchrotron beamlines providing S- $\mu$ -XRF facilities. This is because synchrotron radiation is characterized by orders of magnitude higher photon flux than conventional X-ray tubes which facilitates the generation of sufficient X-ray fluorescence from small irradiated sample spots for elemental analysis. Another reason why  $\mu$ -XRF instruments have been exclusive to synchrotron facilities might have been the challenge of focusing X-ray beams. Synchrotrons are locations with concentrated expertise of X-ray optics which catalyzes the development and usage of optical elements for focusing hard X-rays. The most common optical device for focusing X-ray beams at S- $\mu$ -XRF beamlines are Kirkpatrick-Baez mirrors. KB-mirrors focus the beam by reflecting X-rays at the coated surface of the curved mirrors. The loss of intensity, due to the low reflectance of these surfaces is compensated by the extreme high intensity of the collimated x-ray beam.

## Focusing and collimating X-ray beams in commercial $\mu$ -XRF instruments

Building  $\mu$ -XRF instruments principally based on conventional X-ray tubes has been enabled by the development of X-ray capillary optics, which allow designing much more compact and robust optics for collimating and focusing X-ray beams.

The simplest way to reduce the spot size of an X-ray beam is to use apertures to narrow down the size of the outgoing beam. The problem is that only a small spatial segment from the emitted X-rays is then used for the analysis resulting in relatively low yield of X-ray fluorescence. In practice, apertures are used in  $\mu$ -XRF instruments for spot sizes of 1 mm or larger. Creating smaller spot sizes with apertures is impractical because the final X-ray intensity becomes so low that fluorescence generation in the sample would be insufficient for analysis.

All commercial  $\mu$ -XRF instruments make use of the effective diffraction of X-rays at the surface of glass capillaries for creating smaller spot sizes. The possibility of using glass capillaries to convert divergent X-rays into a parallel beam or to focus X-rays has been first reported by M. A. Kumakhov in 1984 and extensively investigated since then (Kumakhov and Komarov, 1990). Transformation of divergent X-rays into a parallel beam by using glass capillaries is schematically shown in **Fig. 1**. For  $\mu$ -XRF applications two different designs are used: mono-capillary and poly-capillary. Highly collimated X-rays can be produced by mono-capillaries. The advantage of highly collimated X-rays is that  $\mu$ -XRF analysis can be combined with X-ray transmission imaging. Another advantage is that the vertical positioning (working distance) of the sample is less crucial, and that the probed sample volume is better defined. Furthermore, mono-capillaries are offered for  $\mu$ -XRF with spot sizes down to 10  $\mu$ m, which is smaller than spot sizes of presently available poly-capillaries. The downside of these advantages is that the photon flux, emitted by mono capillaries on the sampling spot, is lower compared to poly-capillaries, which are typically arranged to create focused beams.



Figure 1: Collimating or focusing of divergent X-rays with the help of polycapillaries. xrf\_fig1\_small; Source: [X-ray Optical Systems Inc.](#)

## Lateral resolution and fluorescence yield (what is the best capillary option?)

Deciding about the most suitable x-ray optics for our expected applications was an important aspect in the selection procedure. Of special interest was the characterization of the sampling spot to obtain an impression of the achievable spatial resolution. For this purpose a gold wire with a diameter of about 30  $\mu$ m was fixed in calcite containing resin material and a two-dimensional scan was performed with the best possible resolution of the different instruments. Exemplarily, a contour plot of the intensity of Au L $\alpha$  fluorescence is shown on the left side of **Fig. 2**. The asymmetric shape is due to the fact that the gold wire was not perpendicularly fixed in the resin and that fluorescence from the gold wire below the surface contributes to the signal as well. This illustrates that not only the lateral but also the vertical resolution can be of great importance, which will be further discussed below. The escape depth of the Au L $\alpha$  fluorescence is much smaller compared to the L $\alpha$  lines so that the Au L $\alpha$  contour plot provides

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Au M fluorescence is much smaller compared to the L $\alpha$  lines so that the Au M contour plot provides a better representation of the lateral dimensions and the intensity profile of the X-ray beam (Fig. 2b). The diameters of the measured peak ranged from 35  $\mu$ m to 100  $\mu$ m at half maximum and corresponded to the expected dimension when adding the spot size of the beam, as specified by the producer and varying between 10  $\mu$ m and 60  $\mu$ m, to the diameter of the wire. The best lateral resolution was achieved with a mono capillary as anticipated.

