Mineralogical Society at 150: Past Discoveries and Future Frontiers

The University of Manchester

Mineralogical Society of the UK and Ireland

150 Years

PROGRAMME AND ABSTRACTS

Scan this code for a form to assess student presentations

You can also find a link at
https://minsoc-150.org/student-presentations/

Programme of Events

Monday, 22nd June
17.00-18.00 Registration (*Foyer, Schuster Building)* 18.00-20.00 Ice-breaker Reception – Schuster Building
Tuesday 23rd June
Rutherford Lecture Theatre 08.40 – Welcome
08.50-09.00 – Presentation by Sponsor – **Rigaku**
09.00–09.50 - **PLENARY**: Searching for Earth's missing magma oceans Williams, H., Amsellem, E., Matthews, S. and Puchtel, I. HALLIMOND LECTURE
09.50-10.00 – Presentation by Sponsor – **Blue Scientific Ltd.**
10.00-17.50 – Scientific Sessions 1, 4, 8, 10
18.45 – Pre-banquet drinks + group photograph. *Whitworth Hall* 19.30 – Banquet, including presentation of Society History by S. Shaw
Wednesday, 24th June
Rutherford Lecture Theatre 09.00–09.50 - **PLENARY**: Clay-Based Stimuli-Responsive Materials: A Versatile Platform for Smart Functional Systems J. Brendlé GEORGE BROWN LECTURE
09.50-10.00 - Presentation by Sponsor – **Renishaw**
10.00-14.20 – Scientific Sessions 2, 5 and 9
14.30-15.00 – Poster Flash Presentations, Rutherford Lecture Theatre 15.00-17.00 – Poster Session
18.30 – Society Medallists' Reception and Dinner hosted by E. and P. Grew (invitation only)
Thursday, 25th June
09.00-15.30 – Scientific Sessions 3, 6, 7
15.30-15.50 – Break
15.50-16.00 – Presentation by Sponsor – **Elemental Scientific Instruments**
Rutherford Lecture Theatre 16.00-16.50 - **PLENARY**: Research on the Edge Berry, A.J.
16.50–17.30 Presentation of Awards and Closing Ceremony

Moseley Lecture Theatre

Session 1: Universal: Mineralogy: then, now and beyond

Convenors: H. Pendlowski (The James Hutton Institute, Aberdeen), Ralf Gertisser (Keele University)

10.00-10.30	Rumsey, M. (KEYNOTE)	The Importance and the future of collections: Reviewing the critical relationship between national museums and subject specialist societies
10.30-10.50	Hansen, R.F	A short history of synthetic gem materials in the collections of the Natural History Museum, London
10.50-11.10	Gabriel, N.W. and Burleson, L.	Preserving susceptible minerals in museum collections
11.10-11.40	**BREAK**	
11.40-12.00	Brookshaw, D.R., Pearce, S.R., Wright, T. and Hartshorne, C.	The role of detailed mineralogical and chemical analyses in mine waste management
12.00-12.20	Turner, S.M.R., Gray-Wannell, N., Ghosh, U., Zhang, Z., and Hillier, S. REMOTE	Mineralogy of PFAS containing soils in Scotland: Correlations with clay minerals and Fe-oxides
12.20-12.40	**San-Cipriano, A**., Santamaría-López, A., García-Romero, E. and Suárez, M.	Mineralogical and textural characterization of APS minerals from the Madriguera deposit, Segovia (Spain).
12.40-13.10	Di Maggio, R.M. (KEYNOTE)	Tracing Crime through Minerals: The Role of Mineralogy in Forensic Investigations
13.10-14.00	**LUNCH**	
14.00-14.20	Henry, D.J.	150 years of tourmaline studies
14.20-14.40	Cámara, F., Holtstam, D. and Karlsson A.	A new polysomatic series among the lead silicates friisite and jagoite
14.40-15.10	Ma, Lin (KEYNOTE) MAX HEY MEDALLIST	Seeing Mineral Reactions in 4D: Imaging Dynamic Subsurface Processes from Micro- to Nano-scale
15.10-15.40	**BREAK**	
15.40-16.10	Hawthorne, F.C. (KEYNOTE) REMOTE	Crystal Chemistry: New Rules for the 21st Century
16.10-16.40	Hazen, Robert M. and Wong, Michael L. (KEYNOTE)	Time's Second Arrow: Mineral Evolution as a Case Study of a New Natural Law

Rutherford Lecture Theatre

09.00–09.50 - **PLENARY**: Searching for Earth's missing magma oceans
Williams, H., Amsellem, E., Matthews, S. and Puchtel, I. HALLIMOND LECTURE

Session 4: Minerals for a Sustainable Environment

Convenors: John MacDonald (University of Glasgow), David McNamara (University of Liverpool), Faisal Khudhur (University of Edinburgh)

10.00-10.20	**Ardhanari, M.**, Moore. K.M., Gallagher, L., Franks. D.M., Segura-Salazar, J., Yan. X. and Zils, M.	Valuing sand for sustainable resource transitions
10.20-10.50	Bastianini, l., Rogerson, M., Campbell, J., Baltruschat, S., Hartmann, J., Foteinis, S., Millar, R., Yang, A., Lu, X., Thoutam, P., Kapadia, A., Harrington, K., Rosair, G., Higgins, S., Buckman, J., Renforth, P. and Mayes, W. (KEYNOTE)	Minerals in the Anthropocene: Carbonate Formation, Contaminant Dynamics and Engineered Alkalinity
10.50-11.10	Burke, I. T., Mayes W.M. and Renforth, P.	Mineralogical Controls on Carbonation Rates and Vanadium Leaching Behaviour in Alkaline Steel-Slag Systems
11.10-11.40	**BREAK**	
11.40-12.00	McNamara, D.D., Pasquet, P., Gardner, J., and IODP Expedition 395 Science Party	Offshore Mineral Carbonation Potential: Insights from the Mid-Atlantic Ridge
12.00-12.20	**Alexander, J.S.**, McNamara, D., Mariani, E., Gardner, J., Cooper, M.	Mineralogical Controls on Mineral Carbonation of Basalt: Alteration and Zeolitisation in the Antrim Lava Group
12.20-12.40	Stevenson, S.C., Lunn, R. and Stillings, M.	Mechanochemical carbon capture using rock substrates
12.40-13.00	**Doñagueda Suso, B.**, Stevenson, S., Stillings, M., Shipton, Z. and Lunn, R.	Understanding Direct CO_2 Uptake In Polymineralic Rocks Using Mechanochemistry
13.00-14.00	**LUNCH**	
14.00-14.20	Farrell, N.J.C., Yang, L., Flowerdew, M.J., Mark, C., Ardo, B., Taylor, K.G., Bigaroni, N., Pointon, M., Hughes, L., Waters, J. and Paul, L.	Feldspar alteration by disequilibrium CO_2–H_2O fluids in reservoir sandstones: Implications for carbon capture and storage (CCS)
14.20-14.40	Ghasemi, M.	Clay Minerals in Subsurface Hydrogen Storage: A Molecular-Scale Perspective
14.40-15.00	Khudhur, F., Butler, I. and Gilfillan, S.M.V.	The applicability of image-based analyses in the study of CO_2 mineralization
15.00-15.30	**BREAK**	
15.30-16.00	Manning, D.A.C. (KEYNOTE)	Minerals: the Achilles Heel in Enhanced Rock Weathering
16.00-16.20	**Dickinson, H.**, MacDonald, J.M. and Toney, J.	Enzyme-Mediated Multiphase Precipitation (EMMP): Coupled Carbonate–Phosphate Mineralisation for Sustainable Metal Immobilisation and Carbon Removal

16.20-16.40	Aghdam, M.M., Crowley, Q. and Guyett, P.	Multi-Scale Insights Linking Minerals to Gamma Radiation, Radon and Thoron in Building Materials
16.40-17.00	**Lo, Pok Man Ethan**, Littleton, J.A.H., Evans, A.J.M., McElhinney, T.R., Wang, B. and Hunt, S.A.	Phase Diagram of Olivine-Structured Battery Cathodes: $LiMPO_4$ (M = Mn, Fe, Ni)
17.00-17.20	Peacock, C.L., Xiao K-Q., Moore, O.W., Babakhani, P., Zhao, M., Curti, L., Dale, A.W. and Woulds, C.	Mineralogical controls on organic carbon stabilisation and persistence
17.20-17.40	Babakhani, P., Dale, A.W., Sedighi, M. Jazaei, F. and Peacock, C.L.	Artificial intelligence predicts mineral protection of organic carbon in global marine sediments
17.40-18.00	**Aliyeva A.**, Abdullayev, E. and Lemarchand, D. REMOTE	Smectite illitization in mud volcano systems: Implications for geological CO_2 storage – a natural analogue study from Azerbaijan

Blackett Lecture Theatre

Session 8: Crystal records of volcanic, magmatic and mineralisation processes

Conveners: Mike Stock (Trinity College Dublin), Steven Hollis (University of Edinburgh), David Neave (University of Manchester), Owen Weller (University of Cambridge)

10.00-10.20	Cooper, G.F., Bucholz, C.E., Kay, S.M. and Kay, R.W.	Lower crustal melt evolution revealed by crystal scale isotopes in plutonic xenoliths from Mt. Adagdak, Aleutian arc
10.20-10.40	Gertisser, R., Goto, Y. and Li, X.	Tracing magma evolution from caldera-forming to post-caldera volcanism at Toya volcano, Hokkaido, Japan
10.40-11.10	Hughes, H.S.R. (KEYNOTE)	What sulphides can tell us from the mantle to mineral deposits
11.10-11.40	**BREAK**	
11.40-12.00	Bowles, J.F.W., Suárez, S., Zaccarini, F. and Garuti, G.	Crystal records describe the emplacement of the Freetown Intrusion, Sierra Leone.
12.00-12.20	**Church, A.J.**, Broom-Fendley, S., Simonet, C. and Wall, F.	Carbonatite-associated gallium mineralisation: A case study from Monte Muambe, Mozambique
12.20-12.40	**Cisse, D**. and Wafik, A. REMOTE	Did tholeiitic magma differentiation control the petrogenesis of sulfide mineralization in the Kettara intrusion, or were metals subsequently redistributed by fluids and deformation?
12.40-13.00	**Hendrickx, T.J.**, Allaz, J.M., Freudenstein, A.E., Wickland, T. and Bachmann, O.	Late Magmatic Fluids Drive Evolution and REE Mineralization in the Pikes Peak Batholith, Colorado
13.00-14.00	**LUNCH**	
14.00-14.20	Hepworth, L.H.	Syn-magmatic brecciation of a vertically-oriented crystal mush during fault-controlled dyke emplacement in the Rum Central Intrusion, NW Scotland
14.20-14.40	**Hughes, R.R**., Hartley, M.E., Murton, B.J. and Neave, D.A.	Crystal cargoes along the Reykjanes Ridge: insights into magmatic processes at a slow-spreading, plume-influenced mid-ocean ridge
14.40-15.00	**Vitarelli, D.C.**, Tomlinson, E.L., O'Sullivan, G.J., Koch H.A., Daly J.S., Belgrano, T.M., van Acken D., Brodbeck, M. and Corella Santa Cruz, C.R.	Utilizing U-Pb and novel *in situ* Sr-Nd isotope chemistry of apatite to resolve tephrochronology and petrogenetic origins of altered volcanics
15.00-15.30	Higgins, O., Stock, M.J., Geist, D., Neave, D.A., Buisman, I., Bernard, B. and Gleeson, M. (KEYNOTE)	Annual-to-millennial fluctuations in the physical properties of magma storage zones
15.30-16.00	Neave, D.A., Weller, O., Marxer, F., Sodeman, C., Hartley M.E., Holtz, F. and Namur, O.	Clinopyroxene records of magmatic oxygen fugacity: insights from experiments and thermodynamic modelling

16.00-16.20	Roberts, N.M.W., Gardiner, N.J., Mangler, M.F. and Tapster, S.R.	Tracking magmatic processes and lithium fertility through zircon chemistry
16.20-16.40	**Subbaraman, R.**, Hughes, L., Hartley, M.E. and Neave, D.A.	Microstructural record of Icelandic crystal mushes preserved in gabbroic nodules
16.40-17.10	Dutrow, B.L. (KEYNOTE) **COLLINS MEDALLIST**	Serialsomatism of tourmaline: An indicator of geothermal system evolution

Bragg Lecture Theatre

Session 10: Advances in Mineralogical Analysis – Development of Techniques for 21st Century Research

Convenors: George Cooper (Cardiff University), J.F.W. Bowles (Private) and Marie-Laure Bagard (University of Cambridge)

10.00-10.20	Salge, T., King, A.J., Lee, R.M. and Russell, S.S.	Out of Space, Under the Beam: Low-Dose SEM–EDS of Fragile Phases in Carbonaceous Chondrites and Asteroid Bennu Return Samples.
10.20-10.40	Stonadge, G.R. and Spasevski, L.	No WDS? No Problem! Why Do Mineralogists Continue to Overlook EDS?
10.40-11.00	Allaz, J.M., Donovan, J. and von der Handt, A.	Time dependent intensity correction and other recent software advances for quantitative analysis by electron probe microanalyzer (EPMA)
11.00-11.40	**BREAK**	
11.40-12.10	Le Pape, P., Blanchard, M., Ona-Nguema, G., Cabaret, D., Benzerara, K., Juhin, A., Chassé, M., Baptiste, B., Morin, G., Battaglia-Brunet, F., Juolian, C., Fernandez-Rojo, L., Resongles, E., Héry, M., Casiot, C., Landrot, G., Belkhou, R. and Rueff, J.-P. (KEYNOTE)	Analysis of arsenic speciation in contaminated samples: a multi-scale approach from standard XAS to advanced X-Ray spectroscopies
12.10-12.30	Mosselmans, J.F.W.	Developments in geological studies by X-ray spectroscopy techniques at Diamond Light Source
12.30-12.50	**Waters, C.**, Neill, T.S., Morris, K., Baker, M.L., Alcock, M.L., Mosselmans, J.F.W., Ignatyev, K. and Shaw, S.	Developing U L3 and M4,5 -edge HERFD-XANES to investigate uranium (bio)geochemical processes in radioactive waste disposal and nuclear decommissioning.
12.50-14.00	**LUNCH**	
14.00-14.30	Whitehouse, M.J.	Large-geometry SIMS – analytical capabilities and novel applications in the earth, planetary and environmental sciences
14.30-14.50	Stavropoulou, A., Stonadge, G. and Rider-Stokes, B.	Non-destructive SEM-BEX geological sample analysis: a new workflow for high-resolution analysis of unprepared samples
14.50-15.10	Bowles, J.F.W.	The calculation of a mineral age from microprobe analyses of U, Th and Pb
15.10-15.30	Ghosh, U., Upadhyay, D., Dunkel, K.G., Chandra, D. and Barnhoorn, A. REMOTE	Integrated analytical workflow for decoding tourmaline-orbicule crystallisation in granitic environments
15.30-16.00	**BREAK**	

16.00-16.20	Mitsis, I., Christidis, G.E., Gkamaletsos, P.N., Mocuta, C. and Thiaudiere, D.	The Odyssey of a Ni-phyllosilicate: An adventure of the missing smectite.
16.20-16.40	Taylor R.J.M.	Why Automated Mineralogy needed an upgrade

Moseley Lecture Theatre

Session 2: Biogeochemical impacts on mineral cycling in natural and engineered systems

Convenors: John Moreau (Glasgow), Casey Bryce (University of Bristol), Jon Lloyd (University of Manchester)

10.00-10.30	Santos, A. (KEYNOTE)	The evolution of biomining through the lifetime of the Mineralogical Society
10.30-10.50	Stigliano, L., Rehmanji, M. and Cosmidis, J.	Cyanobacterial influence on carbonate precipitation under varying geochemical conditions revealed by high-throughput correlative imaging and Raman spectromicroscopy
10.50-11.10	**Brijit, A.J.**, Singh, V.V., Klier, P., Kumar, N., Kimber, R., Barthélémy, P., Rose, J., Kraemer, S.M. REMOTE	Adsorption and enzymatic degradation of DNA on goethite in the presence of phosphate and divalent cations
11.10-11.40	**BREAK**	
11.40-12.00	Byrne, J. M. HOWIE BEST PAPER PRIZE (KEYNOTE)	Iron biogeobatteries, their influence on redox cycling, and their application
12.00-12.20	Moreau, J.W., Voutsinos, M.Y. and Banfield, J.F.	Mineralogical and metagenomic evidence for enhanced REE cycling in a granitic saprolite soil microbiome
12.20-12.40	Mills, S.J., Missen, O.P., Villalobos-Portillo, E. and Brugger, J.	Nanoparticles and bacterial mediation in the mobilisation of toxic critical metals: implications for tellurium and cobalt cycling
12.40-13.00	Falagán, C.	Nutrient availability dictates microbial ecology in acidic environments
13.00-13.50	**LUNCH**	
13.50-14.20	Watkin, E., Khaleque, H. and Van Alin, A. (KEYNOTE)	Leveraging Microbe-Driven Geochemical Cycles to Enable Sustainable Critical Mineral Recovery

Blackett Lecture Theatre

Session 5: Engineered minerals for existing and emerging technologies

Conveners: Rick Kimber (University of Manchester), Kirill Shafran (BYK Additives, UK), Chris Egan-Morriss (University of Manchester)

10.00-10.20	Chen, L., Mason, A., Pepper, S., Waters, S. and Corkhill, C.L.	Evaluating Disposal of Plutonium Wasteforms
10.20-10.40	**Margreiter, R.**, Neill, T., Shaw, S., Bower, W., Morris, K.	Fate of disposal relevant UO_3 and U_3O_8 in a phosphate cement backfill
10.40-11.00	Shafran, K.	Highly Anisotropic Engineered Minerals – A Treasure Trove of Industrial Applications
11.00-11.40	**BREAK**	
11.40-12.10	Hochella Jr., M.F. and Babakhani, P. (KEYNOTE)	Can engineered minerals significantly slow global warming? An example where this could be the case
12.10-12.30	Dresch, L., Marsh, A.T.M., Bejjarapu, D.S., Neumann, A., Scrivener, K.L. and Matos, P.R.	Mechanical amorphisation of minerals in clay-based mining wastes for the production of low-carbon cements
12.30-13.00	Cosmidis, J., Stigliano, L. and Rehmanji, M. (KEYNOTE)	Towards growing and engineering minerals using bacteria: high-throughput approaches to decoding biomineralization
12.50-13.50	**LUNCH**	
13.50-14.10	Pawley, A.R., Dowling, J., Ownsworth, E., Liu, Y., Covey-Crump, S.J. and Jones M.A.	Mineralogy of high-temperature aircraft engine deposits

Rutherford Lecture Theatre

09.00–09.50 - **PLENARY**: Clay-Based Stimuli-Responsive Materials: A Versatile Platform for Smart Functional Systems
J. Brendlé GEORGE BROWN LECTURE

Session 9: Metamorphism and Fluid-Melt-Rock interactions within the lithosphere
Convenors: Richard Palin (University of Oxford), Richard White (University of St Andrews), Charlotte Simpson (University of Oxford)

10.00-10.20	Yardley, B.	Metamorphism – a perspective on progress since the Mineralogical Society centenary
10.20-10.40	**Fanesi, E.**, Brooker, R.A., Clark, S. M., Liu, X., Koemets, E., Kleppe, A. K. and Lord, O. T.	Cratonic serpentinization: new nanoscale insights into the role of spinel and fluids in hydrogen production
10.40-11.10	Tomlinson, E.L., Rodrigues, R.F., Melai, C., Kamber, B.S., Kaekane, B.K. and Piazolo, S. (KEYNOTE)	Komatiite-peridotite interaction and Mg/Si systematics in the Archaean mantle
11.10-11.40	**BREAK**	
11.40-12.00	Wheeler, J.	Interactions between metamorphism and deformation: some key challenges
12.00-12.20	Waters, D.J.	Grain-scale processes during retrograde transformation of eclogite-facies rocks in W Norway: fluid access and deformation are not strongly coupled
12.20-12.40	Carter, E.J., Burgess, R., Tartèse, R., Coggon, R.M. and Evans, A.D.	A unique sixty-million-year record of low temperature fluid metasomatism in oceanic lithosphere
12.50-14.00	**LUNCH**	

Moseley Lecture Theatre

Session 3: Minerals, Contaminant Dynamics and Remediation in the Environment

Convenors: L. Townsend (Nuclear Waste Services, UK), A. Neumann (Paul Scherrer Institute, Switzerland), K. Rothwell (Stirling University)

09.00-09.20	Bowell R.J., Jamieson H.E. and Dobosz, A.	Natural attenuation of Cobalt and Nickel in mine waste
09.20-09.40	**Wort, C.T.**, Lloyd, J.R., Morris, K. and Shaw, S.	Geomicrobial controls on radionuclide speciation and fate during geodisposal of radioactive waste
09.40-10.00	Robinson, C., Kravvi, K., Hao, J., Morris, K., Gomez Gonzalez, M. and Shaw, S.	Nano-scale interactions of radionuclides with LSS Rock
10.00-10.30	Pearce, C.I., LaVerne, J., Emerson, H., Lawter, H., Szecsody, J., Mackley, R., Zhang, X., Wang, Z., Rosso, K., Schenter, G., Young, L., Orlando, T., Clark, A., Li, X. and Francesconi, L. (KEYNOTE)	Mechanistic Roles of Minerals in Radionuclide Behaviour at the DOE's Hanford Site
10.30-11.00	**BREAK**	
11.00-11.30	Perez, J.P.H. (KEYNOTE)	Redox-active iron (nano)minerals and their impact on contaminant behaviour in natural and engineered systems
11.30-11.50	**Reid, F.**, Singh, V. V., Krämer, S. M., Coker, V. S. and Kimber, R. L.	Adsorption and stability of double-stranded RNA at goethite surfaces
11.50-12.10	**Feng, M.**, Richards, L.A., Polya, D.A., and Lloyd, J.R.	Performance of Fe-modified biochars and carbo-iron in remediating arsenic in groundwater
12.10-12.30	**Attfield, S.A.**, Bryce, C., Bostick, B., Byrne, J.M.	A sustainable and cost-effective method of uranium and arsenic removal using biogenic iron minerals
12.30-12.50	**Shaughnessy, L.**	Developing (bio)remediation options for high pH radionuclide contaminated land and water
12.50-14.00	**LUNCH**	
14.00-14.20	**Cai, He**, Neill, T.S., Morris, K., Stockdale, A. and Shaw, S.	Mechanistic insights into the reductive incorporation of Tc(IV) in Fe(II)-doped LDHs
14.20-14.40	Delina-Agillon, R.E., Bateman, K., Lacinska, A.M., Vosper, M., Perez, J.P.H. and Benning, L.G.	Experimental investigation of toxic metal behaviour during laterite mine waste formation
14.40-15.00	Boyanov, M.I., O'Loughlin, E.J., Kemner, K.M.	Uranium speciation in reducing environments: from uraninite to U(IV) complexes with minerals and organics
15.00-15.20	Majzlan, J., Jurkovič, Ľ., Faragó, T., Koděra, P. and Števko, M.	Weathering of minerals of tungsten and its environmental mobility

