Illuminating the functionality of iron

For the last four years, **Professor Dr Stefan Peiffer** has been chairing an interdisciplinary research network seeking to better understand the role of iron in environmental processes. Here, he talks about the work's significance to a broad range of disciplines, from microbiology to contaminant hydrology

What were the overall aims of the Functionality of Iron Minerals in Environmental Processes (FIMIN) Research Network Programme (RNP), and your role within it?

The scientific aim of FIMIN, which finished in 2013, was to elucidate the functionality of iron minerals. The cycling of electrons and matter through iron minerals is of relevance to multiple and contrasting disciplines within the environmental sciences, including geochemistry, biogeochemistry, microbiology, soil and hydrological sciences and biotechnology. Therefore, FIMIN aimed to: increase understanding of the surface reactivity of iron minerals from a mechanistic point of view; better understand the mechanisms and strategies that microorganisms adopt to cope with surface chemical constraints; integrate this knowledge into the modelling and quantification of electron fluxes in natural systems; and develop sound strategies to make use of the functionality of iron minerals in (bio)technological applications. As an RNP, we intended to achieve these scientific aims by creating an active network kept alive through workshops, travel grants, etc.

Could you elaborate on what is meant by the 'functionality of iron minerals' and why this is significant to so many disciplines?

Iron minerals are an abundant component of the Earth's surface. They perform many functions in the environment thanks to their chemical properties. Firstly, they serve as both electron acceptors and electron donors for microbial processes (in the form of iron oxides and iron sulphides respectively). Additionally, they have large and highly reactive surfaces, making them effective sorbents and important reactants in contaminant degradation and removal, and in nutrient cycling. For this reason, knowledge about their functionality is important to fields including microbiology, biogeochemistry, environmental chemistry and contaminant hydrology.

What are some of the current biggest barriers to a more widely adopted interdisciplinary environment within the European research community?

Scientists must receive supra-disciplinary training if they are to change their perception of scientific problems; university curricula are still overwhelmingly discipline-orientated. However, it is my personal experience that postgraduate students and postdoctoral researchers are willing and curious to look beyond their discipline when the problem they are working on has an interdisciplinary component. For this to happen effectively, the students need to be supported through tailor-made curricula and activities at the appropriate academic level.

How have advances in instrumental and analytical tools – particularly within geochemistry and microbiology – changed our ability to understand the environmental processes in which iron minerals play an important role?

Recent advances in microscopical spectroscopy have allowed us to gain a greater insight into the molecular processes taking place at mineral surfaces – such as catalytic activities – and into microbial surfaces interacting with minerals – such as how electron transfer occurs. This has enabled us to test theories established during earlier observations, or from theoretical considerations.

In particular, the dynamic nature of mineral phases occurring in environments exposed to rapid geochemical changes became evident. This means that minerals are far from being static entities; they rapidly alter their properties and form so-called metastable states. In other words, although minerals found in soils and sediments share a name with those found in mineral collections, they have completely different properties that we are slowly beginning to understand thanks to modern instrumentation. This demonstrates how advances in the field can enable us to better understand the functionality of iron minerals within such systems.

Finally, what are some of the major deliverables that FIMIN has brought to the international iron research community?

Since FIMIN was a research network, the team did not have funds to pursue a specific research question, the result of which could have be regarded as a deliverable. However, we were able to organise an international conference at the Monte Verità conference centre in Ascona, Switzerland, entitled 'Iron Biogeochemistry – From Molecular Processes to Global Cycles', which attracted around 100 attendants, nearly a quarter of whom were from overseas. The conference was a significant achievement for FIMIN, and definitely marked a highlight for the international iron research community.

An interdisciplinary approach to iron

Iron plays a crucial role in numerous environmental interactions, making it an important element for interdisciplinary study. In recent years, the groundbreaking **FIMIN** research network has made great strides in training the next generation of scientists to study the role of iron across a breadth of specialisms

IRON IS THE fourth most abundant element in the Earth's crust, and plays a principal role in a wide range of environmentally significant processes, including metabolic processes, the growth of bacteria and archaea, and sediment diagenesis. However, if we are to fully understand the array of (bio)geochemical reactions relating to the surface properties and transformation reactions of iron minerals that are necessary for such functions, a multidisciplinary approach is required.

In response to growing concerns about a lack of crossover in scientific research in this area, in 2009 the European Science Foundation (ESF) launched the 'The Functionality of Iron Minerals in Environmental Processes' (FIMIN) Research Network Programme. "We identified certain topics as key themes in which young scientists need to be trained in order to acquire enough knowledge to be able to cope with important environmental problems in which the element iron is involved," explains FIMIN's Chair, Professor Dr Stefan Peiffer of the University of Bayreuth, Germany. "These included mining and associated contamination, which is mainly controlled by iron minerals; contaminant degradation under anaerobic conditions, with iron being a key redox species for microbial processes; and control of nutrient mobility in aquatic and soil systems, which is closely linked to the geochemistry of iron."