It is difficult to directly compare fluorescence yield of different capillary optics when different instruments were used, even when normalizing to the different spot sizes. This is because the counting rates depend on a large number of parameters as geometric arrangement of tube and detector, type of detector, type X-ray tube, applied tube power, application of vacuum or He flushing between sample and detector etc. In our tests we did not aim at determining the fluorescence yield as a function of capillary optics. However, we observed the trend that counting rates were, at comparable spot size and identical sample, significantly lower when using mono-capillaries compared to poly-capillaries. Lower counting rates imply that longer counting times are required to obtain similar counting statistics as with high counting rates. Long counting times can be a drawback in elemental mapping and a counting time per pixel of 5 seconds makes surveying an area of 10,000 pixels (1mm<sup>2</sup> in 10  $\mu$ m steps) already an overnight task.



xrf\_fig2\_small

Figure 2: Contour plot of X-ray fluorescence collected from a gold wire (30  $\mu$ m) imbedded into resin material. The left figure shows the contour plot for the Au L $\alpha$  lines and the right figure the Au M $\alpha$  fluorescence. Due to the greater escape depth of the Au L $\alpha$  lines fluorescence from the inclining gold wire below the surface is detected. The Au M $\alpha$  fluorescence only probes the gold wire at the surface of the sample.

### Lateral vs. vertical resolution (what is the best spot size?)

High lateral resolution can be very useful when analyzing quasi two-dimensional samples but the benefit for analyzing three-dimensional heterogeneous samples also depends on the depth to which the X-ray probes the sample. The vertical extension of the probed volume is controlled by two factors a) the penetration depths of the primary beam and b) the escape depth of the generated X-ray fluorescence. The latter is a function of the absorption length of the matrix, which, in turn, depends on the energy of the X-ray fluorescence and the electron density of the matrix. For illustrating how X-ray energy and matrix characteristics influence the analysis depth, a thin sapphire layer was imbedded between two layers of steel. This sandwich was fixed in a resin with an inclining angle of 30°. The absorption length (at which the logarithmic X-ray intensity  $\ln(I/I_0)$  decreases by one unit) of Fe K $\alpha$  radiation in sapphire is 41  $\mu$ m while for Al  $\alpha$  radiation in iron it is only 0.4  $\mu$ m. The consequences of this difference can be seen in Fig. 3 showing the fluorescence intensities of Fe and Al across the steel/sapphire/steel sequence. On the right side of the figure sapphire is inclining under the steel layer, which efficiently absorbs the Al fluorescence from the sapphire below. The width and shape of the edge is, therefore, predominately controlled by the spot size. In contrast, sapphire is relatively transparent for Fe fluorescence and the Fe signal is detected about 400  $\mu$ m away from the steel/sapphire interface at the sample surface. This means that Fe is detected about 200  $\mu$ m below the sapphire layer. The line represents the theoretical intensity change with distance when only considering Fe K $\alpha$  absorption in sapphire. The deviation from the theoretical line is caused by neglecting the change of primary beam intensity with depth. However, in this case, absorption of the primary beam is apparently only of minor importance and the depth of the probed volume for Fe is predominately constrained by absorption of Fe fluorescence in the sapphire layer.