Rutherford Lecture Theatre

Session 6: Critical Minerals and Energy Transition

Martin Smith (University of Brighton), Hannah Grant (British Geological Survey), Adrian Finch (University of St. Andrews), Holly Elliott (British Geological Survey)

09.00-09.30	Josso, P. (KEYNOTE)	Intelligence, strategy, and the shifting landscape of critical raw materials in the UK: the role of CMIC in bridging policy and practice
09.30-09.50	Wall, F.	Thinking about the connections between minerals research and the responsible sourcing of critical raw materials
09.50-10.10	Jenkin, G.R.T., Gibaga, C.R.L., Mubaira, Symons, J., Tanciongco, A., Swift, R., Chambers, J., Yan, Y., Crane, R., Gervasio, J.H., Tungpalan, K., De Oliveira, V., Tibbett, M., Samaniego, J.O., Arcilla, C.A. and the PROMT consortium	Don't dig it up! In situ reprocessing and remediation of Cu mine tailings
10.10-10.30	**Tanciongco, A.**, Jenkin, G.R.T. and Bird, P.	Legacy Slags as Critical Metal Resources: Geochemical Insights from a Cornish Historic Copper Smelting Site
10.30-11.00	**BREAK**	
11.00-11.20	**Bronziet, J.**, Hartley, M.E., Neave, D.A. and Covey-Crump, S.	Using Appinite Geochemistry to Understand Critical Metal Mineralisation in the Scottish Highlands: A Mineral Systems Approach
11.20-11.40	**Kwanang, K.K.**, Santoro, L., Li, M.Y.H., Ngo Bidjeck, L.M. and Ndjigui, P.-D.	Trace elements and REE behaviours in nepheline syenite and related weathering materials in tropical climatic conditions: case study of Eboundja nepheline syenite (Southern Cameroon)
11.40-12.00	Smith, M.P., Maciag, B., Broom-Fendley, S., Li, M.Y.H., Wall, F., Kumar, P., Rooks, C., Grasten, T. and Geraki, K.	Macro- to nanoscale mineralogical controls on the genesis of deep weathered carbonatite REE deposits
12.00-12.20	Broom-Fendley, S., Littler, K., Evenstar, L., Chen, W., Li, M.Y-H., Yang, F., Smith, M. and Wall, F.	Dating carbonatite weathering using U–Pb in apatite
12.20-12.40	**Evans, A.J.M.**, Tibble-Howlings, J., Littleton, J.A.H., Farrell, N.J.C., Neave, D.A., Hartley, M.E. and Hunt, S.A.	Understanding Lithium Leaching from Lithium-Bearing Granite and Polylithionite: Implications for Lithium Extraction from Geothermal Brines
12.40-13.00	Oskierski, H.C., Ncube, T., Alhadad, M., Chischi, J., Abdullah, A.A., Senanayake, G. and Dlugogorski, B.Z.	Mineralogical transformations during extraction of lithium from spodumene
13.00-14.00	**LUNCH**	

14.00-14.30	McFall, K.A., McDonald, I., Hanley, J.J., Kerr, M., Yudovskaya, M.A., Kinnaird, J., and Tattitch, B. (KEYNOTE)	Volatiles and the Many Types of Melt: Why Critical Metals Aren't Always Where Expected In Ore Deposits
14.30-14.50	Jemmali, N., Bertrandsson Erlandsson, V., Melcher, F., Rddad, L. and Souissi, F. REMOTE	Critical Metal Enrichment in Sphalerite from Zn–Pb–F–(Ba–Sr) Deposits, Northern Tunisia: Implications for Mississippi Valley-type Systems
14.50-15.10	**Ryczek, D.J.**, Farrell, N.J.C., Hollis, C., Healy, D. and MCCLENAGHAN, S.H.	Critical Mineral Enrichment in the Carboniferous Carbonate-hosted Deposits of the Pb-Zn-F Orefields of Northern England and Wales
15.10-15.30	Stillings, M.S., Stevenson, S., Donagueda Suso, B., Hope, M., Head, A. and Lunn, R.J.	Evidence for mechanochemical CO_2 trapping as silicon carbonates and mineral lattice cages by comminution of silicate rocks in CO_2
15.30-16.00	**BREAK**	

Rutherford Lecture Theatre

16.00-16.50 - **PLENARY**: Research on the Edge

Berry, A.J.

Blackett Lecture Theatre

Session 7: Evolving Mineralogy of the Earth System: Interactions within the Crust, Mantle and Core

Conveners: Alfred Wilson (University of Leeds), Fred Richards (Imperial College London), Simon Hunt, Tara McElhinney and Josh Littleton (University of Manchester), Ollie Lord (University of Bristol)

09.00-09.20	Mariani, E., Dandekar, S., Dandekar, T.R., Khatirkar, R.K., Pande, K., Gardner, J., Bagshaw, H., Randive, K. and Peshwe, D.	Kyanite-muscovite-dumortierite vein mineralisation mechanisms from advanced microstructural analysis using EBSD.
09.20-09.40	Pandey, R., Singh, N.K., Debnath, S., Giuliani, A., Lorenzo, T., Belyatsky, T., Chalapathi Rao, N.V., Chew, D., Amal Dev, J. and Tomson, J.K. REMOTE	Tracing Paleoproterozoic fluid events using Apatite from the Dharwar Craton and adjoining Granulite Terrane boundary
09.40-10.00	Hazen, R M.	Deep-Time Mineralogical Metaphors: Arrows, Cycles, Trees, and Networks
10.00-10.20	Xiong, F., Mugnaioli, E., Xu, X., Yang, J., Wirth, R., Grew, E.S. and Yates, M.G. (*to be presented by R.M. Hazen*)	Wangxibinite, TiFe: a new mineral with implications for the interpretation of an enigmatic coesite-bearing fragment from the Luobusa ophiolite, Tibet, China
10.20-11.00	**BREAK**	
11.00-11.20	Ledoux, E. E., Buchen, J., Wang, B., Satta, N., Trautner, V., Criniti, G., Méndez, A.S.J., Liermann, H.-P. and Marquardt, H.	The stishovite to post-stishovite transition under cyclic loading in the dynamic diamond anvil cell
11.20-11.40	Sharma, S. and Shukla, G.	Compositional Signatures of (Fe,Al)OOH and Their Implications for the Lowermost Mantle
11.40-12.00	Najorka, J., Collings, I.E., Kleppe, A.K., Koemets, E. and Welch, M.D.	Structural evolution of the hydroxyperovskite $MgSi(OH)_6$ up to 23 GPa: implications for water storage in cold subduction zones
12.00-12.20	Cámara, F., Day, M.C., Wang, Y., Innocenzi, F., Ardit, M., Luth, R.W., Pearson, D.G., Weiss, Y., Timmerman, S., Pamato, M.G., Novella, D., Rotiroti, N., Grässlin, J., Schüermann, C.J., Barbaro, A., Qu, K., and Hou Z. and Nestola, F.	A MED study of nanometric mineral inclusions in fluid-rich diamonds
12.20-12.40	O'Sullivan, G.J., Tomlinson, E.T. and Hoare, B.C.	Diamond ages from the Premier kimberlite
12.40-13.10	Breithaupt, T. (KEYNOTE)	Predicting the strength of the lithosphere: a new microphysical model of semibrittle
13.10-14.00	**LUNCH**	

14.00-14.20	McElhinney, T.R., Heinen, B.J., Walker, A.M., Rogmann, E.-M., Fanesi, E., Vlasov, K., Pamato, M.G., Ezad, I.S., Daisenberger, D., Lord, O.T. and Hunt, S.A.	Reassessing the Onset and Effects of Dynamic Recrystallization in Metals at High Pressure
14.20-14.40	Kubik, E., Makhatadze, G.V., Zhu, D. and Schulze, M.	Isotopic fractionation during core formation on terrestrial planets
14.40-15.10	Jackson, J.M., Zhou, C., Dobrosavljevic, V.V., Zhang, D., Sturhahn, W., Toellner, T.S., Zhao, J., Hu, M., Chariton, S. and Prakapenka V.B. (KEYNOTE)	A spatiotemporal approach to melting investigations: A spotlight on Earth's core-mantle boundary

Session 1: Universal: Mineralogy: then, now and beyond

Gasimov, N., Hamzayeva, T. and **Abdullayev, E.**	Goethite alteration in sulphate-rich brines on Mars: Implications for organic molecule preservation
Pendlowski, H.A.	Layers of Discovery: Clay Mineralogy at the James Hutton Institute
Wang, B., Xu, Z. and Hunt, S.A.	Non-Ambient Raman Spectroscopy of Olivine-Type Lithium Battery Cathodes: $LiMPO_4$ (M = Fe, Mn, Ni, Co)

Session 2: Biogeochemical impacts on mineral cycling in natural and engineered systems

Barclay, M., Coker, V.S. and Kimber, R.L.	Impact of biomolecules on iron (oxyhydr)oxide transformations
Byrd, N., Felgate, H., Egan-Morriss, C., Robinson, C., Nunn, E.J., Morris, K., Natrajan, L.S., Webber, M. and Lloyd, J.R.	Using Engineering Biology to Understand and Enhance Uranium Biomineralisation
Stott, L., Kimber, R. L., Coker, V. S., Lloyd, J.R.	Characterisation of ochreous mining waste in the UK to optimise sustainable bioprocessing of iron oxyhydroxides
Rose, M. N., Morris, K., Shaw, S. and Lloyd, J.R.	Biogeochemical activity in highly saline environments relevant to candidate host-rocks for geological disposal of radioactive waste

Session 3: Minerals, Contaminant Dynamics and Remediation in the Environment

Cooper, J., Neill, T.S., Natrajan, L., Stagg, O. and Coker, V.S.	Criticality safety: Investigating the co-mobility of actinides and neutron absorbers in radioactive waste disposal
Ives, M. and Cumberland, S.A.	Influence of tufa Deposition on the Transport and Mobility of Lead and Zinc in Downstream Environments on the River Lathkill
Jones, W., Graham, J., Morris K., Shaw, S. and Coker, V.	Radionuclide Fate in On-Site Disposal of Activation Product Contaminated Wastes
Koepnick, H.R., Peyton, B.M. and Lauchnor, E.L.	Nitrate-dependent iron oxidation for remediation of selenium and nickel in mining wastewaters
Kraavi, K., Morris, K., Robinson, C., Abrahamsen-Mills, L. and Shaw, S.	Geochemical Controls on Radionuclide Adsorption and Fate in Lower Strength Sedimentary Rock
Morris, K., Coker, V., Foster, L., Lloyd, J.R., Neill, T., Shaw, S., Stetten, L. and Stockdale, A.	The RADioactive waste and Environmental Remediation National Nuclear User Facility: A Unique Capability for Nuclear Minerals, Contaminant Dynamics and Remediation Research
Painter, P.R.W., Litherland, S.P., Byrne, J.M., Corkhill, C.L.	Ni retention during devitrification of high-level radioactive waste glasses

Snow, R., Shaw, S., Morris, K., Bassil, N., Bower, W. and Lloyd, J.	Geological fate and impact of isosaccharinic acid
Varga, S., Litherland, S., Byrne, J. and Corkhill, C.	Underpinning Laboratory-Based High-Level Waste Glass Dissolution Tests

Session 4: Minerals for a Sustainable Environment

Correia, L. T., Azevedo, A. C., Secco, A.V., Dickinson, H. and MacDonald, J.M.	Phyllosilicate Interlayer Engineering (PIE) for sustainable potassium supply from clay mine waste in Brazilian sandy soils
MacDonald, J.M., Owen, A., Brown, D.J. and Gribble, L.	Mineralogical Changes in Anthropogenic Sediments: Implications for a Sustainable Environment
Oskierski H.C., McCutcheon J., Deditius A., Suvorova A., D'Olivio J.P., Southam G.	CO_2 mineralisation in hydrated Mg-silicate microbialites
Skelton, H., Rees, M., Josue, J., Farrell, N., Bigaroni, N., Mecklenburgh, J. and Paul, L.	Mineralogical and microstructural controls on the mechanical behaviour of reservoir sandstones reacted with CO_2-enriched fluids

Session 5: Engineered minerals for existing and emerging technologies

Harvey, P., Egan Morriss, C., Hu, Min, Cavet, J., Coker, V., Gallego Schmid, A., Haigh, S., Hardacre, C. and Lloyd, J.R.	Biotechnological synthesis of nanocatalysts from industrial wastewaters
Rehmanji, M., Stigliano, L. and Cosmidis, J.	A high-throughput, data-driven workflow to tune carbonate (bio)mineral formation in abiotic and biotic systems
Xie, J., Byrd, N., Bueno, A., Coker, V.S., Sankar, M., Cai, R., Haigh, S.J., Lloyd, J.R.	Biorecovery of gold nanoparticles from industrial wastewaters by *Shewanella oneidensis*
Sriwastava, P., Seaman, A., Bola, J., Khare, S., Cosmidis, J., Tosca, N. and Anderson, R.	Protein-Templated Polymorph Selection: Engineering Mineral Crystallisation with de novo Designed Proteins

Session 6: Critical Minerals and Energy Transition

Bryce, A., Burnside, N., Dobson, K. and Currie, D.	Critical raw material and weathering potential of mine waste in the Leadhills-Wanlockhead Orefield
Eygi, A., Skellern, A., Farrell, N., Pawley, A., Bigaroni, N., Mecklenburgh, J., Paul, L. and Waters, J.	Mineralogical and microstructural controls on pore networks in lithium-bearing granites
Holtstam, D., Taddei, A., Förster, H.-J. and Appelt, O.	A quest for the "holy grail" of rare earth discovery: potential original material of gadolinite-(Y) from Ytterby
Dybowska, A., Hubau, A., Schofield, P.. Gianolo, D., Santos, A., Pino-Herrera, D., Hafida, T., Erard, M., Herrington, R.J., Joulian, C. and Guezennec, A.-G.	Optimised physical upgrading of lateritic mine waste to enhance bioprocessing for cobalt recovery

Sutton, B.T.C., Shail, R.K., Gleeson, P., Broom-Fendley, S., Andersen, J.C.Ø., Roberts, N.M.W. and Tapster, S.	The Geological Controls and Mineral Parageneses of the Gunheath Lithium Deposit, St Austell, Cornwall
Zhang Y.H., Rajagoaplan A., Shaw S. and Shang J.L.	Silica Precipitation Occurs Under Low-temperature Alkaline Conditions
Cundell, M., Andersen, J. C. Ø., Broom-Fendley, S., Thorne, R. and Lambert-Smith, J.	A reclassification of the Kit Hill granite and the mineralisation impact on the Redmoor deposit, Cornwall

Session 7: Evolving Mineralogy of the Earth System: Interactions within the Crust, Mantle and Core

Lu, L. and Wheeler, J.	Grain-scale simulations of olivine phase transitions under stress: Insights from a phase-field model and implications for mantle discontinuities

Session 8: Crystal records of volcanic, magmatic and mineralisation processes

Bradshaw, S.J., Gertisser, R. and Goto, Y.	Quantifying Dome Formation at Showa-Shinzan, Mount Usu (Hokkaido, Japan) Using Crystal Size Distribution Analysis
Haines, F.M., Andronico D., Hughes E.C., Stanley, M. and Thomson A.R.	Timescales of pre-eruptive processes before the 23rd November 2013 paroxysmal explosive eruption at Etna using olivine diffusion chronometry
Hollis, S.P., Mongeau, P., Roberts, N., Cooper, M.R., Grant, H., McFall, K., Zagorevski, A., Sparkes, G.W., Tapster, S., Condon, D.J. and Piercey, S.J.	Controls on metal endowment in volcanogenic massive sulphide (VMS) deposits of the Caledonian-Appalachian orogen
Keeley, N., Gertisser, R., Petrone, C. M., Druitt, T., Kutterolf, S., Ronge, T. and the Expedition 398 Scientists	Petrological insights into the magma system of Santorini volcano (Greece) after the caldera-forming Late Bronze Age eruption
MacRae, C., De Hoog, J.C.M., Talavera, C. and Jollands, M.	Developing an H-in-zircon magmatic water proxy using apatite inclusions
Pierce-Jones, T., Hartley, M.E., Namur, O., Vander Auwera, J. and Neave D.A.	Variations in the crystal content of basalts from the Eastern Volcanic Zone of Iceland
Shareef, A.M., Ghosh, S., Sarkar, S., Malviyac, V.P., Arima, M. and Mandal, S.K.	Mantle Source Heterogeneity and Phlogopite-Rich Lithospheric Mantle Contribution to Early Cretaceous Ultrapotassic Magmatism in the Damodar Valley, Eastern India
Spring, B., Gertisser, R. and Karátson, D.	A textural perspective on the eruptive behaviour of Ciomadul volcano, East Carpathians, Romania
Turanski, M., Hollis, S., Diers, S., Dana, C., Fitton, G., Tavazzani, L., Chelle-Michou, C., Glorie, S. and Morey, B.	Constraining the age, geology, geochemistry, and VMS prospectivity of the Tallering Greenstone Belt, Yilgarn Craton, Western Australia

Session 9: Metamorphism and Fluid-Melt-Rock interactions within the lithosphere

Green, H.R., Carter, E.J., Stimpson, I.G., Tartèse, R., Osborne, W. and Savov, I.	Volatile Behaviour During Serpentinisation at Atlantis Massif: Insights from Halogens and Petrology
Nash, I.J., Hollis, S.P., Hastie, A.R., Smithies, R.H., Verbeeten, A., Holder, D. and Stock, E.	Origin of sanukitoid magmas linked to Archaean intrusion-related Au deposits: Insights from the Yilgarn Craton, Australia

Session 10: Advances in Mineralogical Analysis – Development of Techniques for 21st Century Research

De Hoog, J.C.M.[1], Talavera, C.[1], Barosch J.P. [1] and EIMF	The NERC Ion Microprobe Facility: SIMS analyses to support Earth Science and Mineralogy research
Hao, J., Ma, L. and Taylor, K.G.	Applying cutting-edge facilities to investigate mineral-fluid interactions
Heinen, B.J. and Byrne J.M.	Advancing Iron Mineral Characterisation in Geoscience with MinSight: A User-Friendly Web App for Mössbauer Spectroscopy
Collings, I.E., Tidey, J.P., Rumsey, M.S., Missen, O.P., Cortes Calderon, A., Najorka, J., Palatinus, L. and Mills, S.J.	Resolving structures in fine-grained mineral samples using 3D electron diffraction

The Importance and the future of collections: Reviewing the critical relationship between national museums and subject specialist societies

Mike Rumsey

Natural History Museum, London. m.rumsey@nhm.ac.uk

The connections between the *Mineralogical Society* and the *Natural History Museum* are long and deep. In 1876, the eleven scientists who thought to bring together a national society included Thomas Davies, a mineral specimen specialist and assistant to the Keeper of Mineralogy at the Museum. During late 19th and early to mid-20th Century, significant portions of Society business were performed by the mineralogists at the museum and there were several periods with NHM-based presidents. The South Kensington site has always been a natural venue for special events and the production and editing of *Mineralogical Magazine* was led by NHM mineralogists from 1888 to 1999.

This relationship has been extremely beneficial for our science. A more connected pathway between the documentation of scientific research and the deposition of the researched objects has allowed for the most important of scientific principles, that of repeatability. Studies from the earliest days of the Society are preserved within the NHM collection (and other museums) for us all to revisit, reanalyse and be inspired by.

In this keynote for the Universal session, celebrating 150 years, we will review the history of the connection and the importance of collections items as the NHM approaches its own 150th anniversary at South Kensington (2031). We will look at key studies preserved in petrological and mineralogical collections and take a particular focus on type specimens, the most sacrosanct of mineralogical samples, where study is regularly reviewed and revisited as technology advances.

Caring for and managing such an important historical collection is an incredible privilege and bears with it a responsibility to champion and protect its future. As we look to the future of the Society we must acknowledge and reflect on the changes in the UK's Museum and University environments and consider how they may affect the next 150 years of sample preservation. For instance, the funding for our national museums comes from departments more aligned with cultural rather than scientific priorities and there are fewer subject specialist curators than ever before, including none in Wales. We also see that many University departments have either disposed of their collections or turned to the 'nationals' to save the most important samples but without offering any additional funding to do so.

These funding factors and other developments (digitisation, short-termism, research pressures) are big challenges, and there is no better time than now for us to re-affirm and champion the symbiotic relationship between our national museums and the Society's Members. We will take a final look at simple solutions that we as scientists, curators and mentors can do to ensure that the mineralogical advocates of the next 150 years can revisit and build upon the hard work that we all do today.

A short history of synthetic gem materials in the collections of the Natural History Museum, London

Hansen, R.F.

Mineral and Planetary Sciences, Natural History Museum, Cromwell Road, London, UK, SW7 5BD, r.hansen@nhm.ac.uk

---

The Mineral Collection of the Natural History Museum (NHM) comprises approximately 180,000 specimens, representing the geodiversity of the mineral kingdom and the natural world. Within this sits a small collection of around 1000 artificial (human made) chemical substances. When an artificial substance has the same chemical composition and crystal structure as a naturally occurring mineral, in gemmology this is termed as a synthetic.

Synthetic minerals have a range of uses from supporting new mineral characterisation, through to mass production for their distinctive optical, physical or electrical properties for industrial purposes and new technologies. Synthetic corundum (ruby and sapphire), diamond, quartz, beryl (particularly emerald) and spinel have applications in both industry and the commercial gemstone and jewellery business. Their physical and optical properties such as high hardness, bright colour and brilliance mean they are highly desirable as gemstones for their beauty and durability. Historically the natural gems were also coveted for their rarity, but today synthetic gemstones mean they are widely available and affordable.

The human fascination with the natural world and the desire to own precious jewels were leading factors in the experimentation and development of synthetic gem materials in the last few centuries. Fortuitously, specimens of early gem synthetics were acquired by the NHM from the late 1800s through the 1900s, preserving their history and development. Ruby and quartz were successfully synthesised in the late 1700 and 1800 as tiny crystals, but it was not until the start of the 1900s that synthesis methods allowed production on a commercial level. Other synthetic gem minerals followed including synthetic spinel (accidently created in the quest for blue sapphire), beryl variety emerald and diamond.

This presentation will explore the early synthetic gem minerals held in the collections at the NHM, tracing the timeline for development of these gems including production of different colours and change in quality and size of the crystals synthesized.