A DIVERSE NETWORK

Peiffer and his colleagues at FIMIN believe it is essential that the researchers of the future are adequately equipped to face inevitable environmental challenges; an improved understanding of iron's functionality could, among other things, enhance humankind's ability to regulate CO_2 emissions, remediate contaminated sites and supply societies with clean water. Therefore, over the length of its four-year duration (2009-13), FIMIN has made great strides in forging important links between disciplines whilst simultaneously providing researchers with the knowledge, technology and networks necessary to execute world-class research along four themes: the role of iron oxide surfaces in biogeochemistry; iron as a key redox species in microbial processes; the environmental biogeochemistry of iron; and the development


IRON-COATED STREAM BED


DISCHARGE OF IRON-RICH GROUNDWATER

INTELLIGENCE

FIMIN

THE FUNCTIONALITY OF IRON MINERALS IN ENVIRONMENTAL PROCESSES

OBJECTIVES

- To improve understanding of the surface reactivity of iron minerals from a mechanistic point of view
- To understand the mechanisms and strategies microorganisms adopt to cope with surface chemical constraints
- To integrate this knowledge into the modelling and quantification of electron fluxes in natural systems
- To develop sound strategies to make use of the functionality of iron minerals in (bio) technological applications

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FUNDING

European Science Foundation (ESF)

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STEFAN PEIFFER received his PhD from the University of Bayreuth. After postdoctoral stays at EAWAG, Switzerland, and in Bayreuth, he received a full professorship at Aachen University of Technology, Germany, in 2001. Since 2003, he has held the Chair of Hydrology at the University of Bayreuth, where he is currently Director of the Bayreuth Center of Ecology and Environmental Science (BayCEER). For over 20 years, Peiffer has been working on redox processes, with a focus on coupled geochemical and microbial processes in sedimentary and groundwater environments and the interaction between the iron and sulphur cycle. His current research activities include the kinetics and mechanisms of surface-mediated mineral transformations with special emphasis on iron-sulphur interactions and the effect of advective groundwater flow on biogeochemical process rates during groundwater-surface water interactions.

Bayreuth Center of Ecology and Environmental Research

ACIDIC IRON PECIPITATES IN A PUDDLE

of techniques capable of identifying processes related to iron biogeochemistry.

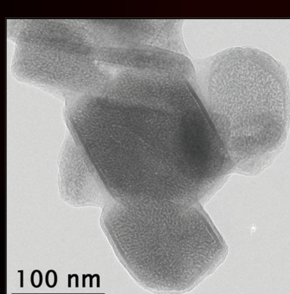
Early stage researchers (ESRs) in disciplines related to FIMIN's aims routinely face a number of diverse challenges. ESRs working in laboratories are often unaware of the high-end techniques which could assist them in researching their topics. In order to combat this, Peiffer and his colleagues took the decision to provide students with a variety of workshops and summer schools. The network also set up workshops to run alongside this approach, enabling participants to establish beneficial links and contacts, and awarded travel grants to support movement between partner institutions.

CUTTING-EDGE TECHNOLOGY

Even when aware of high-end technology, ESRs often lack access to the necessary cutting-edge analytical instruments and supervisors with expertise in using them. "Since modern analytical instrumentation is expensive and resource intensive, FIMIN worked hard to distribute it all over Europe, with no one laboratory having all the equipment at their disposal," Peiffer explains

One significant state-of-the-art geochemical technology that FIMIN facilitated the sharing of was cryogenic X-ray photoelectron spectroscopy (cryo XPS), which is used to examine the way in which sulphur species form when hydrogen sulphide reacts with iron oxide minerals. The reaction is particularly common in a number of oxygen-free environments, and plays a key role in (amongst other things) the carbon cycle. XPS enables researchers to identify elements and their chemical environment at mineral surfaces.

The ESRs studied the sulphuric reaction at cryogenic temperatures in order to preclude the unwanted alteration of their samples. "During this process, my student Moli Wan was able to demonstrate for the first time that a large fraction of the sulphur can be retrieved as surface-bound polysulphides – a result that nobody would have expected and which will completely change our geochemical perception of this reaction," Peiffer recalls.



IRON OXIDE CRYSTALS COATED WITH A RIM OF IRON SULPHIDE

A COMPLEX EVALUATION PROCESS

In the simplest terms, Peiffer and his team are assessing the success of FIMIN based on how many publications are produced by its members. However, given that a number of the ESRs who received FIMIN travel grants are still developing their research, this is not an easy task. Currently, the number of papers that resulted directly from FIMIN activities stands at 10, but there is an expectation that this will significantly rise over the coming months.

"In addition to counting published articles," Peiffer elaborates, "FIMIN is also able to gauge its success by taking into account the number of bi- and trilateral collaborations between research institutes that would presumably not have become active without us, and which have outlasted the FIMIN project". Though difficult to quantify, it is clear that the FIMIN project has enjoyed a significant amount of success, enabling researchers around Europe and beyond to forge links and carry out collaborative work that would not otherwise have been possible.

LIFE AFTER FIMIN

Following on from the success of FIMIN, last autumn Peiffer and his colleagues submitted a proposal to the EU for the creation of an initial training network (ITN) which they hope will be renewed next year. The suggested title of the ITN is 'Phosphorus in an Iron fist: coupling Elemental Cycles across Ecosystems and Scales', in response to the fact that phosphorous is the eutrophying nutrient that leads to algae blooms in multiple freshwater and marine systems. "The chemical rationale underlying this title is that the phosphate ion has a strong affinity to the surface of iron oxides," Peiffer illuminates. "The occurrence of iron oxides should prevent eutrophication because they act as phosphorous traps – this is the 'iron fist'."

However, iron oxides also impact upon a number of other element cycles, including carbon and sulphur, both of which strongly interfere with eutrophication mechanisms, either catalysing or postponing the dissolution of iron minerals. Peiffer and his colleagues are aware that these interactions are highly complex, and the extent to which they are significant varies from one context to the next, and according to environmental factors. "It becomes clear that phosphorous control within a catchment is a complicated topic, and requires extremely specialised researchers," he summarises.

The proposed network will be supra-disciplinary in nature and, as such, will aim to train scientists not only to juggle the multiple disciplines of hydrology, geochemistry and microbiology, but also to master management practices throughout Europe. In pursuit of this goal, Peiffer has established a number of links with companies and environmental agencies, and there is much hope amongst the team that the ITN will prove to be as successful, productive and inspiring as the FIMIN project.