xrf\_fig3\_small

Figure 3: Transect through a sequence of steelsapphiresteel layers inclining with 30° degrees. The orientation of the different layers is schematically shown at the top of the figure. The fluorescence intensity for Fe and Al is normalized to the maximum intensity measured along the transect and the natural logarithm of this ratio is plotted vs. lateral position. On the right side, steel overlaps the sapphire and effectively screens the Al fluorescence from deeper parts of the sample. This leads to relatively sharp edge shapes on the right side. In contrast, Fe fluorescence is detected down to 200  $\mu$ m below the sapphire layer, leading to a smooth edge shape for Fe on the left side. The line shows the expected Fe fluorescence calculated from the sapphire thickness and the absorption of Fe fluorescence in sapphire. These measurements demonstrate how the depth of the probed sample volume depends on the energy of X-ray fluorescence and matrix composition.

This exercise also shows that small beam spots are not necessarily advantageous when dealing with three dimensional, isotropically heterogeneous samples, as we often do in earth sciences. Adsorption lengths of X-ray beams with energies between 4.5 and 8 keV (K $\alpha$  lines of transition elements between Ti and Cu) in silica range from 24  $\mu$ m to 124  $\mu$ m, so that beam spots in the range of 10s of  $\mu$ m might be the best compromise for three dimensional heterogeneous samples, in view of spatial resolution and fluorescence yield.

### Detection limit and quantitative analysis

In general,  $\mu$ -XRF instruments are not suitable to analyze elements lighter than Na. For other elements, detection limits can vary by two orders of magnitudes and more due to differences in the element specific fluorescence yield and the energy of the X-ray fluorescence. The intensity loss of low energy X-rays on their path to the detector can be significant and the importance of X-ray absorption implies that detection limits also depend on the sample matrix. For transition elements detection limits between 10 and 100 ppm seem to be achievable which can be considered as the lowest possible detection limits of current  $\mu$ -XRF instruments. All instruments we tested offer the possibility to analyze the sample under vacuum or under He flux, which increases the sensitivity of the instrument for lighter elements such as Al and Si.

It should be mentioned that also the characteristics of the X-ray detector contributes to the overall performance of the instruments. At the moment, wavelength dispersive detectors are not available with  $\mu$ -XRF instruments and only instruments with energy dispersive (ED) detectors are available. Some producers offer the option to select between different detectors, whereas silicon drift detectors are interesting options because they do not require liquid nitrogen cooling and offer good energy resolution and high maximum counting rates.

The challenges of using  $\mu$ -XRF for quantitative analysis are the same as for conventional XRF instruments and other microanalysis techniques relying on X-ray fluorescence (e.g. electron microprobe) and will not be discussed here. In our tests we used rare earth element (REE) standards in glass matrix. Accounting for spectral interferences of the different REE in complex mixtures are challenging tasks in quantitative XRF analysis. In general, the standard-free (fundamental principle) quantification methods worked well for the different reference samples, in particular when including information from the glass matrix in the quantification. The determined concentrations were in the range of  $\pm 20\%$  of the specified concentrations at REE concentrations around 5 mg/kg.

### $\mu$ -XRF vs other microanalysis techniques

In view of the costs of the instrument and efforts required to perform measurements  $\mu$ -XRF can be possibly best compared to scanning electron microscopy (SEM). Electron beams can be used to generate X-ray fluorescence and SEM instruments, equipped with ED detectors, can be used for elemental analysis. The great advantage of electron beams is that they can be much easier focused than X-rays and resolutions in the nm range are standard for SEM instruments. In contrast to X-ray fluorescence, the analyzing depth is much shallower because the electron beam does not penetrate into the sample as deep as the primary X-ray beam in XRF. A distinct disadvantage of using electron beams for XRF



deep as the primary X-ray beam in AXRF. A principle disadvantage of using electron beams for AXRF spectroscopy is that they create much higher background radiation than X-rays due to the formation of bremsstrahlung in the sample. Furthermore, SEM instruments are, in the first instance, designed for optimal visualization of the sample and not for elemental imaging. Hence, when elemental analysis is the main goal,  $\mu$ -XRF is superior to SEM as long as the spatial resolution of the  $\mu$ -XRF is sufficient. Another aspect is that  $\mu$ -XRF does not necessarily require vacuum, so that the analysis of wet samples is possible. Finally, the sample chamber of bench-top  $\mu$ -XRF is much larger compared to SEM instruments so that the analysis of larger samples is no problem.