Preserving susceptible minerals in museum collections

Gabriel, N.W. and Burleson, L.

Science Department, Natural History Museum, Cromwell Road, London, SW7 5BD, United Kingdom, n.gabriel@nhm.ac.uk

---

According to data compiled by Royce et al. [1], at least 10% of known mineral species are susceptible to environmental conditions (i.e., moisture, temperature, light and pollutants), therefore specific storage conditions are required to ensure the long-term preservation of susceptible mineral specimens in museum collections. However, there is no one-size-fits-all solution for storing minerals because the environmental conditions suitable for one mineral species may be detrimental to another. For example, at 20 °C, the ideal relative humidity for epsomite is between 48-93 % because low humidity causes epsomite to dehydrate into hexahydrite and high humidity leads to deliquescence [2], but exposing pyrite to similar conditions can lead to pyrite decay [3].

The Minerals Gallery in the Natural History Museum in London is a non-climate-controlled space with south-facing windows, so there are large fluctuations in environmental conditions. While the display cases are buffered against some of these fluctuations, they still experience temperature and humidity variations throughout the year; in 2025, an environmental monitor in one display case recorded a temperature range of 11.3-29.9 °C and a relative humidity range of 31.5-66.6 %. Because of this, susceptible minerals on display in this gallery require microenvironments to prevent detrimental changes.

A recent project involved identifying susceptible minerals on display in the Minerals Gallery and rehousing them in glass enclosures with humidity buffers, allowing them to be protected and displayable. Of the 10% of minerals described as susceptible to environmental conditions, 67% of these experience changes related to water (e.g., changes in hydration state, deliquescence, etc.) [1], so hydrated sulphates such as epsomite, kieserite and szomolnokite were prioritised, especially if they displayed signs of active deterioration or if the environmental conditions were at odds with their ideal conditions as summarised in Royce [4]. Since compositional data are vital for determining the appropriate storage conditions for minerals [5], specimens were also analysed with x-ray diffraction and Raman spectroscopy to determine their composition and identify any signs of alteration.

This presentation will explore the analysis of these susceptible minerals, the mineralogy changes that have occurred due to environmental conditions, and the process of rehousing specimens in suitable microenvironments.

References*:*
[1] Royce K et al. (2021) Defining damage and susceptibility, with implications for mineral specimens and objects: Introducing the mineral susceptibility database. Studies in Conservation 68(3): 298-317
[2] Chou I M and Seal R R (2003) Determination of Epsomite-Hexahydrite Equilibria by the Humidity-Buffer Technique at 0.1 MPa with Implications for Phase Equilibria in the System $MgSO_4$-H_2O. Astrobiology 3(3):619-630
[3] Howie F M P (1992) The Care and Conservation of Geological Material. Butterworth-Heinemann
[4] Royce K (2021) The Mineral Susceptibility Database. University of Oxford
[5] Baars C et al. (2021) The importance of correct mineral identification for the determination of appropriate specimen storage conditions in geological museum collections. Geological Curator 11(5): 355-360

The role of detailed mineralogical and chemical analyses in mine waste management

Brookshaw, D.R.[1], Pearce, S.R.[1] Wright, T.[1] and Hartshorne, C.[2]

[1]Mine Environment Management Ltd, 3A Vale Street LL16 3AD, Denbigh
[2]Rupert Finland Oy, Sodankylä, Finland

Advances in mineral characterisation techniques provide opportunities for development of novel approaches to sustainable management of waste rock generated by mining activities [1]. This talk reviews the use (and need) for advanced mineralogy analytical techniques in mine waste management through project examples. Metal mining produces above all rock, which is generally viewed and treated as waste, since it is not the target of the mining activities. These non-ore rocks can contain target metal(s) and other metals in concentrations and forms that lead to high release rates in the surface environment where such rock is placed in storage facilities of various configurations. Metal leaching from the rock in such facilities can occur in circum-neutral conditions (the focus of this talk), where nuances of the metal host minerals can be a dominant factor in the potential for a metal to be mobile [2]. Mining is central to the energy transition (as the source of critical raw materials) and therefore management of materials arising as part of these activities in sustainable ways is likely to be increasingly relevant.

Managing non-ore rock is underpinned by categorizing it according to the acid and metalliferous mine drainage (AMD) risk it poses, into classes such as 'useable' and 'to be managed'. Block models of the site, containing the ore and waste classification, are used to allow planning of the mining operations and management of the non-ore rock which will be excavated, so need to be as accurate as possible. Since leaching behaviour is not a primary property of the rock, detailed understanding of the combination of mineralogy and chemistry of the main rock types and how those link to metal leaching risk, is required. Due to cost and time limitations, block models are often built on the basis of indicators of AMD risk or proxies of those. Often, sulfur (S) is used to indicate potential to produce acidity (assuming it is present as sulfide S) and calcium (Ca) to indicate buffering (assuming it is present in calcite, although many rock forming minerals contain Ca so the buffering may be over-estimated). In addition, specific metals may be added to the model for information or to be included in the classification scheme. The concentrations of these elements in the rock are often obtained through assaying in exploration/deposit development, but it is the mineralogy of the rock that controls how these elements may be released during weathering [2]. With increasing scrutiny of the effects of mining on the environment, detailed understanding of the trace chemical content of minerals and the mineral hosts of metals are becoming increasingly relevant for waste classification and management.

This presentation includes examples that showcase how combining understanding from different types of analyses can be used to refine the understanding of mine waste-related AMD risk in circum-neutral environments. The examples also show how the results of detailed mineralogical analyses of materials viewed as waste, can provide opportunities for identifying potential uses for these materials. Challenges are identified including mismatches between the sensitivity or accuracy of current commercially available mineralogical characterisation techniques (such as X-ray diffraction (XRD) and scanning electron microscopy (SEM)) and the levels at which sensitive elements or minerals are present in the solids. The examples highlight that greater collaboration between academia and industry has the potential to leverage cutting edge techniques to support the development of more sustainable approaches to mine waste management.

References:
[1] Jamieson, HE, Walker, SR and Parsons, MB (2015), Mineralogical characterisation of mine waste. Applied Geochemistry: V57, P85-105.
[2] Parbhakar-Fox, A and Lottermoser, BG (2015), A critical review of acid rock drainage prediction methods and practices, Minerals Enineering: V82, P107-124.

Mineralogy of PFAS containing soils in Scotland: Correlations with clay minerals and Fe-oxides

Turner, S.M.R., Gray-Wannell, N., Ghosh, U., Zhang, Z., and Hillier, S.

The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland. stuart.turner@hutton.ac.uk

---

Per- and polyfluroralkyl substances (PFAS) are a group of ~15,000 endocrine-disrupting synthetic compounds, used in a variety of every-day products including kitchenware non-stick coatings, surfactants and fire-fighting foams [1,2]. The strong C-F bonds of these emerging soil contaminants make them resistant to chemical attack and high temperatures, and their terminal transformation products are pervasive in the natural environment [3,4]. Studies have shown a direct correlation between PFAS concentrations in soil and bioaccumulation in agricultural plants, such as fruits and grains [5]. Human exposure to these 'forever chemicals' leads to negative health effects including increased cholesterol levels, cancers, and developmental effects in unborn children [6].

Clay minerals are being considered for environmental remediation of PFAS primarily due to their small particle size, exchangeable cations and pH dependent surface charge sites [7]. Additionally, a recent study has demonstrated how short-chain PFAS ($CF_2 \leq 7$) mobility is largely controlled by aluminium-oxide mineral(oid) electrostatic sorption in US soils [8]. However, we have been unable to find further studies that consider mineralogy as a factor for PFAS mobility in soils. Rather, soil studies tend to focus on soil organic matter, pH, cation exchange capacity and land use type to explain the presence of PFAS [9]. Where these factors are unable to explain PFAS levels there exists a gap to consider whether changes in mineralogy explain variations, by acting as a sink and a subsequent potential source for PFAS, hence, affecting their fate, transport, and retention in soils.

On-going work at The James Hutton Institute is utilising the National Soils Archive to determine changes in PFAS concentrations of 30 soil sample sites across Scotland over a 30-year period [10]. Using X-ray diffraction (XRD) to determine the quantitative mineralogy of NSIS (National Soil Inventory of Scotland, 1978-1988) soil samples, we are investigating possible correlations with PFAS levels with the aim to ascertain if there is a mineral component to PFAS mobility in Scottish soils.

References:
[1] Lindstrom, A.B., et al., 2011. Environmental science & technology, 45(19), pp.7954-7961.
[2] Glüge, et al., 2020. Environmental Science: Processes & Impacts, 22(12), pp.2345-2373.
[3] Pemberton, E., 2021. Poly-and perfluoroalkyl substances (PFAS): sources, pathways and environmental data. Environment Agency, Bristol, UK.
[4] Xie, Z. and Kallenborn, R., 2023. Current Opinion in Green and Sustainable Chemistry, 42, p.100840.
[5] Ghisi, R., et al., 2019. Environmental research, 169, pp.326-341.
[6] Fenton, S.E., et al., 2021. Environmental toxicology and chemistry, 40(3), pp.606-630.
[7] Mukhopadhyay, R., et al., 2021. Advances in Colloid and Interface Science, 297, p.102537.
[8] Evich, M.G., et al., 2025. Nature Communications, 16(1), pp.3118.
[9] Wang, et al., 2023. O Soil & Environmental Health, 1(1), p.100004.
[10] Chen, Y., et al., under review. Nationwide trends of forever chemicals in Scottish soils over 30 years.

Mineralogical and textural characterization of APS minerals from the Madriguera deposit, Segovia (Spain)

San-Cipriano, A.[1], Santamaría-López, A.[1], García-Romero, E.[2] and Suárez, M.[1]

[1]Department of Geology, University of Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain. asancipriano@usal.es
[2]Department of Mineralogy and Petrology, Complutense University of Madrid, C/ José Antonio Novais 12, 28040 Madrid, Spain.

In the recent years, Aluminium phosphate-sulphates of the alunite supergroup (APS) have gained increasing significance not only as pathfinder minerals during exploration campaigns, or as indicators of physical and/or chemical conditions and hydrothermal processes in a deposit, but as potential host for elements of interest, such as Rare Earth Elements (REE).

The Madriguera deposit in Segovia, central Spain, holds a very interesting APS-kaolinite mineralization. The mineralogical association between APS and kaolinite has been widely documented since the las century [1]. Although known since de Middle Ages, when small-scale artisanal mining was carried out to extract iron and graphite, previous research on this deposit is limited and attributes the mineralization to an advanced argillic alteration process of the sulphide-rich Ordovician-Silurian slaty basement [2]. This alteration process is suggested to take place during Neogen period. Due to their industrial relevance, both, APS minerals and kaolinite, are currently being studied in this deposit.

60 samples were obtained among the two main open pits in the Madriguera deposit. Among these, 51 were collected from "La Tejera" open pit at 1 m intervales along a straight line, perpendicular to the stratification and 9 samples were collected from "Las Herreras" open pit. Those samples were studied using conventional X-ray diffraction (XRD) on powder sample and on the minor than two microns fraction. Additionally, other diffraction analysis has been carried out, using capillary transmission geometry and strictly monochromatic radiation with a Mo anode, allowing a more precise phase identification due to the enhanced resolution of the APS minerals reflections and the minimization of the phyllosilicate's orientation. Whole-rock geochemical analyses were also performed. Finally, scanning electron microscopy (SEM) studies were performed on representative samples for a textural characterization.

The rocks are formed by kaolinite, mica, quartz and small proportion of feldspar together variable amounts of APS ranging between 1-45%. Rarely, hematite, jarosite, and natrojarosite have also been identified. APS minerals occur mainly as micrometric crystals dispersed within the clayey matrix, although they occasionally also appear as small vein-like accumulations and whitish patches with variable crystal size and morphology. Those minerals were identified as members of the alunite series, alunite and natroalunite mainly, with smaller proportions of woodhouseite and svanbergite. Following the classification by Dill [3], these two minerals belong to the woodhouseite series, whereas the Bayliss nomenclature [4] assigns them to the beudantite group. Similarly, trace amounts of crandallite and goyazite were detected which are classified within the crandallite series [3], or within the plumbogummite group [4].

References:
[1] Dill H (1997) Z Angew Geol 43:198–204.
[2] Cañada F (1974) *Bol Geol Min* 85:430–435.
[3] Dill H (2001) Earth-Sci Rev 53:35–93.
[4] Bayliss P et al. (2010) Mineral Mag 74:911–914.

Tracing Crime through Minerals: The Role of Mineralogy in Forensic Investigations

Di Maggio, R.M.[1,2]

[1]Geoscienze Forensi Italia®
[2]IUGS Initiative on Forensic Geology

Forensic sciences encompass the systematic application of scientific methodologies to the judicial domain, with the aim of reconstructing events through the search for and analysis of evidence, together with the interpretation of analytical data. Within this broad disciplinary framework, forensic geosciences have gained increasing prominence over recent decades, both in professional practice and in academic research, owing to their ability to provide objective, reproducible and often decisive information in investigative contexts [1].

Within this field, forensic mineralogy occupies a central position focusing on the study, identification and characterisation of minerals, rocks and related materials (natural, anthropogenic or transformed) recovered as traces or items of evidence. It builds upon the conceptual and methodological foundations of classical mineralogy and petrography, while addressing the specific requirements of the forensic context, including limited sample sizes and the need to preserve evidence integrity.

Many criminal events occur in environments where interaction between humans and the natural setting is unavoidable. Soils, dusts, sediments, lithic fragments, industrial residues, glasses, pigments and building materials may be transferred, even in microscopic quantities, between locations, objects and individuals, becoming silent witnesses to criminal activity. The environmental context may therefore act not only as a repository of traces, but also as a medium for evidence transfer or, in some cases, as an active component of the event itself.

Minerals and geomaterials, as fundamental constituents of the Earth's surface, are integral to human activities. Their ubiquity and distinctive compositional and structural traits make them particularly informative in forensic investigations, allowing questions of origin, geographical provenance, formation processes and modes of use or alteration to be addressed [2].

Within this framework, the presentation will offer an overview of the principal laboratory-based instrumental techniques employed in forensic mineralogy, highlighting their capabilities and limitations in the analysis of forensic samples. Applications of optical and electron microscopy, X-ray diffraction, and spectroscopic techniques will be discussed, emphasising the value of an integrated, multi-technique approach, illustrated through selected case studies [3].

Finally, particular attention will be given to sampling strategies, sample preparation and analytical handling, which are crucial in forensic investigations, where evidence is often unique and non-repeatable. In conclusion, forensic mineralogy emerges as an interdisciplinary field, where the mineralogical tradition meets the demands of the justice system, providing rigorous and innovative tools for the analysis of materials and, through them, for the reconstruction of the events in which they were involved.

References:
[1] Di Maggio RM and Barone PM (2017) Soil Forensic Series 2:VII, 237
[2] Mercurio M et al. (2023) Soil Forensic Series 4:XI, 311
[3] da Silveira Tortolero Araujo Lourenço M et al. (2024) Forensic Sci 4:396–408

150 years of tourmaline studies

Henry, D.J.[1]

[1]Department of Geology & Geophysics, Louisiana State University, Baton Rouge, Louisiana, 70803 USA ; glhenr@lsu.edu

---

Tourmaline has been integral to the advancement of science for several centuries, yet the past 150 years have witnessed an extraordinary expansion in our understanding of its chemistry, crystallography, geochemistry, and petrologic significance [1]. Prior to the founding of the Mineralogical Society of the UK and Ireland (MinSoc) in 1876, tourmaline was primarily known for its unusual electrical behaviour: heating or cooling of a crystal generates opposite electrical charges at opposing ends along the c crystallographic axis, phenomenon known as *pyroelectricity.* Shortly thereafter, in 1880, Pierre and Jacques Curie demonstrated that mechanical compression along the c-axis likewise generates electrical charges at opposite crystal faces, a property termed *piezoelectricity*.

Although the common occurrence of tourmaline in granites and granitic pegmatites was widely recognized during the nineteenth century, it was subsequently discovered in a much broader range of geological environments, including igneous, metamorphic, and sedimentary rocks, as well as a variety of ore deposits and hydrothermal systems. Notable early examples of new environments included its association with the tin ores of Cornwall [2]. By the end of the nineteenth century, the remarkable chemical complexity of tourmaline had become increasingly appreciated.

During the early and mid-twentieth century, studies of tourmaline expanded significantly as a result of (1) the exploration of more diverse geological settings, (2) the development of analytical instrumentation capable of characterizing the chemical and physical properties of minerals, and (3) the growing scientific and technological applications that arose from these advances. In clastic sedimentary rocks, tourmaline was recognized as one of the most important heavy minerals and became widely used to assess sediment maturity, determine provenance, and aid in stratigraphic correlations. At the same time, crystallographic investigations led to a clearer understanding of the tourmaline structure, and by the 1960s–1970s the general structural framework and formula of the mineral were broadly established. Beyond geological applications, tourmaline's piezoelectric properties also found important technological uses during the twentieth century. One notable application, developed after World War I, involved the detection and measurement of pressures generated by conventional and atomic explosions using tourmaline-based piezoelectric sensors.

Since the late twentieth century, studies of tourmaline have expanded dramatically in both scope and number, driven largely by the widespread availability of micro-analytical, crystallographic, and spectroscopic instrumentation. Petrologically, tourmaline has emerged as a powerful petrogenetic indicator in rocks and sediments due to its chemical flexibility, its occurrence in most rock types, its exceptionally wide pressure–temperature stability—from near-surface conditions to the deepest levels of the crust—its capacity to acquire a chemical signature during the evolution of the rock in which it forms, and its remarkable ability to preserve that chemical record through subsequent geological processes. Consequently, tourmaline can provide detailed information on the timing, temperature conditions, and fluid history of its host rocks. Recent studies have also expanded the conceptual framework of its internal structure and dramatically increased the number of recognized tourmaline species from 4 to 42 [e.g., 3]. The future of tourmaline research is promising, with many new and exciting possibilities that will continue to influence scientific inquiry well into the future.

References:
[1] Henry, DJ and Dutrow, BL (2018) J Geosci 63:77-98
[2] Collins JH (1883) Mineral Mag 5:120-130
[3] Henry DJ et al. (2011) Rev in Econ Geol 17: 1-12

A new polysomatic series among the lead silicates friisite and jagoite

Cámara, F.[1], Holtstam, D.[2] and Karlsson A.[2]

[1]Università degli Studi di Milano, Dipartimento di Scienze della Terra 'A. Desio', Milan, Italy, fernando.camara@unimi.it
[2]Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden

---

The recent discovery of friisite (Fii), ideally $Pb_8Al_3Si_8O_{27}Cl_3$ [1] resulted in a new mineral species structurally and genetically related to jagoite (Jg), $Pb_{11}Fe_5Si_{12}O_{41}Cl_3$ [2,3]. Both minerals are lead silicates among the about 50 species known so far that are typical of Pb-rich skarn environments or oxidized zones of polymetallic ore deposits. Fii and Jg have been found at the Långban Fe-Mn-(Ba-As-Pb-Sb-W-Be-B) deposit, located in the Filipstad district (Värmland, Sweden). The study of lead silicates potentially provides valuable insights into mineral formation processes across a range of temperatures, particularly concerning the mobility of lead in nature and in extension, the technogenic environment. Both friisite and jagoite likely crystallised after the main skarn-forming event (post-peak metamorphism) from transformation of earlier formed lead silicates, melanotekite or barysilite, and require temperatures among 300–500°C, the presence of albite, and a Cl-enriched fluid at relatively high a_{SiO2}. Fii and Jg are sheet silicates. Fii has a double layer of SiO_4/AlO_4 tetrahedra. Each single-layer sheet is based on the $(12^2)_3(12^3)_2$ net [4]. Two types of SiO_4 tetrahedra and an Al(Fe^{3+}) tetrahedra form the double layer generated by a class-2 oikodoméic *m* operation. The tetrahedra of the double layer connect in twelve-membered rings and the composition of the double layer is $[Al_2Si_8O_{27}]^{16-}$. A layer of metal-bearing octahedra is sandwiched on each side of the double layer. Lead occurs in three non-equivalent positions: one position located in the single layer, three-coordinated to oxygen atoms and three very distant Cl atoms; another is seven-coordinated and lies in the octahedral layer intercalated with Al-octahedra; the last Pb occupies voids in the double layer, where it is eight-coordinated to five O and three Cl atoms and may be substituted by some Ca and Na. Therefore, friisite can be described as *TOT* (* is a double layer of tetrahedra). Jagoite has a further hypothetical single-layer silicate module (SSPM) built from one layer of octahedra and a single SiO_4 tetrahedra layer sandwiched between the octahedra layers configuring a sequence of *TOTOT*, and has all Al replaced by Fe^{3+}. This further single layer of tetrahedra is also based on the $(12^2)_3(12^3)_2$ net, although three SiO_4 tetrahedra are flipped upside down, allowing for the coordination of the octahedra in both adjacent layers. The additional two layers (TO) have the composition $Pb_3Fe^{3+}[Fe^{3+}Si_4O_{14}]$ (SSPM). Therefore, when this module is added to a hypothetical Fe^{3+}-exchanged friisite ($Pb_8Fe^{3+}[Fe^{3+}{}_2Si_8O_{27}]Cl_3$), it yields the structural formula of jagoite, ($Pb_{11}Fe^{3+}{}_2[Fe^{3+}{}_2Si_8O_{27}][Fe^{3+}Si_4O_{14}]Cl_3$) [3]. It is likely that new polysomatic members or stacking-disordered “jagoite-type” minerals can be found in geological systems like the Pb-rich skarns of Långban-type deposits and in anthropogenic products, like Pb smelter slags.

References:
[1] Holtstam D et al. (2026) Min Mag (in press)
[2] Mellini M and Merlino S (1981) Am. Mineral., 66, 852–858
[3] Holtstam D et al. (2025) Min Mag, 89, 830–842
[4] Hawthorne FC et al. (2019) Min Mag, 83, 3–55

Seeing Mineral Reactions in 4D: Imaging Dynamic Subsurface Processes from Micro- to Nano-scale

Ma, L.[1]

[1]Oxford Road, Department of Chemical Engineering, University of Manchester

---

Mineral reactions are not static features preserved only in the rock record; they are dynamic processes that continuously reshape subsurface pore systems, transport pathways, and sealing behaviour. Understanding these reactions is critical for a wide range of subsurface applications, including hydrocarbon production, geothermal energy, CO_2 sequestration, hydrogen storage, energy storage, and nuclear waste disposal. Rocks in these environments commonly act as reservoirs, seals, and reactive media, yet their full characterisation remains highly challenging because of their fine-grained, heterogeneous, and evolving nature.

In this talk, I will highlight how recent advances in high-resolution imaging are transforming our ability to observe dynamic mineral systems directly. By capturing three-dimensional structures through time, these approaches open the door to 4D mineralogy, allowing mineral reactions and microstructural evolution to be visualised across multiple spatial and temporal scales.