Regarding elemental analysis, transmission electron microscopy (TEM) has the same restrictions as SEM, besides that only tiny samples can be analyzed. The strength of TEM is that visualization and elemental analysis can be combined with complementary information when using electron diffraction (crystal structure) or electron energy loss spectroscopy (redox state, coordination environment).

***"When elemental analysis is the main goal,  $\mu$ -XRF is superior to SEM as long as the spatial resolution of the  $\mu$ -XRF is sufficient"***

Bench-top  $\mu$ -XRF cannot compete with synchrotron  $\mu$ -XRF (S- $\mu$ -XRF) where a beam spot size of 100 nm and lower can be realized (for three dimensional heterogeneous samples the considerations regarding analyzing depth are the same as for bench-top  $\mu$ -XRF). Another strength of S- $\mu$ -XRF is that elemental analysis can be combined with other microanalysis techniques such as micro-X-ray absorption spectroscopy (redox state, coordination environment) or micro-XRD (crystal structure).  $\mu$ -XRF can certainly also not redundantly other high-performance microanalysis techniques such as electron microprobe, SIMS, or LA-ICP-MS.

In conclusion, bench-top  $\mu$ -XRF does not open principally new analytical possibilities in Earth sciences, but it has a great potential to be widely used for elemental imaging when the desired information can be obtained within the constraints of resolution ( $>10 \mu\text{m}$ ), atomic number ( $>10$ ), and detection limit ( $>10 \text{ ppm}$ ). The plus factors are the user friendliness, relatively low costs, and that practically no or only little sample preparation is required. Besides serving as stand alone instrument for elemental analysis, bench-top  $\mu$ -XRF can be very useful for selecting samples and sample areas before applying more sophisticated microanalysis techniques.

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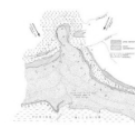
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## D.N. Wadia and the Geology of the Himalaya



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*"A giant among geologists, Darashaw Noshervan Wadia was a great visionary who not only shaped our understanding of the geological making of the Indian subcontinent but also set the national agenda of geological activities when India won freedom." --K. S. Valdiya*

*"Fortunately for India, it found in Wadia an eminent geologist of its own, who would enthuse generations of Indian geologists. To say that he was energetic and hardworking is perhaps an understatement; one found clambering up and down the Nanga Parbat area of the Himalayas, at the height of twelve thousand feet, when he was fifty." --Biman Nath*

### Background (1883-1920)

Darashaw Noshervan (D.N.) Wadia was born in October 1883 in Surat in Gujarat State but in 1894 the family moved to Boroda (also in Gujarat State) in order to get a better education for their son. He attended first a private Gujarati school and then the Sir J.J. English School and it was there that he got his love of science and devotion to knowledge. At the age of 16, Wadia went to Baroda College, then part of the University of Bombay. He took a B.Sc. degree in Botany and Zoology in 1903 and a second B.Sc. degree in Botany and Geology in 1905 (Stubblefield 1970). At that time, geology was only taught in Calcutta and Madras. Wadia was therefore largely self taught as a geologist!

In 1907, at the age of 23, Wadia had the good fortune to be appointed Professor of Geology at the Prince of Wales College in Jammu in the southernmost part of the State of Jammu and Kashmir (Stubblefield 1970). He stayed there until 1921. From there, he could already set his eyes on the distant Himalaya. There is no doubt that his early life amongst the mountains of Kashmir provided inspiration for much of his later work on the structure and stratigraphy of the North-West Himalaya (West 1965, P. 2).

Wadia's main task as a lecturer in Geology was preparing the students for the Punjab University Examinations. However, he experienced great difficulty teaching the geology of India because of the lack of suitable textbooks. He therefore took the extreme solution of writing his own. The first edition of The Geology of India for Students was published in 1919 and the sixth edition, The Geology of India, was published in 1966. The Geology of India is a remarkable book. The sixth edition is 536 pages long and divided into three main sections, the first, relatively short, on the Physical features of India, the second a huge contribution on the stratigraphy of India from the Archaean to the Pleistocene and Recent and finally a relatively short section on the Economic Geology of India. This book had a profound influence on generations of students of geology in India and is still in use today (West 1965).

During his time in Jammu, Wadia used to take his students on adventure trekking and investigative field trips in the Siwalik Hills of the Jammu region. Among the fossils he collected during these years were a 10 ft-long long tusk and skull fragments of an elephant-like mammal, Stegodon ganesa, which he found in the Upper Siwalik Formation six miles north of Jammu (Stubblefield 1970; Vygyan Prasara undated). In 1928, Wadia subsequently identified a skull of Actinodon risinensis, collected from the Lower Gondwana beds near Zewan in Kashmir (West 1965). These two fossil discoveries were of great import (Thakur 2003).

### Geological Survey of India (1920-1938)

In 1920, the Geological Survey of India received authority to increase its complement of scientific officers from 20 to 32. Wadia was appointed to one of these positions at the relatively late age of 37 in 1921. He was the first Indian to be appointed to the GSI whose degrees came from an Indian university (Stubblefield 1970). At that time, the GSI was resuming its mapping in the Himalaya in some areas where topographic maps at one inch to the mile had become available. Wadia began his career at the GSI by mapping 2000 square miles of the mountainous Poonch State in the Lesser Himalayas and an additional 2100 square miles in the adjacent parts of the Punjab. This formed the basis of his first substantial memoir for the GSI in 1928 (Wadia 1928). One of the principal findings of this study was his explanation of the unique knee bend of the mountain chains around the knot called Nanga Parbat as the result of the interaction of the Himalaya with the tongue like projection of the Archaean Shield (West 1965; Stubblefield 1970; Thakur 2003) (Fig. 1; Thakur 2003, P. 71). The tectonics of the Nanga Parbat Syntaxis has recently been the subject of a Memoir of the Geological Society (Khan et al. 2000). For this work, Wadia was awarded the Back Award of the Royal Geographical Society in 1934 and the Lyell Medal of the Geological Society in 1943 (West 1965).

In 1930-31, Wadia continued his mapping of the high ground around Nanga Parbat (peak at 26,620 ft) with only old 1/2 and 1 inch topographic maps available to him (West 1965; Stubblefield 1970). He described the mountain as 'a peak of arresting grandeur...Its southern flank exposes a rock face whose butterressed cliffs, 12,000 ft high pierce the sky almost in one leap'. The surrounding slopes were concealed under many square miles of uninterrupted snow fields. Wadia described the Nanga Parbat mountain mass, the central and most commanding feature of the whole district as above 15,000 ft and 'almost inaccessible to the single field geologist, unequipped with elaborate mountaineering outfit, parties of carriers, etc.' (Thakur 2003). However, Wadia was able to deduce the geology of the higher parts of the mountain above the snow line by examining the moraine deposits. On this basis, he considered the geology of the mountain to be 'rather simple' to

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which his director replied that it must be rather pleasant to possess the philosophical temperament to regard this complexity as simple (Stubblefield 1970). Nonetheless, field work in this barren area undertaken at the age of 50 would have required great tenacity from him (West 1965).