Dynamic in situ X-ray tomography, using both laboratory-based and synchrotron sources, provides new opportunities to investigate thermo-hydro-mechanical-chemical (THMC) processes in rocks under subsurface conditions. Experiments have explored high temperatures (from <10 °C up to ~1000 °C) [1], high pressures (up to ~65 MPa) [2], fluid transport and multiphase flow [3], and chemically reactive environments such as brines and drilling fluids [4]. Time-lapse observations reveal how mineral reactions and deformation modify pore connectivity, transport pathways, and sealing behaviour over time.

Despite major progress, important challenges remain in representativity, upscaling, experimentation under subsurface-realistic conditions, and prediction of long-term behaviour. Continued advances in 4D imaging and digital-rock analysis will be key to moving from static description to predictive understanding of dynamic mineral–fluid systems, with important implications for the safe and effective use of the subsurface in the energy transition.

References:
[1] Wang, K. et al., 2021. International Journal of Coal Geology, 244, 103816.
[2] Figueroa Pilz, F. et al., 2017. Journal of Geophysical Research: Solid Earth, 122, 2553–2570.
[3] Related multiphase flow imaging studies.
[4] Godinho, J.R. et al., 2019. Minerals, 9, 480.

Crystal Chemistry: New Rules for the 21st Century

Hawthorne, F.C.[1]

[1]Earth Sciences, University of Manitoba, Winnipeg, MB R3T 2N2, Canada; frank.hawthorne@umanitoba.ca

---

Despite being used (and useful) for over 100 years, our current models for Crystal Chemistry are neither realistic nor correct. Earnshaw's theorem [1] shows that point-charge models are not stable, and the traditional ionic model bears no resemblance to reality. Here, I present a new set of new rules for Crystal Chemistry that significantly increases our understanding of the factors affecting the stereochemistry of mineral and inorganic crystal-structures.

The electric field in a crystal is a vector field; bond strengths from cations to anions are positive and bond strengths from anions to cations are negative. Moreover, in a vector field, the line integral between any two points is independent of the path between those two points and is only dependent on their positions. The incident bond-strengths at all ions must equal the formal charges at those ions. Noether's theorem [2] requires that bond-strengths along non-degenerate paths between symmetrically equivalent ions in the structure must sum to zero. This leads to Rule 1, the a-priori bond-strength rule: *A-priori bond-strengths may be calculated for all bonds in a structure by constructing a bond-strength table that includes all bond-strengths as unknown variables. The corresponding charge-conservation equations can be solved for all the unknown bond-strengths.* The resultant bond-strengths are dependent only on the formal charges of the constituent ions and the bond topology of the structure. Although calculation of bond strengths in this approach is independent of bond lengths, the resulting bond strengths correlate strongly with the observed bond-lengths, indicating that the formal charges of the constituent ions and the bond topology of the structure generally dominate the variation in bond lengths.

Ion radii derived from experimental bond-lengths do not represent the radii of ions in crystals as we cannot objectively divide bond lengths into the radii of the constituent ions. Moreover, theoretical bonded-radii calculated by quantum mechanics (*e.g*. [3]) show a wide variation in radii of particular anions (*e.g*., $0.5 < r^{O2-} < 1.4$ Å). It is apparent that radius ratios of bonded ions have no physical meaning. However, mean bond-length is a proxy variable for ion radius and hence sums of ion radii have physical meaning. This leads to Rule 2, the ion-radius rule: *Ratios of ion radii have no physical meaning whereas sums of ion radii can be used in crystal chemistry (e.g. correlating site occupancies with observed mean bond-lengths).* Thus the radius-ratio rule of Pauling [4] must be discarded.

The *characteristic Lewis acidity* of a cation is defined as its *characteristic bond-strength*, which is equal to its formal-charge/characteristic-coordination-number. The characteristic Lewis basicity of an anion is defined as the characteristic strength of the bonds formed by the anion. This leads to Rule 3, the bond-strength-matching rule: *Stable structures will form where the Lewis acidity of the cation closely matches the Lewis basicity of the anion.* Where a structure topology is not known, this rule will give an *a- priori* estimate of whether a particular chemical formula can (or cannot) occur. For a specific chemical formula and a proposed topology, individual cation and anion coordination numbers can adjust, thereby modifying the structure topology to optimize matching of Lewis acidities and Lewis basicities.

All of these rules will be illustrated with mineral examples.

References:
[1] Earnshaw S (1842) Trans Cambridge Philosophical Soc 7:97–112
[2] Noether E (1918) Nachr. Ges. Wiss. Gottingen, Math-phys. Klasse, 235–257. English translation at https://arxiv.org/abs/physics/0503066
[3] Gibbs et al. (2013) J Phys Chem A 117:1632–1640
[4] Pauling L (1960) The Nature of the Chemical Bond. 3rd Ed., Cornell University Press, Ithaca, NY, 644 p

Time's Second Arrow: Mineral Evolution as a Case Study of a New Natural Law

Hazen, R.M.[1] and Wong, M. L.[1]

[1]Earth and Planets Laboratory, Carnegie Institution for Science, Washington DC, USA; rhazen@ciw.edu

---

A pervasive wonder of the natural world is the evolution of varied systems, including stars, planets, minerals, and life—all of which have increased in diversity and patterning over deep time. However, no law of nature describes and explains, much less quantifies and predicts, the behaviour of complex evolving systems. Accordingly, we propose a new law of nature, the "law of increasing functional information," that applies to the evolution of both abiotic systems (notably minerals) and life [*1,2*]. This postulated increase in functional information represents a second arrow of time—one that is consistent with the increase in entropy (the first arrow of time) but is not derivable from the laws of thermodynamics [*3*].

This concept is now being applied and tested by other groups in fields as wide-ranging as the evolution of languages, the behaviour of AI systems, the seasonal variations of soil microbiomes, and the search for new cancer therapies [*4-6*]. Mineral evolution, which explores the diversification of Earth's mineral kingdom on more than 4.5 billion years, is an especially revealing test case of this proposed law of nature [*7*].

[1] Wong ML et al. (2023) Proc Natl Acad Sci USA 120, e2310223120
[2] Wong ML et al. (2025) Royal Soc Interface Focus 15, 20250009
[3] Hazen RM & Wong ML (2026) Time's Second Arrow: Evolution, Order, and a New Law of Nature. NY: Norton
[4] Thomas F et al. (2024) Evolution, Medicine, & Public Health 2024, 172-177
[5] Dujon AM et al. (2025) Aging Cell 2025, 0:e70207
[6] Johnson NC & Marin C (2025) The ISME Journal 19, wraf137
[7] Hazen RM & Wong ML (2024) Proc Natl Acad Sci Nexus 3, pgae248

Back to table of contents

HALLIMOND LECTURE

Searching for Earth's missing magma oceans

Williams, H., Amsellem, E., Matthews, S. and Puchtel, I.

Department of Earth Sciences, Cambridge University, Downing Street, Cambridge CB1, UK
E-mail: hmw20@cam.ac.uk

Magma ocean (MO) crystallisation events, most recently in the aftermath of the Moon-forming impact established the Earth's initial internal structure and chemistry, with cumulates and residual liquids from this event potentially being preserved at the base of the mantle today. The presence of this material has been inferred in the source of modern and ancient mantle plumes where it may account for some of the unusual chemistry and radiogenic isotope signatures of associated ocean island basalts (OIB). However, detecting residual MO material using radiogenic isotope systems alone remains contentious, as these do not directly record mantle mineralogy or physical properties. Iron (Fe) stable isotopes offer a solution to this conundrum, as the Fe isotope compositions of mantle-derived melts primarily reflect mineral-specific partitioning, extending to lower mantle phases such as bridgmanite, ferropericlase, and metallic iron produced by bridgmanite-induced FeO disproportionation. I will present new iron isotope data for plume-related Archean komatiites, which also display decoupled hafnium-neodymium isotope systematics and distinct 182-tungsten and 142-neodymium isotope signatures, interpreted to be derived from a residual silicate melt formed during MO crystallisation. Correlations between stable iron isotope signatures and radiogenic isotope tracers in these samples provides the first direct observational evidence for a mantle source component formed from a silicate liquid residual from MO crystallisation, which accumulated disproportionation-derived Fe-metal. Such material would remain stable in the lower mantle until entrainment by a mantle plume and may account for some of the isotopic anomalies observed in modern OIB today.

Valuing sand for sustainable resource transitions

Ardhanari, M[1,2], Moore. K.M.[1], Gallagher, L.[2], Franks. D.M.[2], Segura-Salazar, J.[2,3] and Yan. X.[4], Zils, M.[5]

[1] Camborne School of Mines, Department of Earth and Environmental Sciences, Penryn Campus, Penryn, United Kingdom
[2] The University of Queensland, Global Centre for Mineral Security, Sustainable Minerals Institute, Brisbane, QLD, Australia
[3] The University of Queensland, Julius Kruttschnitt Mineral Research Centre, Sustainable Minerals Institute, Brisbane, QLD, Australia
[4] Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn, United Kingdom
[5] The University of Exeter, Business School, Faculty of Environment, Science and Economy, Exeter, United Kingdom

---

The valuation shifts needed to transition away from natural sand extraction towards ore-sand, a more resource efficient circular economy alternative, are explored. Abundant and cheap to produce, sand, along with aggregates, is the second most exploited material globally. Its irresponsible extraction has resulted in profound environmental and social destruction. In parallel, more mining projects are being commissioned to meet material needs for a renewable energy transition and urban infrastructure expansion. Only a small fraction of the material excavated is 'valuable' ore, with the large majority being classified as waste. Total resource recovery and mineral coproduction is a potential goal in mining circularity, where all minerals recovered are responsibly utilised and no mineral is regarded as 'waste'. The currently unused bulk material fraction can be processed into human-made sand (ore-sand), a companion product to metallic ore minerals and an alternative to primary sand extraction, thereby minimising unnecessary extraction of natural sand.

Valuation is a key instrument for assessing mineral coproduction, in that how minerals are valued determines the economic and social feasibility of upscaling coproduction in mining projects. If produced responsibly at scale, ore-sand could drastically reduce mine waste and minimise the socio-environmental impacts of natural sand extraction. To explain how value and valuation frameworks can be designed to influence real decision-making at the firm, value chain and societal levels, we investigate the mismatch between commercial and public valuations of sand, and how it affects ore-sand uptake. A hybrid methodology of expert opinion supplemented by a systematic review from the Scopus and Web of Science platforms, and focussed literature analysis was used to understand patterns and trends in valuation frameworks spanning firm, value chain and societal contexts used to ascribe value to mineral resources.

Our findings highlight a mismatch between how companies and societies value mineral resources. For companies, sand is often a commodity or waste to be managed for companies, while it is critical to ecosystems conservation and coastal livelihoods societally. We find that reconciling between the valuation systems, in a just and safe operating space (i.e. within ecological limits while meeting societal needs) requires a synthesised valuation framework. Applying this synthesised framework to ore-sand, we explore how valuation processes can be redesigned to catalyse the transition from natural sand to ore-sand at scale. The contribution of this work is to build the socio-environmental case for mineral circularity operationally within individual firms and in policymaking at the societal level.

Minerals in the Anthropocene: Carbonate Formation, Contaminant Dynamics and Engineered Alkalinity

Bastianini, L.[1], Rogerson, M.[2], Campbell, J.[3], Baltruschat, S.[4], Hartmann, J.[4], Foteinis, S.[3], Millar, R.[3], Yang, A.[5], Lu, X.[5], Thoutam, P.[5], Kapadia, A.[6], Harrington, K.[5], Rosair, G.[3], Higgins, S.[3], Buckman, J.[3], Renforth, P. [3] and Mayes, W.[7]

[1] University of Glasgow, Glasgow, UK, Laura.Bastianini@glasgow.ac.uk
[2] Northumbria University, Northumbria, UK
[3] Heriot-Watt University, Edinburgh, UK
[4] Hamburg University, Hamburg, Germany
[5] University of Oxford, Oxford, UK
[6] The University of Manchester, Manchester, UK3Affiliation address
[7] University of Hull, Hull, UK

Highly alkaline waters generated by lime, steel, cement and energy production represent some of the most chemically extreme anthropogenic environments on Earth. Once regarded primarily as environmental liabilities, these systems are increasingly recognised as large-scale natural laboratories for understanding carbonate mineral formation and as potential platforms for carbon dioxide removal. This keynote explores how mineralogical insight into anthropogenic carbonate systems can inform both environmental management and engineered climate solutions. A comparative sedimentological and mineralogical analysis of carbonate precipitates downstream of lime and steel disposal sites reveals striking parallels with natural travertine and tufa systems. Using integrated microfacies analysis (petrography and electron microscopy), X-ray diffraction and hydrochemical data, these systems exhibit organised proximal, middle and distal precipitation zones analogous to natural carbonate depositional models. However, anthropogenic systems show key macroscopic distinctions, including swamp-dominated proximal environments and tufa-like barrage-and-pool sequences further downstream. At the microscale, fabrics resemble travertines but lack subsurface facies and, under extreme pH conditions, develop sparry crusts without clear natural equivalents. These observations demonstrate that calcite precipitation in hyperalkaline systems is neither homogeneous nor purely thermodynamically controlled, but instead governed by complex kinetic, hydrological and geochemical feedbacks. Beyond calcite, highly alkaline industrial waters foster the formation of transient and metastable carbonate phases. The first documented occurrence of ikaite ($CaCO_3 \cdot 6H_2O$) crystallisation in steel-slag leachate systems reveals precipitation pathways likely initiated through amorphous calcium carbonate (ACC). Field-based FTIR combined with rapid XRD validation enabled identification of this temperature-sensitive mineral, which incorporates significant inventories of trace metals such as Pb and Cd. Given ikaite's instability above ~8 °C, seasonal warming poses a risk of contaminant pulses, highlighting the importance of transient mineral phases in contaminant dynamics and carbon budgeting. Building on this understanding of hydrated carbonate phases, experimental work on the dissolution kinetics and stability of ACC and ikaite in seawater demonstrates their potential role in ocean alkalinity enhancement (OAE) for carbon dioxide removal. Both phases dissolve spontaneously in seawater, increasing total alkalinity, with dissolution rates strongly temperature dependent. ACC, in particular, offers advantages due to high surface area, stability when appropriately stabilised, and favourable particle transport dynamics. These findings connect mineral precipitation processes observed in anthropogenic alkaline systems to engineered pathways for climate mitigation. Taken together, this work reframes anthropogenic hyperalkaline environments as sedimentologically structured, mineralogically dynamic systems that both challenge traditional depositional models and expand the role of mineralogy in sustainability science. By integrating facies analysis, transient mineral identification and dissolution kinetics, mineralogical research can underpin improved environmental risk assessment, resource recovery, and scalable carbon dioxide removal strategies in the Anthropocene.

Mineralogical Controls on Carbonation Rates and Vanadium Leaching Behaviour in Alkaline Steel-Slag Systems

Burke, I. T.[1], Mayes W.M.[2], and Renforth P.[3]

[1]School of Earth, Environment and Sustainability, University of Leeds, Leeds, LS2 9JT, UK.
[2]School of Environmental and life Sciences, University of Hull, Hull, HU6 7TS, UK
[3]School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK.

Vanadium (V) mobility in alkaline steelmaking residues is controlled by the dissolution–precipitation behaviour of Ca-rich silicate phases and the geochemical evolution of hyperalkaline leachates. Microfocus XANES and SEM analyses of basic oxygen furnace (BOF) slag demonstrate that V was hosted primarily in dicalcium silicate and released as V(V) during silicate dissolution, after which a portion becomes incorporated into neo-formed Ca–Si–H phases within a developing alteration rind. [1] Aerated weathering enhances $CaCO_3$ precipitation, reducing aqueous Ca and thereby increasing dissolved V concentrations, whereas air-excluded conditions maintain higher Ca and suppress V via $Ca_3(VO_4)_2$ solubility controls. [1]

Mineralogical characterisation of a >20 Mt legacy blast furnace (BF) slag deposit at the former British steel site at Consett shows that buried melilite-dominated slag undergoes limited natural carbonation, with <1% of its theoretical carbonation potential realised. [2] Slow dissolution of Ca-silicate framework silicate underpins minimal development of secondary carbonate and Ca–Si–H phases, supporting the long term production of $Ca(OH)_2$ dominated leachates with low V concentrations. [3] Long-term monitoring of alkaline slag drainage waters (36-year dataset) at this site highlights persistent hyperalkalinity (pH >10), with modest declines in alkalinity and Ca, and the sustained leaching of trace metals, including V, albeit at relatively low concentrations. [4] These results confirm that high-pH leachates remain geochemically active over decades, with Ca–CO_3 system kinetics controlling the conditions under which V may either remain mobile or be captured by secondary mineral phases.

Additional field observations of leachate carbonation and laboratory neutralisation experiments shows that V was present predominantly as the vanadate oxyanion (HVO_4^{2-}). Although V can be initially removed through limited incorporation into $CaCO_3$ precipitates, V was much more strongly attenuated at lower pH via sorption to neoformed Fe-(oxyhydr)oxide surfaces. [5] Formation of ferrihydrite enhances V uptake, whereas clay mineral surfaces exert minimal influence across alkaline–circumneutral pH ranges. Together, this work demonstrates that V behaviour in steel slags is dictated not only by total V content but by the mineralogical evolution of Ca-silicate, carbonate, and Fe-oxide phases, which regulate V speciation, solubility, and downstream fate under hyperalkaline conditions.

References:
[1] Hobson A.J. et al. (2017) Environ Sci Technol 51: 7823-7830
[2] Mayes W.M. et al. (2018) Environ Sci Technol 52: 7892-7900
[3] Pullin H. et al. (2019) Environ Sci Technol 53: 9502-9511
[4] Riley A.L. and Mayes W.M. (2015) Environ Mon Assess 187: #463
[5] Hobson A.J. et al. (2018) Sci. Tot. Environ. 643: 1191-1199

Offshore Mineral Carbonation Potential: Insights from the Mid-Atlantic Ridge

McNamara, D.D.[1], Pasquet, P.[2], Gardner, J.[3], and IODP Expedition 395 Science Party[4]

[1]Earth, Ocean and Ecological Sciences, University of Liverpool, UK, d.mcnamara@liverpool.ac.uk
[2]Bureau of Economic Geology, Austin, Texas, USA
[3]SEM-SRF, University of Liverpool, UK
[4]Texas A&M University, Texas, USA

Mineral carbonation is a carbon dioxide (CO_2) storage option that shows growing promise as part of the broader portfolio of technologies supporting global decarbonisation goals. The process involves the reaction of CO_2 with rocks rich in minerals that contain high amounts of metal cations that can be made available for carbonate formation, particularly magnesium and calcium. One such lithology that has seen increasing exploration for mineral carbonation are basaltic lavas. In recent years, both academic research and industrial pilot projects have demonstrated the feasibility of accelerating carbonation processes within basaltic lithologies. While the technology is still developing and currently operates at relatively small scales compared to global emissions, there is scope to explore how such an industry could potentially be upscaled.

One potential avenue for expansion of this industry would be to explore beyond the onshore basaltic deposits and look to the vast quantities of basalt that comprise the oceanic crust. These offer larger and more voluminous reservoirs for mineral carbonation and potentially allow easier infrastructural operations to onshore disposal developments. To determine how successful carbonation processes would be in offshore oceanic basalts and evaluate how much CO_2 storage might be possible within them, their geological nature needs to be better characterised and understood.

We present initial findings on the composition, structural network, and physical properties of oceanic crustal basalts across an age range of 2.5-33Ma using data and samples acquired during International Ocean Discovery Program Expedition 395. Data and drillcore off oceanic basaltic crust across the Reykjanes Ridge provide us with the first high resolution analysis of both the parent and altered composition of ocean floor basalts, their structural networks, and how much natural carbonation has already occurred via hydrothermal circulation of seawater over millions of years. Results will provide new insight into fluid flow networks required for CO_2 injection, while allowing us to potentially constrain the CO_2 storage capacities of ocean crust basalts. This work will assist in narrowing down site selection of drill sites but determining crustal regions with higher potential for carbonation to succeed (higher available Mg and Ca cation content, open structural fluid pathways, low degree of natural carbonation or other hydrothermal alteration) and assist in determining the true potential of an offshore mineral carbonation industry.

Mineralogical Controls on Mineral Carbonation of Basalt: Alteration and Zeolitisation in the Antrim Lava Group

Alexander, J.S.[1], McNamara, D.[1], Mariani, E.[1], Gardner, J.[1], Cooper, M.[2]

[1]Department of Earth, Ocean, and Ecological Sciences, University of Liverpool, Liverpool, United Kingdom, jonathan.alexander@liverpool.ac.uk
[2]Geological Survey of Northern Ireland, Belfast, Northern Ireland

---

In-situ mineral carbonation in mafic rocks provides a permanent pathway for geological CO_2 storage, but reaction kinetics are fundamentally governed by mineralogical alteration, which modifies bulk rock assemblages and permeability–porosity evolution [1]. A national screening of mafic and ultramafic lithologies across Ireland identified 29 geochemically feasible formations, with the Antrim Lava Group (ALG) emerging as the most favourable candidate based on scale, thickness, mineralogy, and proximity to major emission sources. Petrographic and SEM-EDS analyses indicate that relatively fresh ALG basalts contain abundant Fe-, Ca- and Mg-bearing silicates, including forsteritic olivine, augite, and labradoritic plagioclase, supporting strong theoretical carbonation capacity. However, hydrothermal alteration exerts a primary control on effective reactivity. Olivine phenocrysts are consistently rimmed by iddingsite recording Mg mobilisation and Fe oxidation, potentially limiting carbonation via diffusive barriers. Nevertheless, lamellar microfractures within iddingsite rims, together with hairline fracturing associated with Cr-spinel inclusions, provide microscale permeability pathways that may facilitate reactive fluid ingress. Vesicles and fractures are extensively infilled by Ca-rich zeolites (chabazite-Ca and thomsonite-Ca), reducing effective porosity and potentially limiting injectivity, yet simultaneously providing a secondary source of reactive Ca through potential dissolution and cation exchange during CO_2 injection [2,3,4]. Preliminary borehole core logging and fracture analyses indicate structurally heterogeneous permeability at reservoir scale. Natural carbonate precipitation is limited, suggesting preservation of substantial reactive silicate capacity. These results demonstrate that alteration exerts a dual control on basalt-hosted carbon storage by stabilising reactive phases while regulating fluid–rock interaction. Detailed mineralogical characterisation is therefore essential for evaluating sustainable CO_2 storage in altered mafic systems. Further work aims to verify whether secondary phases, such as chabazite-Ca, enhance carbonation via cation release during potential dissolution or inhibit injection by blocking flow paths.