During his time at GSI, Wadia was also able to extend his studies on vertebrate fossils from the Siwalik strata of the Potwar and Kashmir at the British Museum from 1926-1927 and to visit geological institutions in Germany, Austria and Czechoslovakia (Stubblefield 1970). He also attended the 3rd International Congress of Soil Science in Oxford in 1938. In 1937, he contributed two papers on the tectonic relations of the Himalayas with the North Indian Foreland and on the palaeogeography and climate during the Permo-Carboniferous at the International Geological Congress in Moscow, although he was unable to attend in person. In 1938, he also published a catalogue of fossil primates discovered in the Tertiary deposits in India (West 1965).

Wadia's contribution to the soil science in India was very significant (Vygyan Prasar undated). Wadia not only noted the neglect of soil science in India but also showed the way for improvement in his own writings. In 1935 Wadia, jointly with M. S. Krishnan and P. N. Mukherjee, published the first soil map of India. This was published by the GSI and paved the way for later soil maps. Wadia's work therefore had considerable bearing on agricultural development in the country. He represented India at the 3rd International Congress of Soil Science held at Oxford in 1935 and also participated in an excursion arranged by the Congress to study the soil profiles in England, Wales and Scotland.

In 1938, Wadia reached the retirement age in the GSI (55). In that year, he gave the Presidential Address to the Geology Section of the Indian Science Congress during its Jubilee Meeting in Calcutta (Stubblefield 1970). He also provided a chapter dealing with geology and geography to the Congress Volume entitled Progress in Science during the last twenty-five years and gave a president's address on the Himalayas to the Geology Section.

### Government Mineralogist Ceylon (1938-1945)

On his retirement from the GSI in 1938, Wadia accepted an offer from the Government of Ceylon to become its Government Mineralogist. His main recommendation was that a systematic survey of the island should be undertaken in order to prepare an accurate geological map of the island. This work was impeded by the lack of qualified staff. However, he managed to produce a number of reports to the government on water supply, peat, glass sands, gem gravels and minerals of economic value (Stubblefield 1970). He also produced accurate geological maps of the island and geological investigations concerning water supply, dam-sites and other engineering projects (Vygyan Prasar undated).

Wadia's first wife had died in the 1930s and in 1940 he married Meher Medivala in Colombo in 1940. She was a mineralogist and graduate of the University of Bombay and was to be his constant companion for the rest of his life. She was an established scientist in her own right and published a book on Minerals of India in 1966 (Mrs. Meher D.N. Wadia 1966).

In 1942, Wadia became General President of the Indian Science Congress. At the 1943 meeting of the Congress in Calcutta, Wadia spoke on 'Minerals' share in the war' (Wadia 1943). He pointed out that this was the first time in the 4 millenniums of India's recorded history that the enemy has assaulted the eastern frontiers of the country and reported on India's response to the invaders, through its munitions factories, its electric, chemical and technical plants and industrial research laboratories. He also pleaded for a justly planned international mineral policy to preserve peace and goodwill among countries (Stubblefield 1970). This speech, published in Science, was an impressive contribution in the time of war.

### 1945-1969

In 1945 Wadia was appointed the Geological Advisor to the national government of Jawaharlal Nehru to initiate and formulate a mineral policy for India (Vygyan Prasar undated). He realized that the estimates of raw mineral resources needed reassessment (Stubblefield 1970). Following Independence in 1947, supplies of some minerals (salt and gypsum) were indeed found to be in short supply with the passing of territory to Pakistan. In 1947, he announced the setting up of a Mineral Advisory Board to advise on mineral development. In 1948, Wadia became the first Director of the Indian Bureau of Mines assisted by two officers. The Bureau drafted the Mines and Minerals Act (1948), the Mineral Concession Rules (1949) and the Petroleum Concession Rules (1949). In 1949, Wadia left the Bureau to serve on the Atomic Energy Commission.