References:
[1] Delerce S et al. (2023) Geochim Cosmochim Acta **360**:106-121
[2] Ragnarsdóttir (1993) Geochim Cosmochim Acta **57**:2439-2449
[3] Heřmanská M et al. (2022) GHGT-16
[4] Alqahtani A et al. (2025) Sci Rep **15**:958

Mechanochemical carbon capture using rock substrates

Stevenson, S. C.[1], Lunn, R.[1] and Stillings M.[1]

[1]University of Strathclyde, Glasgow, siobhan.stevenson@strath.ac.uk

---

It has been known for some time that rocks can capture carbon dioxide from the atmosphere, but this has relied on high temperatures in excess of 400 °C, and specific rocks rich in valuable metals such as magnesium.[1,2] These processes are inefficient, resulting in relatively low capture rates, from 0.255 mgCO_2/g up to 13.43 mgCO_2/g for ultramafic rocks with high concentrations of magnesium.[3] For those with the greatest uptake, the results are highly dependent on achieving the correct pore structure and surface area during the pre-treatment.

Mechanochemical reactions can provide an alternative pathway to processes that could previously only be conducted at elevated temperatures. This is a process which produces a high surface area in a very short space of time, thereby bypassing kinetic limitations in reactions of solids. By employing mechanochemistry, it has been found that polymineralic rocks both rich and poor in Mg can be made to capture carbon in much higher quantities by milling the rocks in an atmosphere rich in CO_2.[4] Our research shows that there are intrinsic differences between mechanochemical CO_2 capture in rocks, versus pure mineral systems: in pure mineral systems both the trapped CO_2 and the metals are soluble. This implies that the reaction occurs in different places within the crystal structure in rocks, as opposed to pure mineral systems. To expand upon this, we have produced mineral mixtures based upon the constituent proportion of minerals in the whole rock. These ersatz rocks were subjected to the same conditions, and their carbon capture performance studied. The carbon uptake was considerably higher than might be expected from the composition – some members such as quartz were shown to uptake virtually none in isolation – however, much of the trapped carbon was soluble. This demonstrates that the idiosyncrasies of the polymineralic rocks distinguish them from being merely a mixture of minerals acting upon one another.

By studying the whole rocks, minerals, and composite mixtures with a range of techniques, we have been able to elucidate the manner in which carbon is stored. Thermal analysis showed that CO_2 was lost at multiple steps of increasing temperature, indicating different forms of storage. However, the associated temperatures, combined with powder X-ray and neutron diffraction data did not suggest metal carbonates. ICP-OES measurements indicated large differences in the metals lost, but also significantly more leaching of Si and Al in air- vs CO_2-milled rocks. This suggested formation of silicon carbonates, which have previously been observed under high pressure conditions.[5] However, from infrared & Raman spectroscopies, CO_2 molecules were observed in the samples, as well as stretching of various bonds. This was corroborated using X-ray absorption spectroscopy, where we probed the environment surrounding K, Ca, and Fe atoms. Adsorbed CO_2 was ruled out by the temperature at which it was lost; it must be more solidly bound. By use of solid state ^{13}C and ^{29}Si NMR, we were able to observe both the signal belonging to the carbonates, and of immobilised caged CO_2.

References:
[1] K. S. Lackner, C. H. Wendt, D. P. Butt, E. L. Joyce and D. H. Sharp, Energy, 1995, 20, 1153–1170.
[2] K. S. Lackner, D. P. Butt and C. H. Wendt, Energy Convers Manag, 1997, 38, S259–S264.
[3] S. J. Knak Jensen, M. Bregnhøj, J. Thøgersen, P. Nørnberg, A. B. Nielsen, J. Skibsted and K. Finster, Chem Phys Lett, 2023, 816, 140395.
[4] M. Stillings, Z. K. Shipton and R. J. Lunn, Nature Sustainability 2023 6:7, 2023, 6, 780–788.
[5] M. Santoro, F. Gorelli, J. Haines, O. Cambon, C. Levelut and G. Garbarino, Proc. Natl. Acad. Sci. U. S. A., 2011, 108, 7689–7692.

Understanding Direct CO_2 Uptake In Polymineralic Rocks Using Mechanochemistry

Doñagueda Suso, B.[1], Stevenson, S.[1], Stillings, M.[1], Shipton, Z.[1] and Lunn, R.[1]

[1]Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK.
beatriz.donagueda@strath@ac.uk.

Developing more sustainable processes in industry to reduce carbon emissions (CO_2) is crucial to meeting 2050 global climate targets. Decarbonisation of mining and mineral processing is a priority, they contribute between 4% and 7% of global greenhouse gas emissions.[1] Most decarbonisation processes use high temperatures and pressures to extract pure CO_2, or to trap it in the form of metal carbonates, such processes are expensive and inefficient.[2] Mechanochemical processes can provide an alternative energy source and negate the need for increasing pressure and temperature to drive chemical reactions. Mechanical stimulus releases energy through the breakage of chemical bonds, causing localised temperature increases and allowing surface reactions to occur that are not possible without significant external energy inputs—providing a clean and green solution for some processes.[3] Recently, our group has demonstrated that using mechanochemistry in common polymineralic silicate rocks, such as basalt and granite, provides a potential alternative for direct capture of CO_2 with a trapping efficiency of 14.5–19.6 $kgCO_2$ $tonne^{-1}$.[4] Unlike previous mineral carbon sequestration technologies, mechanochemical treatment of polymineralic rocks with CO_2 does not trap the CO_2 gas as metal carbonates, but as stable silicon carbonates. Moreover, this CO_2 trapping acts to increase the solubility of metals such as magnesium and calcium from the rock, making them available for additional CO_2 trapping in the form of metal carbonates.

Understanding how the mineralogy of the rocks affects the CO_2 capture rates and the subsequent metal leaching is essential to optimizing the mechanochemical process. In the experiments presented herein, we study two families of common igneous polymineralic silicate rocks, basalt and granite. We investigate CO_2 trapping in rocks with similar chemical compositions, but with differing crystal sizes that are naturally produced as a result of different cooling rates during rock formation. The variation in crystal sizes effects the mass of CO_2 trapped in the rock, likely due to changes in the density of mineral and crystal boundaries where CO_2 may be preferentially located. In this research, we show that boundary density present in the rock is correlated to the efficiency of mechanochemical CO_2 storage in the rock. Analytical techniques such as SEM-EDX, PXRD, IR, Raman, and BET surface area analysis, alongside subsequent leaching experiments, are used to understand initial rock mineralogy, assess changes to the rocks during milling and understand the effect on subsequent metal solubility; thus providing an insight into where dislocations are created, where the gas is potentially stored, and the effect on neighbouring metal bonds

References:
[1] O. Bashir Wani O. et al. (2022) Chem. Eng. J. 433: 134203
[2] A. Sanna A. et al. (2014) Chem. Soc. Rev. 43 (23): 8049-8080
[3] J.L. Do J.L. et al. (2017) ACS Cent. Sci. 3 (1): 13-19
[4] M. Stillings M. et al. (2023) Nat. Sustain. 6 (7): 780-788

Feldspar alteration by disequilibrium CO_2–H_2O fluids in reservoir sandstones: Implications for carbon capture and storage (CCS)

Farrell, N.J.C.[1], Yang, L.[2], Flowerdew, M.J.[3], Mark, C.[4], Ardo, B.[1], Taylor, K.G.[1], Bigaroni, N.[1],. Pointon, M.[3], Hughes, L.[1], Waters, J.[1], Paul, L.[1]

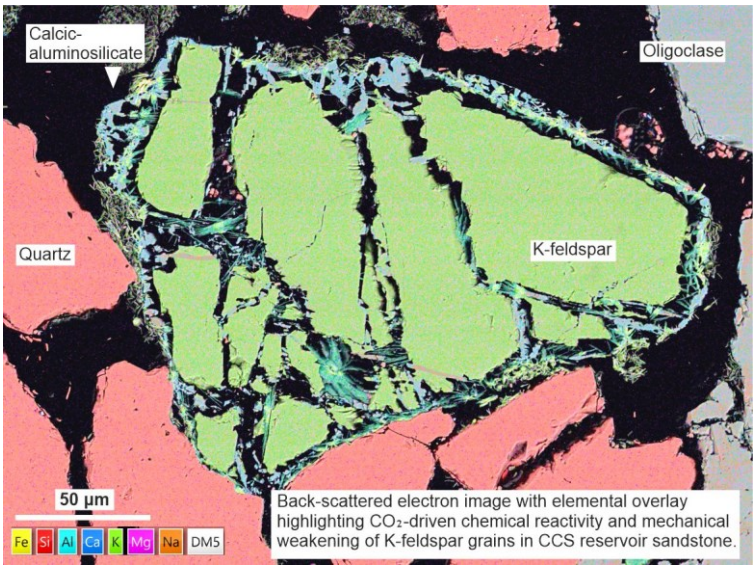
1. Department of Earth and Environmental Sciences, Williamson Building, University of Manchester, Manchester, United Kingdom natalie.farrell@manchester.ac.uk
2. Institute of Marine Sciences (CNR-ISMAR), Bologna, Italy
3. CASP, Cambridge, United Kingdom
4. Department of Geology, Swedish Museum of Natural History, Stockholm, Sweden

---

Understanding how the minerals in reservoir rocks respond to CO_2 injection is vital for the success and safety of Carbon Capture and Storage (CCS) projects. Feldspars are the most common mineral in the Earth's crust and act as primary framework grains in sandstones. Compared to quartz, feldspars are mechanically weak and chemically reactive. Dissolved feldspars can re-precipitate as clays, which in CCS reservoirs could impact fluid-flow. While caprock mineral stability is well studied, reservoir mineral reactivity, particularly of feldspars, remains understudied. To address this knowledge gap, this contribution presents microstructural and geochemical data from batch experiments that reacted CO_2-enriched fluids with feldspar-bearing sandstone sampled from the Captain Sandstone Member, the primary reservoir for the Acorn CCS Project (UK).

Experiments were conducted in a hydrostatic pressure vessel at 70 MPa confining pressure, 50 MPa pore pressure, and temperatures ranging from 80°C to 550°C, using CO_2-enriched water to simulate reservoir conditions. Pre- and post-reaction samples were analysed using XRD, SEM-EDS, and XCT to assess microstructural and mineralogical changes. Results show that CO_2:feldspar interactions differ significantly from control experiments involving water alone. At reservoir-relevant temperatures (80°C), incongruent dissolution of K-feldspar weakened grains which led to microfracturing. At 250°C, CO_2 fluids caused total dissolution of calcite grains and cement and selective leaching of calcium from oligoclase, enriching the pore fluid with Ca^{2+}. Above 400°C, coupled dissolution–precipitation processes were observed, including congruent K-feldspar dissolution, secondary porosity development, and localised precipitation of Ca-aluminosilicates and K-bearing phases around dissolving K-feldspars (Fig 1). These transformations could alter reservoir flow pathways and induce mechanical risks, i.e. destabilising nearby faults or initiating reservoir collapse.

Given feldspars' prevalence in crustal rocks and CCS sandstone reservoirs, their reactive behaviour under in-situ conditions and in the presence of aggressive fluids demands greater attention.



Back-scattered electron image with elemental overlay highlighting CO_2-driven chemical reactivity and mechanical weakening of K-feldspar grains in CCS reservoir sandstone.

Clay Minerals in Subsurface Hydrogen Storage: A Molecular-Scale Perspective

Ghasemi, M.

Department of Chemical Engineering, The University of Manchester, Manchester, M13 9PL, UK

Underground hydrogen storage is increasingly recognized as a key technology for enabling large-scale and long-term energy storage in future low-carbon systems.[1] Its feasibility and security depend on coupled transport, interfacial, and mechanical processes within subsurface porous media. Clay minerals, which are abundant in both reservoirs and caprocks, play a critical role due to their high surface area, surface charge, swelling capacity, and nanoconfined pore structures. Because many of these processes originate at nano- and meso-scales where experiments are limited, molecular modelling provides a necessary framework to resolve hydrogen behaviour in clay-rich geological environments and to support reliable upscaling.[2] This contribution integrates molecular-scale insights developed over the past five years to clarify key physicochemical mechanisms governing underground hydrogen storage, with emphasis on clay–fluid interactions. Hydrogen interfacial properties, such as interfacial tension[3] and wettability[4], are strongly influenced by clay mineralogy, surface chemistry, and thermodynamic conditions. The discussion then addresses caprock integrity, focusing on hydrogen transport in clay nanopores[5], competitive interactions with cushion gases[6], and swelling and mechanical responses in expandable clays.[7] Together, these findings demonstrate how molecular modelling links nanoscale clay-hydrogen interactions to macroscopic storage performance, providing a mechanistic basis for evaluating containment security in clay-rich subsurface systems.

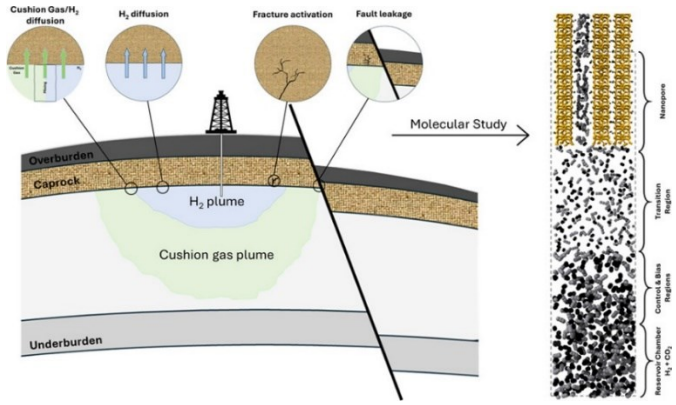


Fig. 1. Schematic illustration of underground hydrogen storage highlighting key reservoir-caprock processes and their molecular-scale origins resolved through atomistic simulations.

References: [1]Heinemann, Niklas, et al. "Enabling large-scale hydrogen storage in porous media–the scientific challenges." *Energy & Environmental Science* 14.2 (2021). [2]Van Rooijen, W. A., et al. "Interfacial tensions, solubilities, and transport properties of the H_2/H_2O/NaCl system: A molecular simulation study." *Journal of Chemical & Engineering Data* (2023). [3]Omrani, Sina, et al. "Interfacial tension–temperature–pressure–salinity relationship for the hydrogen–brine system under reservoir conditions: integration of molecular dynamics and machine learning." *Langmuir* (2023). [4]Ghafari, Mohamad Ali, et al. "Wetting preference of silica surfaces in the context of underground hydrogen storage: a molecular dynamics perspective." Langmuir (2024). [5]Ghasemi, Mehdi, et al. "Molecular dynamics simulation of hydrogen diffusion in water-saturated clay minerals; implications for Underground Hydrogen Storage (UHS)." *International Journal of Hydrogen Energy* (2022). [6]Kahzadvand, Kamiab, et al. "Risk of H_2 Leakage into caprock and the role of cushion gas as a barrier in H_2 geo-storage: a molecular simulation study." *The Journal of Physical Chemistry C* (2024). [7]Ghasemi, Mehdi, et al. "Molecular Insights into Caprock Integrity of Subsurface Hydrogen Storage: Perspective on Hydrogen-induced Swelling and Mechanical Response." *ACS Sustainable Chemistry & Engineering* (2026).

The applicability of image-based analyses in the study of CO_2 mineralization

Khudhur, F., Butler, F. and Gilfillan, S.M.V.

School of GeoSciences, Grant Institute, James Hutton Road, The University of Edinburgh, EH9 3FE, U.K.

Permanent CO_2 storage through mineralisation in subsurface formations presents an important climate change mitigation strategy. Understanding the progression of this reaction and its limiting factors is vital for estimating CO2 uptake potential in a given formation. Recent advancements in image acquisition and processing methods presents strong opportunities for characterization of the reaction at the micro- and nano-scales. In particular, time-resolved X-ray computed microtomography and scanning electron microscopy techniques provide important insights into identifying reacting and produced minerals, pore space evolution, accessible reactive surface area and transport controls of the mineralization reaction. Advanced processing techniques such as deep learning segmentation and correlative microscopy can also extend the capability of 2D methods to 3D volumes. When combined with other bulk chemistry analyses such as X-ray diffraction and core flooding, image analysis can help in calculating parameters that are important in reactive transport modeling. While this is of utmost importance in CO2 uptake estimation on large scales, several challenges must be addressed, including representativeness, segmentation quality and error estimations.

Reference
Khudhur, F. W. K.; Butler, I. B.; Gilfillan, S. M. V. Small Is the New Large: Demonstration of How Microanalyses Elucidate Large-Scale CO 2 Uptake Through Mineralization. *Adv. Sustain. Syst.* 2026, *10* (2). https://doi.org/10.1002/adsu.202501549.

Minerals: the Achilles Heel in Enhanced Rock Weathering

Manning, David A. C.

School of Natural & Environmental Sciences, Newcastle University, Newcastle upon Tyne, U.K., NE1 7RU.

Since COP26 in Glasgow, Enhanced Rock Weathering (ERW) has burgeoned as a multimillion dollar industry, very much funded by providers of Artificial Intelligence (AI). ERW is one approach to removing atmospheric CO_2: silicate mineral weathering releases cations that are counterbalanced in the soil solution by bicarbonate derived from the atmosphere.

To some extent, the intellectual focus of ERW has been on Monitoring, Reporting and Verification (MRV). MRV follows independently-determined protocols, and requires a multidisciplinary team of very well qualified experts to be able to provide a robust claim of the amount of CO_2 that has been removed. It is not easy to do this.

In marked contrast, hardly any attention is given to the details of the rocks that are used for ERW. Most ERW practitioners use 'basalt', but in a recent survey of the peer-reviewed literature (including top journals like Nature), the majority of papers fail to provide the evidence needed to justify using the name 'basalt'. This is the Achilles Heel of ERW: too few practitioners actually know what the rock is that they are using.

ERW depends on the rock containing silicate minerals that weather rapidly, such as anorthite-rich plagioclase, olivine and pyroxenes (which is why basaltic rocks are favoured). In addition, wollastonite and dunite are also widely referred to in the literature, and wollastonite is used in practice as an alternative to basalt. Nepheline weathers rapidly, and so nepheline-bearing basalts and phonolites should be considered, especially as they also provide K (derived from nepheline) as an essential crop nutrient.

The shortcomings regarding the rock types that are reported by those interested in ERW in peer-reviewed journals are readily addressed: the multidisciplinary MRV teams and academic teams both need expertise in petrology, which is readily available from university departments that teach this subject as part of a geology degree. What is needed is undergraduate-level characterisation of the rocks that are used – long-established, foundational material. Furthermore, teaching ERW as part of petrology classes really engages students, and motivates them to take an interest in what are often regarded as difficult intellectual tasks. These tasks now support a new multimillion dollar industry.

Enzyme-Mediated Multiphase Precipitation (EMMP): Coupled Carbonate–Phosphate Mineralisation for Sustainable Metal Immobilisation and Carbon Removal

Dickinson, H.[1,2], MacDonald, J.M.[1] and Toney, J.[1]

[1] School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G128QQ, UK.
[2] School of Social and Environmental Sustainability, University of Glasgow, Dumfries, DG1 4ZL, UK.
heloisa.dickinson@glasgow.ac.uk

Sustainable remediation of ecotoxic metals requires not only high removal efficiencies, but also the formation of stable mineral phases that minimise secondary pollution, support circular-economy strategies, and align with SDG and GHG-conscious environmental management. Carbonate mineralisation strategies that utilise urease-catalysed urea hydrolysis, including enzyme-induced (EICP) and ureolytic microbial-induced carbonate precipitation (MICP), can immobilise metals effectively, yet are often constrained by substantial ammonium by-product generation. Here we present Enzyme-Mediated Multiphase Precipitation (EMMP), a circular mineralisation strategy that utilises biomass- and bone-derived residual materials to couple carbonate and phosphate precipitation in a single stage, reducing net ammonium release while generating stable mineral assemblages and enabling mineral-based carbon sequestration. To evaluate its performance, EMMP was applied to aqueous systems individually amended with one of nine environmentally relevant metals/metalloids (As, Cd, Co, Cr, Cu, Li, Ni, Pb, Zn) at 2, 5, and 20 mM. System response (pH, precipitate mass, ammonium in solution) and metal removal were quantified by ICP-OES and colourimetry, while precipitates were characterised by SEM–EDS, and PXRD with Rietveld refinement. Across treatments, high removal efficiencies were achieved for most elements, exceeding 95% for Pb, Cd, and Zn and ≥80% for Co, Ni, and Li. Chromium removal remained high despite operation under mildly acidic conditions (pH ~5) in some treatments. Mineralogical analysis identified calcite and struvite as dominant phases, with minor apatite-group phases in selected systems and clear metal-dependent morphological variability, indicating overlapping retention pathways including precipitation, co-precipitation, adsorption, and biomolecule-mediated interactions. Relative to ureolysis-only controls (defined as 100% ammonium production), ammonium in solution was reduced to <5% for Cr, Cu, Pb, and As, ~20–45% for Ni, Co, and Cd, and ~70–85% for Li and Zn. By integrating biomass-derived residual materials with multiphase mineralisation pathways, EMMP provides a scalable framework for contaminant immobilisation that couples mineral stability, ammonium mitigation, and carbonate-based carbon sequestration within a sustainability-oriented design1.

References:
[1] Dickinson, H., MacDonald, J. & Toney, J. L., 2025. Enzyme-mediated multiphase precipitation: An innovative strategy for ecotoxic metal immobilization in aqueous systems**.** Journal of Environmental Chemical Engineering, 13(5), 119087. https://doi.org/10.1016/j.jece.2025.119087

Multi-Scale Insights Linking Minerals to Gamma Radiation, Radon and Thoron in Building Materials

Aghdam, M.[1,2] , Crowley, Q.[1,2] and Guyett, P.[1,3]

[1] Department of Geology, School of Natural Sciences, Trinity College Dublin, Ireland
[2] Trinity Center for the Environment, Trinity College Dublin, Ireland
[3] Centre for Microscopy and Analysis, Trinity College Dublin, Ireland

---

Ionizing radiation in the form of gamma and alpha radiation is present in building materials. Whereas legislative limits of 1 mSv/yr are commonly applied to gamma radiation in building materials no such limit exists for alpha radiation. Instead, the alpha emitters radon and thoron are regulated through an indoor reference level that does not exceed 300 Bq/m³ for residential with an "action level" of 200 Bq/m³ for residential buildings in the UK and Ireland. Despite these legislative efforts, challenges exist in terms of monitoring ionizing radiation in building materials, with potential negative impacts related to Sustainable Development Goal 3 Good Health and Wellbeing, and 11 Sustainable Cities and Communities.