In 1948, Wadia attended the International Geological Congress in London and presented a paper on the fluvial sediments of NW India (Stubblefield 1970). In his capacity as head of the Indian delegation, Wadia also conveyed an invitation on behalf of the Indian Government to host the XIX Congress in New Delhi to coincide with the centenary of the formation of the GSI. However, the conference went to France and it was not until 1964 that India was able to host the IGC the XXII International Geological Congress in Delhi with D.N. Wadia as President.

In addition, the Indian Atomic Energy commission had been set up in 1948 and Wadia was appointed to guide the work on the Commission's Raw Materials Division. This division grew under him into a 'well-knit unit of 470 geologists and geophysicists, mining and drilling personnel'.

In 1963, Wadia gave the Meghnad Saha Lecture on The Himalaya Mountains: Their age, origin and sub-crustal relations in which he essentially summarized his ideas on the formation of the Himalaya developed over a life time (Wadia 1963).

In 1965, the D.N. Wadia Commemorative Volume consisting of 60 separate articles was published in Wadia's honour by the Mining, Geological and Metallurgical Institute of India (Jhingran 1965).

Wadia was also heavily involved in founding the Indian Institute of Himalayan Geology in Dehra Dun of which he was made the first honorary director. The institute was named the Wadia Institute of Himalayan Geology after his death.

### Post Script

Wadia received many prestigious honours and awards. In 1957, he was elected a Fellow of the Royal Society of London (Vygyan Prasad undated.). He was also President of the Geology Section of the Indian Science Congress (1921 and 1938); General President of the Indian Science Congress (1942 and 1943); President of the National Institute of Sciences of India (later renamed as Indian National Science Academy) during 1946-47; Honorary D.Sc. from

as Indian National Science Academy) during 1946-47, honorary D.Sc. from Delhi University (1947), Inaugural President of Indian Society of Soil Sciences (1949); President of the Geological Society of India (1951-52); President of the Mining, Geological and Metallurgical Institute of India (1951-52); President of the XXII International Geological Congress at Delhi (1964) and Chairman of the Indian National committee for Oceanic Research. In 1962, he became the first geologist to be made a National Professor by the Indian Government.

Wadia was a field geologist through and through. For months on end, he would leave his camp at day-break for a good 20 miles traverse on foot in trackless mountain or on a much longer ride on mule or horse back, a late lunch his first meal of the day. With the passage of years, work became tantamount to life itself (Stubblefield 1970). 'The best work is done with the least amenities' was his favourite dictum. He died on June 15, 1969 at the age of 86. He was without doubt the best India has produced.

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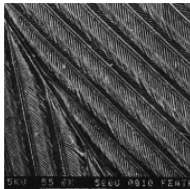
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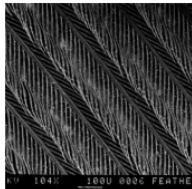




## Chirpy Chirpy Cheep Cheep: Geochemistry for the Birds



SEM image of a bird feather ...



SEM image of a bird feather ...

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In this age of bird flu and global change, pinpointing bird migration routes and monitoring any changes in them has become of considerable interest. In the past, all sorts of methods have been used as tools in this type of research, but Laura Font may have found a new and better way.

Dr. Laura Font is currently based at the Faculty of Earth and Life Sciences at the Vrije Universiteit in Amsterdam, where she is a Marie Curie post-doctoral fellow in the Petrology Department. She started her project in February 2008. Prior to that, Laura was employed at Durham University, which she joined in 2004 on a NERC fellowship. She graduated from the Universitat de Barcelona in 1997, then worked in France, obtained her Ph.D. from the University of Southampton in the U.K., and moved to Italy as a post-doctoral fellow before returning to the U.K.

In Durham, Laura's research involved measuring Sr and Pb isotopes in plagioclase from volcanic samples. It was at Durham where Laura started developing her method to use Sr and Pb isotopes in bird feathers to track bird migration routes.