This study investigates both gamma and alpha radiation in building materials commonly available in Ireland, the UK and across the EU. Using Ireland as a case-study a national radon-thoron (^{222}Rn-^{220}Rn) map was created from the TELLUS radiometric dataset available from Geological Survey Ireland. Based on the expected radon and thoron concentrations, quarries supplying building materials were selected for further mapping and sampling. Next, UAV-based LiDAR and gamma spectrometry were used to create high spatial resolution (1x1m) 2D maps and 3D models of gamma dose rate, uranium (U), thorium (Th) and potassium (K) concentrations. Finally, Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) were used to map mineralogy and elemental concentrations for representative rock samples to predict radon and thoron emissions from quarry materials. SEM imaging and elemental mapping identified uranium- and thorium-bearing minerals such as zircon, monazite, and uraninite. These minerals are primary sources of gamma radiation and radioactive gas release. A Two-Stage Least Squares (2SLS) regression model was developed which links both mineralogy and elemental distribution to radon and thoron exhalation rates with >95% accuracy.

Our approach in beneficial in terms of gaining radiological protection insights over a range of spatial scales, linking mineralogy to national scale radiation protection maps thereby adding value to legacy national datasets. The novel combination of UAV-based LiDAR and radiometric surveys provides a means to rapidly create site-specific maps and 3D models, helping to aid decision-making for the extraction and use of natural materials in the construction sector. SEM-based mineralogy and element mapping builds an understanding of the mineralogical affinity and distribution of ionizing radiation. The methodologies described here can be replicated in other countries to fill data and knowledge gaps relating to the safe and sustainable supply of building materials to better align with relevant UN Sustainable Development Goals.

References:
[1] UNSCEAR (2022) United Nations New York.
[2] Aghdam, MM and Crowley Q (2025) App Sci 15:6470.
[3] Aghdam MM et al (2024) Front Public Health 12: 1443332.
[4] Tkaczyk AH et al (2020) J Radio and Nuc Chem 326:75–86.

Phase Diagram of Olivine-Structured Battery Cathodes: $LiMPO_4$ (M = Mn, Fe, Ni)

Lo, Pok Man E.[1], Littleton, J.A.H.[1], Evans, A.J.M.[1,2], McElhinney, T.R.[1], Wang, B.[1] and Hunt, S.A.[1]

[1]Department of Materials, The University of Manchester, Oxford Road, M13 9PL
[2]Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, M13 9PY

Lithium manganese (II) phosphate ($LiMnPO_4$) occurs naturally as lithiophilite, a common accessory mineral in lithium-rich granitic pegmatites and is the manganese end member in a solid solution with the iron end member triphylite ($LiFePO_4$). These olivine-structured (α) phosphates, alongside lithium nickel (II) phosphate ($LiNiPO_4$), have shown great potential as cathode materials in lithium-ion batteries due to their superior electrochemical performance, in addition to the relatively low manufacturing costs, low toxicity, reduced environmental footprint, and high safety levels, compared to other cathode materials. While investigations on the physicochemical properties of these materials are predominantly focused on ambient pressure (P) and temperature (T) conditions, this work expands beyond the current understanding and aims to map out the phase stability of these minerals in P-T space. High P-T studies are significant for two main reasons: i) to assess the stability of existing materials at non-ambient conditions for specialised applications and ii) to synthesise and characterise new stable phases that may have more advantageous electrochemical properties.

In this work, we report – to the best of our knowledge – the first P-T phase diagrams of $LiMnPO_4$, $LiFePO_4$ and $LiNiPO_4$ up to 9 GPa and 1200°C and delineate the phase stability field between the α structure and a high P-T Na_2CrO_4 orthorhombic (β) structure for all three materials. High P-T experiments were conducted in a 1000-ton large volume multi-anvil apparatus and phase structures were determined *ex-situ* using Raman spectroscopy and X-ray diffraction. We find that the α-β transition in $LiFePO_4$ and $LiMnPO_4$ phases have negative Clapeyron slopes while the α-β in $LiNiPO_4$ has a positive Clapeyron slope. The room pressure-room temperature phase of $LiNiPO_4$ is the β structure.

Mineralogical controls on organic carbon stabilisation and persistence

Peacock, C.L.[1]*, Xiao, K-Q.[2], Moore, O.W.[3], Babakhani, P.[4], Zhao, M.[5], Curti, L.[1], Dale, A.W.[6] and Woulds, C.[1]

[1] University of Leeds, Leeds, UK
[2] Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China
[3] University of York, York, UK
[4] University of Manchester, Manchester, UK
[5] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[6] GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
*C.L.Peacock@leeds.ac.uk

The interconnected processes of organic carbon production, transformation and storage are strongly controlled by soil and sediment minerals, whose ubiquity and reactivity govern organic carbon stability and persistence in terrestrial and marine environments. Mineral-carbon interactions include adsorption, coprecipitation, aggregation and geopolymerisation, that together act to shuttle carbon from less stable forms that are more easily remineralised to more stable forms that survive microbial attack. In this regard the concept of the 'mineral carbon pump' provides a framework for understanding how mineral phases contribute to the stabilisation and persistence of organic carbon by transforming labile substrates into stabilised forms within mineral-associated pools [1, 2].

In natural systems mineral-carbon interactions modulate atmospheric carbon dioxide and oxygen and play a critical role in the global carbon and oxygen cycles [e.g., 3, 4, 5]. In engineered contexts these same mineral-carbon interactions could be harnessed to provide a nature-based solution towards improving soil ecosystem functioning, and mitigating climate change, where minerals such as iron oxyhydroxides might be used to lock carbon away from the atmosphere [e.g., 1, 2, 6].

Recent advances in spectroscopy, microscopy and computational modelling provide exciting insights into the mechanisms of organic carbon uptake and release at mineral interfaces, that can be used to investigate the role of mineral-carbon interactions in the Earth system.

Here we will explore the mechanisms, products and impacts of mineral-carbon interactions for carbon storage over past and present timescales, which highlight how these might be used to enhance carbon storage on future timescales towards a sustainable environment. By integrating mineralogical controls into studies of soil and coastal sediment carbon dynamics, we can inform strategies to enhance organic carbon sequestration, supporting efforts to improve soil health and contribute to climate change mitigation through more stable carbon storage in soils and blue carbon environments.

References:
[1] Xiao et al. (2023) Nat. Rev. Earth Environ. 4:135-136
[2] Xiao et al. (2025) Innov. 6:100737
[3] Moore et al. (2023) Nat. 621:312-317
[4] Zhao et al. (2023) Nat. Geosci. 16:262-267
[5] Babakhani et al. 2025) Nat. Geosci. 16:78-83
[6] Georgiou et al. (2022) Nat. Commun. 13:3797

Artificial intelligence predicts mineral protection of organic carbon in global marine sediments

Babakhani, P.[1]*, Dale, A.W.[2], Sedighi, M.[1] Jazaei, F.[3] and Peacock, C.L.[4]

[1] Department of Civil Engineering and Management, University of Manchester, Manchester, UK
[2] GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany
[3] Department of Civil, Construction, and Environmental Engineering, University of Memphis, Memphis, TN, USA.
[4] School of Earth, Environment and Sustainability, University of Leeds, Leeds, UK
*peyman.babakhani@manchester.ac.uk

Quantifying carbon preservation in the global marine sediments is critical to understanding Earth's climate dynamics [1-3] and to assessing the potential strategies for climate change mitigation, such as marine-based carbon dioxide removal (mCDR) at large scales [4]. To date, such quantifications at large scales have been hindered by the lack of sufficient field data and limitations of the mechanistic model for upscaling, e.g., having site-specific parametrisation, being fragile when executed for diverse natural conditions and being computationally time-consuming in general [2,3].

Recently, we advanced the conceptual-mathematical reactive-transport model (RTM) for carbon cycling in marine sediments to take into account the cycling and preservation processes of dissolved organic carbon (DOC) species, including thier hydrolysis, interactions with minerals and their molecular transformation from species with high reactivity to species with low reactivity (a process called geopolyerisation [2]. This model provided new insights into how organic carbon is preserved in marine sediment and what processes are dominant. For instance, we found that kinetic sorption and transformation of DOC were the dominant controls on organic carbon preservation. We also found that a synergistic effect between kinetic sorption and geopolymerization created a mineral shuttle for organic carbon by sorbing DOC in the surface sediment and releasing it at depth.

More recently, we used several artificial intelligence (AI) algorithms to emulate the structure of the RTM. We then used the developed emulators to predict DOC preservation and budgets in global marine sediments – a task that was not feasible at the proper accuracy using the RTM [3]. We validated the AI-based emulators at low-resolution global maps where the solution of the RTM was partly possible and against algebraic equations where they were available.

Global-scale predictions showed that 24% of particulate organic carbon (POC) deposited to the global seafloor is protected in mineral matrix after hydrolysis to DOC and sorption to minerals. Furthermore, 11% of the input POC returns to seawater as DOC. Our model also revealed that 50% of the total solid-phase organic carbon in the upper metre of sediments is formed by DOC sorption to minerals.

We used different types of AI algorithms (deep learning, basic feedforward neural network, and random forest algorithms). We found that emulating complex mechanistic models does not necessarily require a complex AI algorithm, and a simple traditional algorithm, like a feedforward artificial neural network, provides the best prediction performance. This indicated that the Principle of Parsimony, also known as Occam's Razor Principle, may hold in the context of AI modelling. We further systematically investigated the impact of the complexity of AI structure on the accuracy of prediction in problems with different levels of complexity, and showed that with increasing AI structure complexity, the prediction accuracy decreases. The overall modelling framework and the emulators developed in this study can be used within global circulation models for identifying potential climate change mitigation strategies.

References:
[1] Moore et al. (2023) Nature 621:312-317
[2] Babakhani et al. (2025) Nat. Geosci. 16:78-83
[3] Babakhani et al. (2026) The Innovation
[4] Babakhani et al. (2022) Nat. Nanotechnol. 17(12), 1342-1351

Lower crustal melt evolution revealed by crystal scale isotopes in plutonic xenoliths from Mt. Adagdak, Aleutian arc

Cooper, G.F.[1], Bucholz, C.E[2], Kay, S.M[3], Kay, R.W[3].

[1]School of Earth and Environmental Sciences, Cardiff University, Main Building, Cardiff, CF10 3AT, UK CooperG3@cardiff.ac.uk.
[2] California Institute of Technology 1200 E. California Blvd, Pasadena, CA 91104, USA
[3] Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14850, USA

Subduction zone magmas represent the integrated result of both source heterogeneity and an array of crustal processes, such as differentiation, mixing, homogenisation and assimilation. Therefore, disentangling the relative importance of the compositional heterogeneity of the mantle source, versus subsequent modification of melts in the crust is difficult when targeting the volcanic end products. Mt. Adagdak on Adak Island, Central Aleutians, has erupted a range of plutonic xenoliths ranging from ultramafic wehrlites and clinopyroxenites to more evolved hornblendites and amphibole gabbros. These plutonic xenoliths represent portions of the sub-volcanic plumbing system and have the potential to reveal both previously obscured heterogeneity of melts generated in the sub-arc mantle and the extent and depth of subsequent assimilation within the crust.

We characterised the major element distribution of 33 plutonic xenoliths by SEM mapping. Of these, we selected a sub-set (covering the range of types from least to most evolved) for trace element (LA-ICPMS) and isotopic analysis. Selected core and rim domains from clinopyroxene, amphibole and plagioclase were then milled for Sr-Nd isotopic analyses by TIMS to determine the extent to which the geochemical and isotopic heterogeneity of volcanic arc magmas are imprinted as they pass through the crust (due to crustal and/or sediment assimilation) or are reflective of their mantle source.

Here, we present the trace element and crystal scale Sr and Nd isotope record of phases contained in plutonic xenoliths and compare these to the previosuly published whole-rock record. Isotopic heterogeneity within Adagdak plutonic xenoliths covers most of the whole-rock variation observed on Adak Island. In particular, amphibole gabbros show the greatest heterogenety ($^{87}Sr/^{86}Sr$ 0.703257-0.703521). Within each sample, crystal cores typically record larger isotopic variation than their rims. These findings indicate that mantle melts entering the crust are homogenised within lower- and mid- crustal storage regions in the Adagdak plumbing system.

Tracing magma evolution from caldera-forming to post-caldera volcanism at Toya volcano, Hokkaido, Japan

Gertisser, R.[1], Goto, Y.[2], and Li, X.[3]

[1]School of Life Sciences, Keele University, Keele, ST5 5BG, UK
[2]Muroran Institute of Technology, Muroran, 050-8585, Japan
[3]Key Laboratory of Submarine Geoscience and Prospecting Techniques, Ocean University of China, Qingdao, 266100, China

---

Understanding how magma evolves from caldera-forming eruptions to subsequent post-caldera activity is critical for constraining the longevity and behaviour of large, and often hazardous, silicic caldera systems.

Toya volcano in Hokkaido (Japan) provides an exceptional natural laboratory to investigate the development of a large silicic magmatic system from caldera formation to post-caldera volcanism. Approximately 110,000 years ago, Toya experienced a major silicic caldera-forming eruption that created the 10 × 11 km-wide Toya caldera [1] and generated voluminous pyroclastic flow deposits known as the Toya Ignimbrite [2]. This eruption was followed by multiple episodes of post-caldera volcanism. The earliest of these produced the Nakajima Islands, an andesitic–dacitic lava dome complex occupying the centre of the caldera [e.g. 3]. Subsequent activity led to the construction of Mount Usu, a small basaltic-to-rhyolitic stratovolcano on the southern caldera rim. One of Japan's most active volcanoes, Usu has had a prolonged history of both effusive and explosive eruptions that continues to the present day [e.g. 4–6].

Here, we present new major- and trace-element data together with Sr–Nd–Pb–O isotopic analyses for the Toya Ignimbrite and the post-caldera centres of Nakajima and Usu. These data are used to evaluate the temporal and spatial evolution of the Toya magmatic system from the caldera-forming stage to subsequent post-caldera activity.

The Toya Ignimbrite, a medium-K high-silica rhyolite, is geochemically and isotopically distinct from Nakajima and Usu. Strongly radiogenic Sr and Pb isotopic compositions coupled with low $\delta^{18}O$ values indicate assimilation and/or melting of high temperature hydrothermally altered volcanic crust during generation of the ignimbrite magma. Post-caldera magmatism at Nakajima is medium-K andesitic to dacitic in composition. The presence of medium-K basaltic-to-andesitic enclaves suggests replenishment of a shallow andesitic–dacitic reservoir by less evolved magma that differentiated at greater depths within the continental crust beneath Toya. A subsequent shift in activity toward the caldera rim, evident at the small, undated Chinkojima Island and at Usu, is accompanied by the eruption of lower-K mafic to silicic magmas with more radiogenic Pb isotopic signatures than those of Nakajima. This indicates tapping of geochemically and isotopically distinct magma reservoirs located along the caldera margin.

Together, these results demonstrate that post-caldera volcanism at Toya was not simply the waning stage of a single silicic reservoir, but instead reflects the temporal and spatial development of multiple, compositionally distinct magma storage regions. Such complexity has important implications for assessing the long-term magmatic evolution and hazards at Toya volcano and similar large silicic caldera systems.

References:
[1] Goto Y et al. (2018) J Geogr 127:139-156
[2] Goto Y et al. (2018) J Geogr 127:191-227
[3] Goto Y et al. (2015) Bull Volcanol Soc Japan 60:17-33
[4] Goto Y et al. (2019) Bull Volcanol 81:37
[5] Goto Y et al. (2013) Bull Volcanol Soc Japan 58:529-541
[6] Global Volcanism Program (2024) Toya (285030)

What sulphides can tell us from the mantle to mineral deposits

Hughes, H.S.R.[1]

[1]Camborne School of Mines, University of Exeter, Penryn Campus, Cornwall, UK TR10 9FE

From batteries to fuel cells, metals such as nickel, cobalt and the platinum-group elements (PGE) are essential to the development of sustainable technology. Produced from only a handful of deposits in a few countries and accentuated by the current geopolitical landscape, concerns over their security of supply mean that these elements are classified as critical raw materials (CRMs). Nickel, cobalt, the PGE and some other CRMs have a strong affinity for iron-rich metallic phases and/or sulphur (siderophile and chalcophile behaviour, respectively). As a result, their most significant reservoirs lie in the Earth's core and mantle. In the mantle, these chalcophile metals are hosted in base metal sulphides (BMS), although in some cases silicate or oxide minerals contain most of their budget. Further, a proportion of PGE occurs in tiny platinum-group minerals (PGM).

To understand how these elements become mineralised and concentrated into ore deposits, we must determine how they are mobilised from their mantle hosts and transported into the Earth's crust. Estimations of the abundance of chalcophile elements in the 'Primitive Upper Mantle' are largely derived from mantle xenoliths and diamonds [1,2] but studies do not generally capture the range of upper mantle lithologies, such as eclogites and peridotites [3]. Indeed, mantle xenoliths containing BMS and sulphide inclusions in diamonds are our only direct samples of these metals at depth.

During partial melting of the mantle, BMS release part of their metal budget into the magma generated, but it remains difficult to fully quantify this process given the diversity of sulphide compositions, let alone understand how micron-scale (or smaller) PGM become mobilised. Nonetheless, identifying the mechanisms that transfer these metals from the mantle into the crust is crucial, as it influences the fertility of magmas, including exotic low-degree partial melts, with important implications for mineral exploration.

A range of analytical methods are used to assess chalcophile metal budgets in rocks, including mineral mapping, major and trace element analysis (EPMA to LAICPMS), stable isotope analysis ($\delta^{34}S$ or $\Delta^{33}S$), and compositional modelling. The problem is that at temperatures below 1100^{o}C, sulphide liquids – whether in crustal magma conduits or entrained from the mantle – undergo subsolidus re-equilibration. They fractionate through a high temperature monosulphide solid solution (MSS) to end-member sulphide minerals at room temperature (e.g., pentlandite, pyrrhotite, chalcopyrite). This process redistributes metals between the BMS phases that we can analyse in the laboratory, whether they are mantle-derived (xenoliths or diamonds) or sourced from ore deposits. For some materials, experimental approaches may be used to 'undo' this fractionation and evaluate total sulphide metal budgets.

This talk explores the question: *Like a time capsule for chalcophile metals, can Earth's upper mantle be mapped to reveal a region's 'prospectivity' – and if so, what does this mean from a minerals systems perspective?*

References:
[1] Aulbach S et al. (2012) Geochim. Cosmochim. Acta 93: 278-299
[2] Becker H et al. (2006) Geochim. Cosmochim. Acta 70: 4528-4550
[3] McDonald I et al. (2017) Geochim. Cosmochim. Acta 216: 335-357

Crystal records describe the emplacement of the Freetown Intrusion, Sierra Leone

Bowles, J.F.W.[1], Suárez, S.[2], Zaccarini, F.[3] and Garuti, G.[3]

[1]12 chemin de Grand Jean, 24100 Creysse, France john.bowles@UCLmail.net
[2]Department of Geology, University of the Basque Country (UPV/EHU), 48940 Leioa, Spain
[3]Geosciences Programme, Faculty of Science, University Brunei Darussalam, Jalan Tungku Link, Gadong, Bandar Seri Begawan BE1410, Brunei

---

The Freetown Intrusion is a layered gabbroic and noritic intrusion that outcrops as a peninsula on the coast of West Africa 8° north of the equator. The intrusion appears to have a considerable extension beneath the Atlantic [1]. Research in the area is greatly hindered by deep tropical weathering, lateritic hardpan, raised beaches and closed canopy tropical forest. There is good outcrop along the coast and on hill tops; stream sections contain both outcrop and many tumbled blocks. This study centres on a rare 250 m section of almost continuous outcrop on a steep hill slope. The age (196-201 Ma) and the location on the Pan-African 2 suture suggest that intrusion was aided by regional stresses that opened this suture prior to the opening of the Central Atlantic [1]. Intrusion occurred in several episodes (the Zones of Wells [2]) separated by significant time intervals. There is little evidence of the closed chamber mineral fractionation seen at Skaergaard but clear indication of a constant supply of new magma under open chamber conditions [1, 2, 3]. Igneous layering is present varying in scale from millimetric layering to layers 10's of metres in thickness. Wells [2] identified cyclic layering with olivine-rich rocks at the base of each cycle progressing to anorthosite at the top, although few cycles show the complete sequence. There are thick layers of anorthosite in the centre of the peninsula. Xenoliths of similar rocks occur; the xenoliths range in size from millimetres to 10's of metres. They are often more noritic and tend to occur where there has been an interruption to intrusive activity. Isotopic evidence indicates that these xenoliths are distinct from, and older than, the igneous activity which formed the intrusion [1, 2, 3, 4].

Clinopyroxene analyses are restricted to compositions close to diopside and orthopyroxene analyses are near to enstatite with no continuous fractionation trend towards more Fe-rich compositions. Locally the pyroxene shows a reverse trend towards less Fe-rich compositions corresponding to the introduction of fresh magma with alteration of pre-existing pyroxene. The alteration of pyroxene to less Fe-rich compositions is marked by exsolution of Fe oxides as structurally oriented lamellae and, on the fine scale, to a general clouding of the mineral.

Results obtained by the use of the MagMin_PT programme [5] suggest that the pyroxenes equilibrated at 920–1000°C and 3–9 kbar (300–900 MPa). Rims to some clinopyroxenes that have a distinctly different composition (higher Al_2O_3 and less CaO) appear to have equilibrated at higher temperatures (1170°C) but similar pressures (7 kbar). With data for olivine, plagioclase and amphibole these results demonstrate a reworking of the pyroxene. This raises the question of the origin of the pyroxene and the stage in the process of intrusion when this reworking occurred.

References:
[1] Bowles J et al. (2024) J Afr Earth Sci 211:105160 18pp
[2] Wells M (1962) Overseas Geol Min Res Bull Suppl 4:1-115
[3] Chalokwu C and Seney P (1995) Geol Mag 132:261-266
[4] Callegaro et al. (2017) J. Petrol 58:1811-1840
[5] Gündüz M and Asan K (2023) Min Mag 87:1-9

Carbonatite-associated gallium mineralisation: A case study from Monte Muambe, Mozambique

Church, A.J.[1], Broom-Fendley, S.[1], Simonet, C.[2], Wall, F.[1]

[1]Camborne School of Mines, University of Exeter, Penryn Campus, Penryn, Cornwall TR10 9FE, United Kingdom
[2]Altona Rare Earths Plc, 25 Eccleston Place, Eccleston Yard, London, SW1W 9NF, United Kingdom

---

Most carbonatite investigations focus on rare earth element (REE) mineralisation, for which they, alongside alkaline-silicate rocks, form the main ore type mined worldwide[1]. Recent investigations, however, indicate that carbonatites also show potential as a source of gallium. Gallium is of increasing economic interest owing to its important role in the production of semiconductors and solar panels. Almost all gallium worldwide is extracted as a by-product of bauxite and sphalerite mining[2]. Owing to its economic importance and supply limitations, it is considered a critical raw material in the UK, EU and USA.

Typically, REE, Nb, and fluorite mineralisation occur in magmatic/hydrothermal units within and associated with carbonatite complexes. Carbonatites are often surrounded by fenite, an alkali metasomatic aureole. Our recent observations at the Monte Muambe Carbonatite complex, Mozambique, indicate that the fenite there hosts elevated Ga concentrations exceeding ~400 ppm in whole-rock assays[3]. These are an order of magnitude higher than concentrations typically found in continental rocks[4]. Notably, Ga concentrations are especially elevated in areas of hydrothermal fluorite mineralisation within fenite. In these areas, the high Ga concentrations occur in metasomatic Orthoclase, which has Ga contents up to 6877 ppm, more than a hundred times higher than average Ga contents in feldspar (~24 ppm)[5], and ten times above the highest reported grade in feldspar (696 ppm)[6].

The association between fluorite mineralisation and Ga enrichment in K feldspar suggests a causal link. While the mechanisms controlling the transportation and enrichment of Ga are relatively poorly understood, experimental studies suggest that Ga can complex with F to become mobile in hydrothermal fluids[7]. We postulate that the carbonatite-derived fenitising fluid was also responsible for the fluorite mineralisation, and that the process of F transport and deposition led to the preferential partitioning of Ga into the fenite. The exact mechanism behind this process is unclear, and subject to further investigation.

Our results indicate that Ga may be a new potential resource that can be extracted from carbonatite complexes, in addition to the REE, F, and Nb typically exploited. Monte Muambe acts as an excellent testing ground on the processes controlling enrichment. In our presentation we discuss the primary mechanisms of transport and enrichment of Ga, and the potential for exploitation of this new deposit type by Altona Rare Earths.

References:
[1] BGS (2024) UK 2024 Criticality Assessment. Open Report OR/24/047
[2] Foley N et al. (2017) Gallium. USGS Professional Paper 1802-H
[3] Altona RE (2026) Announcement: Strong initial fluorspar and gallium assay results
[4] Taylor S and McLennan S (1995) Rev of Geophys 33:2 151-265
[5] DIGIS Team (2021) GEOROC Compilation: Rock types
[6] Xu C et al. (2015) Lithos 227: 107-121
[7] Wood S and Samson I (2006) Ore Geol Rev 28: 57-102

Did tholeiitic magma differentiation control the petrogenesis of sulfide mineralization in the Kettara intrusion, or were metals subsequently redistributed by fluids and deformation?

Cisse, D.[1]and Wafik, A.[1]

[1]Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakech, Morocco – d.cisse.ced@uca.ac.ma [1]Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakech, Morocco – wafik@uca.ac.ma

---

The Koudiat Kettara intrusion, located in the Central Jebilet (Morocco), consists of a differentiated mafic–ultramafic magmatic suite spatially associated with sulfide mineralization dominated by pyrrhotite. While previous studies have emphasized the role of deformation and fluid circulation within regional shear zones in modifying the ore body, the contribution of magmatic processes and mineral crystallization to the initial formation of the sulfide assemblages remains poorly constrained. A key question therefore arises: to what extent did magmatic differentiation within the Kettara intrusion control the formation of sulfide mineralization, and how were these assemblages subsequently modified by fluids and deformation?

The Koudiat Kettara massif corresponds to a differentiated intrusive sequence evolving from ultrabasic rocks such as wehrlites to more evolved lithologies including leucogabbros, mesogabbros and ferrogabbros, as well as felsic terms such as quartz diorites, trondhjemites and sodic aplites. Petrographic observations indicate that the magmatic evolution of this intrusion was controlled by several stages of fractional crystallization.

The earliest stage involves the crystallization and fractionation of spinel, olivine, calcic plagioclase and pyroxene, producing ultrabasic to basic cumulates and residual melts enriched in Fe, Ti and Na. The second stage corresponds to continued fractionation of plagioclase and pyroxene accompanied by significant ilmenite precipitation, generating silica-enriched intermediate residual melts. The third stage is marked by the fractionation of plagioclase together with the appearance of magmatic amphibole replacing clinopyroxene, producing evolved melts responsible for late plagiogranitic differentiates. The appearance of amphibole suggests an increase in water activity during the late stages of magma evolution and possible interaction with external fluids.

Petrographic and mineralogical observations show that sulfide assemblages composed mainly of pyrrhotite, with subordinate chalcopyrite, pyrite, sphalerite and galena, are spatially associated with evolved magmatic facies. Textural relationships observed in thin sections reveal cumulate and intercumulate structures, spinel inclusions within olivine, and partial alteration of ultrabasic minerals into tremolite and chlorite. These features suggest that early magmatic differentiation may have contributed to the initial concentration of sulfides during magma evolution.

However, the sulfide assemblages also record evidence of later modification. Local fracturing, recrystallization and partial redistribution of sulfides indicate that tectonic deformation and fluid circulation along regional structures may have contributed to the reorganization of pre-existing mineralization and the precipitation of secondary Cu–Zn–Fe phases.

Overall, the mineralogical and petrographic characteristics of the Kettara intrusion suggest that sulfide mineralization records a complex evolution involving initial magmatic concentration linked to fractional crystallization followed by partial redistribution during fluid circulation and deformation. Further geochemical and isotopic investigations will be required to better constrain the origin of metals and the timing of these processes.

Late Magmatic Fluids Drive Evolution and REE Mineralization in the Pikes Peak Batholith, Colorado

Hendrickx, T.J.[1], Allaz, J.M.[1], Freudenstein, A.E.[1], Wickland, T.[2], and Bachmann O.[1]

[1]ETH Zürich, Department of Earth and Planetary Sciences, Clausiusstrasse 25, 8092 Zurich, Switzerland (tobias.hendrickx@eaps.ethz.ch)
[2]CU Boulder, Department of Geological Sciences, 2200 Colorado Ave, Boulder, CO 80309, USA

The A-type Pikes Peak batholith (PPB) is a renowned locality for rare-earth element (REE) and gem-quality minerals (e.g., amazonite, topaz, aquamarine) in granitic pegmatites [1]. These assemblages crystallize from late-stage, F-rich magmatic fluids derived from second boiling. Our study of the PPB and its satellite alkaline centers, including the concentrically zoned Lake George Ring Complex (LGRC), demonstrates that these fluids are the primary drivers of both (REE-)mineralization and significant textural (re)crystallization.

The mineral chemistry of interstitial phases records the evolution of this magmatic volatile phase (MVP). Notably, we identify a positive correlation between the REE content of granitic fluorite and that of associated pegmatitic fluorite in the South Platte district. This indicates that the fluids forming the large REE-rich pegmatites – some over 50 meters in diameter – are genetically related to the surrounding granite and its volatile-rich mineral phases. Consequently, the REE signature of granitic fluorite serves as a proxy for the MVP and a predictor for the presence of REE-mineralized pegmatites [2]. Within pegmatites, extensive REE-zoning in fluorite acts as a tape recorder for the changing composition of the pegmatitic liquid.

The influence of the MVP is further evidenced by feldspar textures. WDS-EPMA quantitative mapping reveals abundant perthite exsolution, albite overgrowths, and “patch perthite” [3] in the LGRC. Furthermore, the albitization of Ca-rich plagioclase (ca. An_{25}) to near-end-member albite (ca. An_5) by Na-rich fluids generated abundant fluorite, which is coeval with the crystallization of REE-rich minerals in associated pegmatites. These textures and end-member feldspar compositions indicate extensive (re)crystallization from a cool (< 500°C), fluid-saturated environment rich in flux elements such as F. This is supported by Ti-in-zircon thermometry, which yields lower crystallization temperatures in the alkaline centers than in the main Pikes Peak granite (PPG).

New high-precision CA-ID-TIMS U-Pb zircon geochronology refines the magmatic framework of the PPB. These Th-corrected $^{206}Pb/^{238}U$ ages date the core of the LGRC between 1078.25 ± 0.70 Ma and 1079.45 ± 0.85 Ma, contrasting with ages between 1082.61 ± 0.68 Ma and 1086.29 ± 0.66 Ma for the local PPG. Our results overturn previous zircon ages [4] that placed the LGRC early in the magmatic sequence. These data fill a temporal gap in the existing geochronological record of the PPB [5] and reveal continuous magmatism in the Pikes Peak batholith lasting up to 15 myr.

Our findings highlight how late magmatic fluids prolong activity in large A-type systems well beyond the traditional granite solidus (ca. 700 °C). Crystal records beautifully preserve evidence of this magmatic-hydrothermal transition and provide clues about the local mineralization potential of the REE and other critical metals in these highly evolved granites.

References:
[1] Simmons W.B. et al. (1987) Geo et Cosmo Acta, 5: 455–502
[2] Hendrickx T.J. (in review) Am Min
[3] Norberg N. et al. (2013) Am Min, 98: 1429–1441
[4] Guitreau M et al. (2016) Precam R, 280: 179–194
[5] Fonseca Teixeira L.M. et al. (2025) Geosphere

Syn-magmatic brecciation of a vertically-oriented crystal mush during fault-controlled dyke emplacement in the Rum Central Intrusion, NW Scotland

Hepworth, L.H.[1]

[1]1Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK

The Rum Central Intrusion (CI), part of the ~60 Ma Rum Layered Intrusion (RLI) in NW Scotland, comprises a chaotic mix of mafic and ultramafic rocks exhibiting extensive syn-magmatic deformation, and is thought to record the collapse of the central part of the intrusion towards the active feeder conduit[1]. The deformation observed in these rocks has long been attributed to a combination of gravity-driven and "soft-sediment" processes at the floor of a liquid-rich magma body, such as magmatic debris currents, slumping, and liquefaction[1, 2]. However, recent work highlighting that much of the intrusion was constructed from numerous smaller magmatic bodies calls for a re-examination of this model of the CI[3].

A detailed field-based study, including high-resolution outcrop mapping and structural analysis, shows a genetic link between the observed deformation (e.g. layering, brecciation, folding) and syn-magmatic faults, which were capable of facilitating magma emplacement and deformation. Critically, no evidence was found for previously reported way-up criteria[1, 2], a prerequisite for gravity-driven deformation models, suggesting that all processes occurred within a dyke-like crystal mush zone. Based on detailed field-based and petrographic evidence, it is suggested that the peridotite breccia, previously thought to represent a magmatic debris flow deposit[1, 2], formed by cataclastic deformation of a rapidly crystallised picrite within a syn-magmatic fault conduit. Evidence is further presented for post-brecciation modification of the peridotite breccia, which is used to suggest that the breccia effectively represents a partially assimilated chilled margin of a larger dyke-like body.

The CI, like other parts of the RLI, hosts a number of critical- and precious-metal deposits. The observations in this study challenge long-held views of syn-magmatic deformation in the RLI and provide the contextual information about the rheological properties of crystal mushes required to understand the role played by syn-magmatic deformation in controlling the formation of metal ore deposits in layered mafic intrusions.

References:
[1]Troll et al. (2020) J Petrol 61
[2]Upton et al. (2023) Geol Today 39: 130–143
[3]Hepworth et al. (2020) Contrib Mineral Petrol 175: 17

Crystal cargoes along the Reykjanes Ridge: insights into magmatic processes at a slow-spreading, plume-influenced mid-ocean ridge

Hughes, R.R.[1], Hartley, M.E.[1], Murton, B.J.[2] and Neave, D.A.[1]

[1] Department of Earth and Environmental Sciences, University of Manchester, Manchester, M13 9PL, UK, rebecca.hughes-3@manchester.ac.uk
[2] National Oceanography Centre, University of Southampton, European Way, Southampton, SO14 3ZH, UK

The Reykjanes Ridge (RER) is a 1000 km-long slow-spreading segment of the Mid-Atlantic Ridge that extends southwest from the Reykjanes Peninsula, Iceland. The Icelandic mantle plume exerts a spatially variable chemical and thermal influence on the ridge, that is expressed in systematic changes in glass geochemistry, magma flux, crustal thickness and magma storage depths along the ridge [1, 2]. The RER is arguably one of the best-studied segments of mid-ocean ridge globally. However, very little is known about the nature of magmatic processes along the RER. Specifically, we do not know whether there are systematic changes in the assembly, storage and transport of magmas along the ridge with varying proximity to the mantle plume.

We present the first systematic investigation of magmatic processes along the RER through a geochemical and petrological study of mid-ocean ridge basalts (MORBs) dredged from a ~900 km transect along the ridge. The crystal cargoes of these samples preserve records of recharge, mixing and ascent, as well as the pressure-temperature conditions of magma storage. We combine electron probe microanalysis (EPMA) with textural observations from backscatter electron (BSE) and energy dispersive spectroscopy (EDS) mapping to reconstruct the complex magmatic histories of individual crystals and of crystal populations. The machine learning tool GPyEDS [3] was used to create an efficient workflow for interpreting EDS maps. This facilitated the processing of a large sample set, which enabled our regional-scale study of the RER.

Observations of zoning and resorption textures in individual crystals reveal how magmatic conditions changed during crystal storage and growth. We identify distinct crystal textures and crystal populations that recur along the ridge, and we determine the spatial distribution of these variations. Crystal content and clinopyroxene abundance increase at the onset of the plume's thermal influence, a geophysical boundary characterised by thicker crust and a transition from a median valley to an axial rise. We identify the signature of mush disaggregation and entrainment, and we assess whether the relative importance of this process changes along the RER with proximity to the mantle plume.

This work represents a new contribution to the surprisingly sparse observations of crystal cargoes in global MORBs, and demonstrates the value of examining magmatic processes on a regional scale. This approach will allow us to place constraints on how crystallisation and magma storage at mid-ocean ridges may vary according to magma flux, crustal thickness and mantle chemistry on a global scale.

References:
[1] Murton B.J. [2002]. J Pet 43:1987–2012
[2] Baxter R.J.M. and Maclennan J. [2024]. EPSL 631: 118633
[3] Toth N. [2025]. JGR: Machine Learning and Computation 2.

Utilizing U-Pb and novel *in situ* Sr-Nd isotope chemistry of apatite to resolve tephrochronology and petrogenetic origins of altered volcanics

Vitarelli, D.C.[1], Tomlinson, E.L.[1], O'Sullivan, G.J.[1], Koch H.A.[1], Daly J.S.[2], Belgrano, T.M.[2], van Acken D.[2], Brodbeck, M.[2], and Corella Santa Cruz, C.R.[2]

[1] School of Natural Sciences, Trinity College Dublin, the University of Dublin, College Green, Dublin 2, D02 PN40, Ireland
[2] UCD School of Earth Sciences, UCD Earth Institute and SFI Research Centre in Applied Geosciences (iCRAG), University College Dublin, Dublin, Ireland

---

Volcanic ash and tephra deposits from explosive volcanism serve as important marker horizons for stratigraphic correlation and precise geochronology [1,2]. However, when the original glass composition is altered, geochemical correlation of ash beds through conventional tephrochronology methods becomes infeasible [3] and hinders the application of tephrochronological methods, especially for older deposits. While identifying potential volcanic sources for ash beds can help remedy this, older volcanics, particularly those of explosive origin, often suffer from post-emplacement alteration and physical mixing/incorporation of country rock material, limiting what geochemical and petrographic information can be gleaned from samples.

We examine the use of apatite, a robust, ubiquitous mineral phase, as an alternative correlation tool. We present U-Pb ages, trace element, and novel *in situ* Pb, Sr, and Nd isotope data for apatites from Carboniferous volcanics from across Ireland and Scotland, and for a number of altered volcanic ash beds (bentonites) in Irish Carboniferous limestones. Variations in Sr-Nd isotopic ratios suggest differences in the nature of the mantle source regions of Irish and Scottish magmatism. Sr-Nd-Pb isotopic signatures in apatite from Irish volcanics suggest magma was generated from a HIMU-type source, while signatures in apatite from Scottish samples reflect interaction between the source and continental crust. We use this proximal apatite data to demonstrate the utility of apatite for discriminating between proximal volcanic sources of distal tephra, and to establish proximal-distal correlations for the Irish bentonite layers.

References:
[1] Lowe DJ (2011) Quat Geochronol 6:107-153
[2] Huff WD (2016) American Mineralogist 101:43-70
[3] Sell BK & Samson SD (2017) Quat Res 76:157-166

Annual-to-millennial fluctuations in the physical properties of magma storage zones

Higgins, O.[1]*, Stock, M.J.[2], Geist, D.[3], Neave, D.A.[1], Buisman, I.[4], Bernard, B.[5] and Gleeson, M.[6]

[1] Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[2] Discipline of Geology, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland
[3] Geology Department, Colgate University, Hamilton, NY USA
[4] Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK
[5] Instituto Geofísico, Escuela Politécnica Nacional, Quito, Ecuador
[6] Department of Earth and Planetary Science, University of California Berkeley, McCone Hall, Berkeley, CA, USA
*Corresponding author (oliver.higgins@manchester.ac.uk; ORCID iD: 0000-0001-9960-934X)

Basaltic melts may variably disaggregate macrocrysts (large crystals) from crystal mushes during the assembly of magma bodies beneath ocean-island volcanoes, modulating magma system architecture and eruptive dynamics. Here, we use a suite of plagioclase-rich basalts to show that the entrainment efficiency (the ability for melts to disaggregate and entrain macrocrysts from crystal mushes) is temporally variable on inter-eruption timescales at ocean-island volcanoes. Macrocryst cargoes are predominantly out of equilibrium with their carrier melts in both chemistries and mass proportions (ratios of different macrocryst phases). Geochemical and petrological evidence reveals that macrocryst mass proportions are established in a density-stratified melt-rich reservoir shortly before eruption, whereas the absolute crystallinity is a function of crustal physics, likely driven by fluctuations of annual-to-millennial melt supply. Using a new thermobarometer for basaltic melts, we are able to correlate the depth of the pre-eruptive reservoir with geophysical observations. Variations in entrainment efficiency explain decoupled crystallinity–temperature–time relationships which may also govern the structure of basaltic intrusions (i.e., igneous bodies that are unperturbed by frequent eruptions), including those bearing platinum-group metals.

Clinopyroxene records of magmatic oxygen fugacity: insights from experiments and thermodynamic modelling

Neave, D.A.[1], Weller, O.[2], Marxer F.[3], Sodeman, C.[2], Hartley M.E.[1], Holtz, F.[3] and Namur, O.[4]

[1]Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK, david.neave@manchester.ac.uk
[2]Department of Earth Sciences, University of Cambridge, Cambridge, UK
[3]Institute of Earth System Science, Leibniz Universität Hannover, Hannover, Germany

---

Iron plays a central role in both setting and recording magma redox states, which are commonly expressed in terms of oxygen fugacity deviations from known equilibria such as fayalite-magnetite-quartz (FMQ). Magmas erupted in different tectonic settings are characterised by different oxygen fugacities, which has important implications for understanding how processes including magmatic evolution, ore mineralisation and volcanic degassing vary in space and time. For example, mid-ocean ridge basalts are relatively reducing (FMQ), arc basalts are relatively oxidising (up to FMQ+2) and ocean island basalts range from relatively reducing to highly oxidising (<FMQ to ≥FMQ+2). However, current tools for estimating magmatic oxygen fugacity (e.g., Fe-XANES on glasses, two-oxide oxybarometry) are subject to diverse limitations related to the ranges over which they are calibrated, the presence of specific key phases and overprinting by secondary processes (e.g., reductive SO_2 degassing, diffusive re-equilibration or the presence of Fe-oxide nanolites in glasses), making it challenging to interrogate how and why oxygen fugacity varies between different magmatic systems. Fortunately, recent studies have demonstrated that electron probe microanalysis (EPMA) can return robust estimates of clinopyroxene Fe^{2+} and Fe^{3+} contents from stoichiometry when analyses are performed with sufficient care (e.g., long counting times)[1]. Importantly, this improved ability to measure clinopyroxene crystals opens routes towards developing new ways to investigate oxygen fugacity variability within and between natural and experimental magmas. Unfortunately, relating the valence state of Fe in clinopyroxene to magmatic oxygen fugacity is challenging because the steric effects imposed by clinopyroxene's mineral structure affect the relative incorporation of Fe^{2+} versus Fe^{3+}. In striving to overcome these challenges, we present a combination of experimental observations and thermodynamic calculations designed to investigate the incorporation of Fe^{3+} into clinopyroxene crystals under magmatic conditions. Experiments were performed at magmatic temperatures (ca. 1150 °C) and pressures (100–500 MPa) on Icelandic basalts at a range of oxygen fugacity conditions (ca. FMQ-2 to FMQ+2) using an internally heated pressure vessel (IHPV). Thermodynamic calculations were performed using the MAGEMin Gibbs energy minimiser[2]. Experimentally observed and thermodynamically calculated phase equilibria demonstrate that clinopyroxene Fe^{3+} contents are sensitive to oxygen fugacity and can thus preserve information about magmatic oxygen fugacity in the geological record, particularly via Fe^{2+}–Mg exchange reactions with coexisting phases. Nevertheless, more experimental work is required to disentangle the effects of temperature, magma composition and kinetics on Fe valance in magmatic clinopyroxene crystals; much of this work is already underway.

1. Neave et al. 2024. https://doi.org/10.1007/s00410-023-02080-2.
2. Riel et al. 2022. https://doi.org/10.1029/2022GC010427.

Tracking magmatic processes and lithium fertility through zircon chemistry

Roberts, N.M.W.[1], Gardiner, N.J.[2], Mangler, M.F.[3] and Tapster, S.R.[1]

[1]Geochronology and Tracers Facility, British Geological Survey, Nottingham, UK
[2]School of Earth & Environmental Sciences, University of St Andrews, St. Andrews, UK
[3]School of Ocean and Earth Science, University of Southampton, Southampton, UK

Ubiquitous in felsic igneous rocks, physically resilient, and capable of incorporating a wide range of trace elements, zircon is an exceptional recorder of magmatic processes. In mineral systems, zircon provides not only precise geochronological constraints but also a suite of geochemical proxies, including temperature, redox state, water content, and melt composition. These indicators are now widely used to assess metal fertility, making zircon a valuable tool in mineral exploration. Although trace metal concentrations in zircon have received less attention, previous studies have shown, for example, elevated Sn contents in Sn-bearing igneous systems [1].

Lithium incorporation and diffusion in zircon have been previously investigated through a wide range of empirical and experimental studies, particularly those aimed at constraining the conditions of crust formation and subsequent alteration on the early Earth (e.g. [2–5]). In this contribution, we assess zircon Li concentrations as a potential proxy for Li-mineralised systems. Drawing on both new and published datasets, we show that zircon from several fertile- to mineralised systems exhibits elevated Li contents, including examples from the Cornubian Batholith of southwest England and the Southeast Asian Tin Belt.