Previously, other isotopes (H, C and O) as well as certain trace elements have been used to infer migration routes. Sulfur isotopes in combination with hydrogen isotopes were also tried, in an attempt to distinguish between birds foraging in the marine realm and terrestrial feeders. The problem with such methods is that their discriminatory power is relatively limited, and fractionation mechanisms in birds complicate matters in some cases. Other methods such as the use of tags or leg bands and the counting of birds at specific locations are labor-intensive and do not carry an overwhelming success rate. In addition, censuses do not provide any data on origin.

**The problem with (previous) isotope methods is that their discriminatory power is relatively limited, and fractionation mechanisms in birds complicate matters in some cases.**

Using feathers to obtain information about bird migration is relatively easy and its impact on birds is minimal. While many bird feathers do have a blood supply when still attached to the bird, these veins do not run along the entire shaft. A large part of a feather could therefore be clipped off without impacting a bird's flight at all. However, this process is often not even necessary as birds naturally lose enough feathers that can simply be collected on-site. To use the composition of bird feathers as a much less invasive and less labor-intensive method is therefore quite promising.

Previous studies involving bones, claws and shells had already shown that Sr isotopes do not appear to fractionate in birds and therefore reflect a bird's natural environment (there are geological situations involving preferential release of Sr during weathering that require special care, but for most geological samples, the relationship is also quite straightforward). However, what is seen most notably in bones tends to reflect the bird's environment over its entire lifetime--birds are relatively long-lived. Bird migration research wants to acquire data on the bird's environment at, for example, prior to and after migration (i.e. much shorter time-scales). Feathers represent such specific points or shorter periods because they periodically renew their feathers. Bird feathers consist largely of keratin, like human hair and finger nails, and reflect what the organism has consumed. The analysis of Sr isotopes in bird feathers is not a new idea in itself but Dr. Font's method is a different story.

**Sr isotopes do not appear to fractionate in birds and therefore reflect a bird's natural environment**

First of all, a method had to be devised to remove all dust from the feathers as this dust would constitute serious sample contamination. Tests were carried out in which a bird's dust bath was simulated by sweeping feathers through a sandy soil, followed by various cleaning methods and SEM imaging to inspect the feathers' cleanliness. Using several blasts of nitrogen gas turned out to be the best way to remove both dust and wax deposits.

The next problem is that the Sr content in most feather samples is incredibly low. Multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) is not able to measure quantities as low as < 12 ng Sr because of Kr interferences (Kr is present in the Ar plasma). Dr. Font's new method uses ultra-low blank ion-exchange chemistry followed by thermal ionization mass spectrometry (TIMS). Sample preparation is necessary to preconcentrate the Sr and to remove as much organic material as possible from the sample. The organics would interfere with the column chemistry and if you load a "dirty" sample on a TIMS Re filament, you are not going to get good results (if any at all).

To optimize ionisation, the feather-derived samples are loaded onto a very small area of the filament by running a 1-A current through it and melting two strips of parafilm onto the filament to define the loading area. After loading a mix of sample and TaF5 activator, the parafilm is burned off with a 2-A current. At the end, more activator is loaded on top of the sample to seal the sample onto the filament and prevent any sample loss.

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by Angelina Souren

sample used.

Dr. Font is now developing a new method for the analysis of Pb isotopes in bird feathers that will use the same fraction as used for the Sr analysis (collected from the columns after the Sr fraction). In 2007, feathers had already been collected at various sites in Europe and Africa for the new project. In 2008, Dr. Font collected feathers from Pied Flycatchers and Collared Flycatchers in Gotland in Sweden as well as soil, water, bird prey and feces samples. Hopefully this method will continue to reveal new exciting behaviors that the Sr method did before it. In the end, it's nice to see work that oozes so much elegance and thoroughness in all its details, not to mention an innovative and exploring spirit.

For more details on this method, see Font et al. (2007) Sr isotope analysis of bird feathers by TIMS: a tool to trace bird migration paths and breeding sites. *Journal of Analytical Atomic Spectrometry*, 22, 513-522.

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