However, the application of Li in zircon as a direct mineralisation proxy is complicated by the commonly high Li concentrations observed in Archean to Hadean zircon, despite their largely barren I-type or TTG magmatic associations. These high Li contents in ancient zircon are likely not primary and should not be used to infer melt Li concentrations via modelled partition coefficients. Our analysis of Phanerozoic mineralised systems shows that the canonical model—where Li partitioning is inversely correlated with both P incorporation and temperature—breaks down in these cool, highly evolved, fluid-rich magmatic environments.

Importantly, this work highlights both the opportunities and challenges of using zircon as a crystal archive of supra-solidus magmatic conditions. The complex behaviour of Li in zircon, whether incorporated into lattice sites or residing in cryptically altered domains, underscores the need for accurate microanalysis, improved constraints on partitioning, and an integrated understanding of crystal growth and alteration processes. Despite these complexities, zircon Li contents still offer practical utility for identifying Li-fertile magmatic systems, and provide insights into the physicochemical evolution of the melts from which these economically important mineral resources form.

References:
[1] Gardiner N et al. (2021) Chem Geol 585:120580
[2] Ushikubo T et al (2008) Earth Planet Sci Lett 272:666–676
[3] Tang et al (2017) Earth Planet Sci Lett 474: 110-119
[4] Wang Y and Trail D (2022) Cont. Min. & Pet 177:15
[5] Shang S et al (2024) Geology 52:794–798

Microstructural record of Icelandic crystal mushes preserved in gabbroic nodules

Subbaraman, R.[1], Hughes, L.[1], Hartley, M.E.[1] and Neave, D.A.[1]

[1] Department of Earth of Environmental Sciences, University of Manchester, Manchester M13 9PL, UK.
rahul.subbaraman@manchester.ac.uk

Cohesive yet porous frameworks of solid crystals with interstitial melts – crystal mushes – form geometrically complex plumbing systems beneath many active volcanoes [1,2]. In oceanic settings like Iceland, percolating melts and exsolved fluids may generate small eruptible lenses within mush-rich reservoirs stacked between solidified rock [3,4]. Examining pre- and syn-eruptive crystal mush textures can help improve models of magma behaviour (e.g., [5]), as they leave evidence that helps us decode magma storage, remobilisation, and ascent.

We collected gabbroic nodules from Gígöldur in Central Iceland, likely representing fragments of crystal mushes (e.g., [6]). These nodules provide a rare opportunity to investigate mush microstructures and fabrics. EBSD maps were acquired for four nodules spanning troctolite, gabbro, and anorthosite, providing crystallographic, textural, and deformation information. This study addresses the following questions:

- Are there deformation structures, crystallographic preferred orientations (CPO), and shape preferred orientations (SPO) present?
- If present, are deformation microstructures controlled by dynamic or static recrystallisation?
- How do CPO and SPO vary with lithology and mineralogy, and what are their origins – deformation, crystal growth, or settling?
- If present, is strain localisation preferentially associated with specific minerals or textural domains?
- Do observed fabrics primarily reflect magmatic alignment, compaction, or post-crystallisation overprint?

The EBSD results of nodules will be contextualised through comparison with fabrics from ophiolites, layered intrusions, and arc cumulates [e.g., 7,8,9,10].

References:
[1] Cashman et al. (2017), Science 355(6631), [1280].
[2] Edmonds et al. (2019), Phil Trans R Soc A 377(2139): 20180298.
[3] Holness et al. (2007), J Petrol 48(7): 1243–1264.
[4] Maclennan (2019), Phil Trans R Soc A 377(2139): 20180021.
[5] Sparks and Cashman (2017), Elements 13 (1): 35–40.
[6] Holness et al. (2019), Phil Trans R Soc A 377(2139): 20180006.
[7] Vukmanovic et al. (2019), J Petrol 60(8):1523–1542.
[8] Mock et al. (2021), JGR Solid Earth 126, e2020JB019573.
[9] Wieser et al. (2020), Nature Communications, 11: 14.
[10] Holness et al. (2017), J Petrol 58(4), 643-674.

Serialsomatism of tourmaline: An indicator of geothermal system evolution

Dutrow, B.L.[1]

[1]Department of Geology & Geophysics, Louisiana State University, Baton Rouge, LA, U.S.A.
dutrow@lsu.edu

Harnessing geothermal energy is a cornerstone for a lower carbon future. With world-wide resources, characterizing and understanding the long-term system evolution is critical to continued development but remains a challenge. Geothermal (hydrothermal) systems evolve as a complex interplay of non-linear coupled processes among thermal, mechanical, and chemical energy in the fluid-rock system. Typically, numerical modelling of these systems is a primary approach for investigation. An alternative approach is to use mineral chemistry and assemblages to provide key insights not afforded in numerical models. Patterns in mineral zoning reflect feedback amongst the coupled processes of diffusion, reactions, advection and deformation. Tourmaline, a chemically complex borosilicate that incorporates the fluid-mobile element boron, records such interactions. Found in many modern and ancient geothermal systems, tourmaline has an exceptional ability to capture geochemical and thermal conditions during growth. Its flexible chemistry and sensitivity to its environment archive the evolution of system conditions within its zoning.

When the system is near critical conditions, calculations show that small variations in pressure and temperature (T) strongly affect the aqueous phase composition and that the Gibbs free energy of ionic species dominates the equilibrium state among minerals and ions [1]. The resulting pattern is oscillatory zoning displayed by mineral products of the multiple overprinted metasomatic events, serialsomatism, intrinsic to geothermal activity. As an example, in the Geysers Geothermal system, California, U.S.A., intricately zoned tourmalines (10 μm to 100 μm) display sub-micrometre to micrometre scale chemical zonation in Na, Fe, Mg, and Al. Grains have Mg-rich schorl cores alternating with concentric bands of schorl and foitite. Such fine fluctuations reflect the changing fluid compositions resulting from thermal-chemical-mechanical feedback. Tourmaline acts as a geochemical 'meter' of these processes. When the oscillatory zoning in tourmaline is superimposed on sector zoning, a detailed record of the system's thermal history may be retrieved. A sector- and oscillatory-zoned tourmaline from the Siglo XX fossil hydrothermal system in Bolivia captures the system evolution. Chemical data for each oscillation in time-equivalent sectors indicate multiple heating and cooling events using the intersector element-partitioning thermometer of van Hinsberg and Schumacher [2]. Initial tourmaline growth began at about 350°C, and continued during cooling to around 300°C, followed by reheating to approximately 380°C, and the final growth during a cooling cycle to around 300°C at which point growth ceased. These findings showcase the power of mineral-based methods to reconstruct the thermal evolution of geothermal systems and complement traditional modelling techniques for understanding the system's evolution and thermal history.

The expansion of lower carbon geothermal energy, from the first geothermal energy generator developed in 1904 at Larderello, Italy, is made possible by the discoveries of minerals and their embedded information. Such advances derive from strong professional societies, their publications and endeavours. Congratulations on the 150th anniversary of the MinSoc. As the world strives to a lower carbon future, mineralogy, supported by professional societies, plays an essential role for expansion and characterization of advanced lower carbon technologies.

References:
[1] Norton D and Dutrow B (2001) GCA 65:4009-4017
[2] van Hinsberg V and Schumacher J (2007) CMP 153:289-301
[3] Unwin J (2019) Power Tech online

Out of Space, Under the Beam: Low-Dose SEM–EDS of Fragile Phases in Carbonaceous Chondrites and Asteroid Bennu Return Samples

Salge, T.[1], King, A.J.[1], Lee, R.M. [2] and Russell, S.S.[1]

[1]Planetary Materials Group, Natural History Museum, London, United Kingdom, tobias.salge@mailbox.org
[2]School of Geographical and Earth Sciences, University of Glasgow, United Kingdom

---

Highly aqueously altered carbonaceous chondrites present challenges for electron probe X-ray microanalysis. A fine-grained phyllosilicate matrix hosts ~10 µm and smaller grains of mechanically harder phases including olivine, magnetite, chromite and Fe-Ni metal. Hardness contrasts induce preparation-related surface relief, while delicate phases – including Mg–Na phosphate and organics – are beam-sensitive at high electron dose.

Recent advances in low-voltage scanning electron microscopy and energy-dispersive spectrometry (SEM–EDS) enable sub-micrometre elemental mapping over large areas at high resolution (up to 400 megapixels). Low beam currents (~1 nA) and short dwell times (500 µs) minimise elemental migration (e.g., Na) and preserve fragile phases. Improved SEM imaging resolution at low current permits the selection of topographically optimal regions for quantitative analysis at 15–20 kV [1]. Low-voltage analysis (6 kV) with a high-sensitivity annular SDD enhances the detection of light elements (C, N, Na). We present a non-destructive approach for analysing unprepared particles without carbon coating in high vacuum at 50–300 pA.

These approaches are demonstrated on asteroid Bennu samples returned by NASA's OSIRIS-REx mission and the carbon-rich meteorite falls Winchcombe and Cold Bokkeveld, establishing an efficient workflow for targeted high-resolution analysis and correlative TEM characterisation [1].

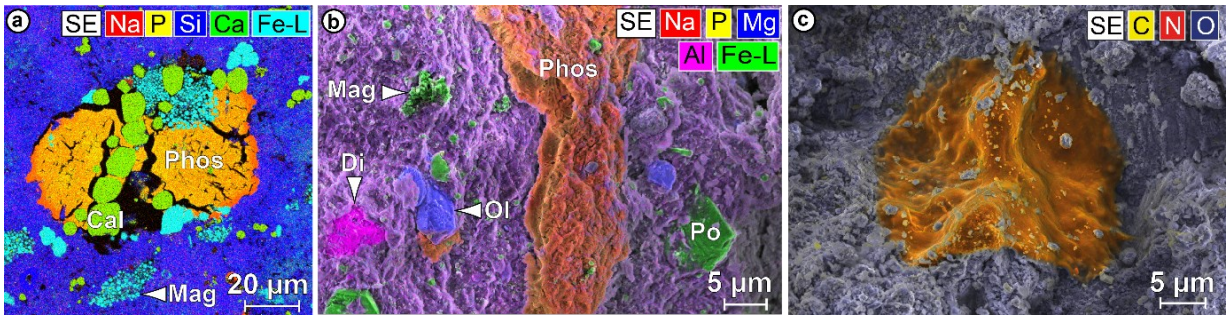


Fig. 1 (a) Polished Bennu particle (OREX-803065-0) showing zoned Mg–Na phosphate (6 kV, 587 pA, 204 kcps, 86 nm pixels) [2]. (b) Mg–Na phosphate occurring as sheets/coatings on an unprepared Bennu grain surface (OREX-501059-0, 6 kV, 283 pA, 68 kcps, 53 nm pixels) [3]. (c) Fragment of the Winchcombe meteorite fall showing an organic grain (6 kV, 158 pA, 38 kcps, 36 nm pixels) [4].

References:
[1] Lee et al. (2025) MAPS 60, 2017–2032.
[2] McCoy et al. (2025) Nature 637, 1072–1077.
[3] Salge et al. (2024) 86th Annual Meeting of the Meteoritical Society, #6326.
[4] King et al. (2022) Sci. Adv. 8: eabg3925.3

No WDS? No Problem! Why Do Mineralogists Continue to Overlook EDS?

Stonadge, G.R.[1] and Spasevski, L.[1]

[1]Oxford Instruments, Halifax Road, High Wycombe, HP12 3SE, George.stonadge@oxinst.com

---

Wavelength-dispersive X-ray spectroscopy (WDS) has long been regarded as the benchmark for quantitative microanalysis in mineralogical studies [1]. However, substantial technological developments in modern energy-dispersive X-ray spectroscopy (EDS) now provide analytical performance that challenges this traditional hierarchy [1]. Over the past two decades, innovations in detector design, signal processing and spectral deconvolution have transformed EDS into a high-resolution, high-throughput tool capable of delivering robust chemical data across mineral systems [2,3]. Despite this, EDS remains underutilised in many areas of mineralogical research and great scepticism about its quality is still a barrier to publication.

Here we present a comprehensive evaluation of advanced EDS capabilities using 850 analyses of glass and mineral standards with elements ranging from 100 ppm to 75 wt.%. Measurements were acquired using Oxford Instruments latest-generation Ultim Max ∞ EDS detectors and Tru-Q®-IQ spectral processing algorithms. When benchmarked against WDS-certified values, EDS results are commonly within ±5% for elements ranging from 0.2-75 wt.% and ±8% for elements ranging from 100 ppm-0.2 wt.%. Standard deviation as measured by repeat analysis is frequently below 2.5%, ranging up to 9% for trace concentrations.

Importantly, this degree of accuracy and precision can be maintained at count rates up to 400 kcps, allowing for such high standard of data to be collected within a fraction of a second for major elements and 10's of seconds for minor constituents. Crucially for mineralogical applications, these combined advances in speed and accuracy allow EDS to extend seamlessly into two-dimensional space. Rapid, high-density EDS mapping now permits cm- to nanoscale imaging of major, minor and trace element distributions across large minerals at acquisition speeds far surpassing traditional WDS mapping. This has opened new opportunities for investigating magmatic [4], volcanic [5], metamorphic and metasomatic processes, where fine-scale elemental zoning, diffusion gradients and defect-related microstructures reveal essential petrogenetic information.

By delivering rapid, cost-effective, and high-quality in-situ chemical data, modern EDS can significantly expand the analytical capabilities of scanning electron microscopes. Yet the question remains: why has the geological community been slow to recognise that EDS has now matched WDS in performance and to fully embrace its potential?

References:
[1] Goldstein et al. (2017) Scanning electron microscopy and X-ray microanalysis 4:262-5.
[2] Pinard et al. (2024) Microscopy and Microanalysis 30:44-96
[3] Spasevski et al. (2025) Microscopy and Microanalysis 31:48-241
[4] Stonadge et al. (2023) Geology 51:1158-1162
[5] Guyett et al. (2024) Journal of Analytical Atomic Spectrometry 39:2565-2579

Time dependent intensity correction and other recent software advances for quantitative analysis by electron probe microanalyzer (EPMA)

Allaz, J.M.[1], Donovan, J.[2] and von der Handt, A.[2]

[1]Dept. of Earth and Planetary Sciences, ETH Zürich, 8092 Zürich, Switzerland; julien.allaz@eaps.ethz.ch
[2]CAMCOR, University of Oregon, Eugene, OR 97403, USA
[3]Dept. of Earth, Ocean & Atmospheric Sciences, The University of British Columbia, Vancouver, BC, Canada

---

Quantification of element concentrations from Be and higher at the (sub-)micrometre scale has been possible for 75 years with the EPMA and its wavelength dispersive spectrometer (WDS) [1], along with the scanning electron microscope equipped with an energy dispersive spectrometer (EDS). By utilizing scanning (stage or beam deflection), 2D element distribution maps can be obtained. Sadly, nowadays EPMA is considered to be a "basic" geochemical tool, which can "only" provide major and minor element analyses down to 100-1000 µg/g at best. However, it remains one of the few methods that can achieve relative precision better than 0.5% and accuracy of 1 to 2%. Over the years, hardware improvements have made it more reliable and stable, and new soft X-ray detectors from JEOL allow for detection of low energy X-rays and thus light elements, including Li [2], along with sub-micrometre sampling, thanks to low voltage analysis. Developments in methods over past decades have been significant and permit even more precise and accurate analyses with powerful software tools. We present here several new and recently published approaches with examples that enable faster analysis and detection limits in the 1 to 10 µg/g range under some circumstances.

Standard-based quantitative X-ray analysis by WDS or EDS relies on the ratio between X-ray intensity of an element in an unknown and in a standard (k-ratio) combined with the matrix correction to return accurate results. With better mass absorption factors [3] come more accurate results even with simple standards (such as synthetic oxides that are not a perfect "matrix match" for silicates, for instance). Providing that reference materials of good quality are considered, accurate quantification of elements down to 5000 µg/g is possible with EDS alone, and WDS should be preferred for elements difficult to analyse by EDS (e.g., light elements or spectral interferences) or for key minor to trace elements (< 1000 µg/g) that require high sensitivity measurements [4]. Faster analyses are possible by using higher current to reduce the analysis time, combining the power of EDS and WDS [4], or using the mean atomic number background correction [5], which permits peak-only analysis with a greater precision on bremsstrahlung correction. The latter is even suitable for trace element analysis in many matrices using a "blank" correction [6]. Element maps can be fully quantified the same as point analysis, with the k-ratio and matrix correction calculated on each pixel [7]. Finally, when beam sensitive materials are analysed (e.g., carbonate, apatite, alkali-rich phases), time dependent intensity (TDI) corrections should be considered, not only for point analysis, but also for element mapping. Element mapping can help in very difficult situations, to minimise the time spent on each pixel (10-100 ms instead of > 10 s), improving precision by averaging pixels.

We present examples acquired on JEOL or Cameca EPMAs by the authors using the software suite *Probe for EPMA* (from Probe Software, Inc.). They include notably short quantitative analysis of P in olivine with detection limits around 5 µg/g (~120 s per point), and around 20 µg/g for hour-long element maps [8], accurate analysis of F, Cl, and traces in apatite with TDI correction [4,9], and element mapping in beam sensitive carbonate and in hydrosulphate (alunite-jarosite).

References:
[1] Castaing (1951) PhD thesis, ONERA, Paris 166 pp.
[2] Takahashi et al. (2016) IOP Conf Ser: Mater Sci Eng 109:012017
[3] Chantler et al. (2005) NIST Standard Reference Database 66, http://physics.nist.gov/ffast
[4] Allaz et al. (2026) Am Min, in press
[5] Donovan and Tingle (1996) J Microsc Microanal 2:1-7
[6] Donovan et al. (2016) Am Min 101:1839-1853
[7] Donovan et al. (2021) Am Min 106:1717-1735
[8] Chatterjee et al. (2026) Geochim Cosmochim Acta, in press
[9] Keller et al. (2023) Earth Planet Sci Lett 622:118400

Analysis of arsenic speciation in contaminated samples: a multi-scale approach from standard XAS to advanced X-Ray spectroscopies

Le Pape, P.[1], Blanchard, M.[2], Ona-Nguema, G.[1], Cabaret, D.[1], Benzerara, K.[1], Juhin, A.[1], Chassé, M.[1], Baptiste, B.[1], Morin, G.[1], Battaglia-Brunet, F.[3], Juolian, C.[3], Fernandez-Rojo, L.[4], Resongles, E.[4], Héry, M.[4], Casiot, C.[4], Landrot, G.[5], Belkhou, R.[5], Rueff, J.P.[5]

[1]Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie (IMPMC), UMR 7590 CNRS – Sorbonne Université – IRD – MNHN, 4 place Jussieu, 75252 Paris, Cedex 5, France, pierrelp.hm@gmail.com
[2]Géosciences Environnement Toulouse (GET), Observatoire Midi-Pyrénées, Université de Toulouse, CNRS, IRD, UPS, 14 Avenue Edouard Belin, 31400 Toulouse, France
[3]BRGM, Water, Environment, Process Development and Analysis Division, 3 av. Claude Guillemin, BP 36009, 45060 Cedex 2, Orléans, France
[4]HydroSciences Montpellier (HSM), Université de Montpellier - CNRS - IRD, Montpellier, France
[5]Synchrotron SOLEIL, F-91192 Gif-Sur-Yvette, France

Arsenic (As) is a toxic contaminant that locally accumulates in surface environments, thus potentially causing ecosystemic problems. Worldwide, high As concentrations in waters are observed in aquifers subjected to inputs from igneous mountain ranges erosion, in geothermal fluids, or around mining sites, in particular those exploiting sulfide ore. In mining environments exposed to acid mine drainage (AMD), research is currently active for developing eco-compatible (*e.g.* using local resources) passive bioremediation technologies to immobilize As from As-rich waters. In such complex bioprocesses, key physico-chemical parameters have to be identified and controlled to promote highest As removal rates. Such bioremediation issues require identifying the chemical reactions governing As chemistry at the molecular scale, for which redox- and ligand-sensitive synchrotron-based techniques are of particular interest.

I will first show how standard X-ray absorption spectroscopy (XAS) at the As K-edge has been used to probe As speciation (redox and solid species) and helps identifying the geochemical processes at stake in both oxic and anoxic laboratory pilot systems, which were designed to decontaminate As-rich AMD waters in the framework of the INGECOST-DMA research project [1-3]. Taking as an example samples from anoxic bioprocesses dedicated to water decontamination [2-3], I will discuss the interest of additional spectral imaging through scanning transmission X-Ray spectroscopy (STXM) at the As $L_{2,3}$-edges to reveal the spatial distribution of As species at the microscale in As-sulfide-encrusted biofilms. Then, I will discuss how high-resolution X-ray spectroscopies such as high-energy-resolution fluorescence detected X-Ray absorption near-edge structure (HERFD-XANES) and resonant inelastic X-Ray scattering (RIXS) at the As K-edge could help improving the determination of As speciation in complex biogeochemical systems [4]. Finally, I will present prospective work with X-Ray emission in the off-resonant region (XES-HEROS) at the As K-edge, which may open perspectives to determine As speciation in samples for which usual analysis is difficult.

References:

[1] Fernandez-Rojo et al., Water Research 123, pp. 594-606, 2017.
[2] Le Pape et al., Journal of hazardous materials 321, 764-772, 2017.
[3] Battaglia-Brunet et al., Water Air Soil Pollution 232, 330, 2021.
[4] Le Pape et al., Journal of analytical atomic spectroscopy 33, pp. 2070-2082, 2018.

Developments in geological studies by X-ray spectroscopy techniques at Diamond Light Source

Mosselmans, J.F.W.[1]

[1]Diamond Light Source, Ltd, Harwell Campus, Didcot, UK fred@fredmoss.plus.com

---

In the period since it opened in 2007, Diamond Light Source spectroscopy beamlines have contributed to hundreds of studies within the broad spectrum of geology. As the synchrotron experimental portfolio has expanded and beamlines themselves been developed, a vast range of different geological problems have been looked at by the synchrotron. A review of the Diamond publication database suggests more than 250 papers have been published from the I14, I18, B18 and I20 beamlines in the subject area of earth science.

This selective review will range from some of the earliest Diamond studies the microfocus spectroscopy beamline I18 contributed to, such as a study of the Santa Caterina meteorite [1] and on microbial communities in shale cliffs [2], through Extended X-ray Absorption Fine Structure [EXAFS] studies e.g. uranium speciation in Mexican deposits in Chihuahua[3], X-ray absorption near edge analysis to understand oxygen fugacity in silicate melts [4] to some of the most recent published experiments highlighting technique developments such as High Energy Resolution Fluorescence Detection (HERFD) on I20 being used to obtain EXAFS data on very dilute gadolinium in marine sediments [5] and the use of the I14 nanoprobe to look at biomineralisation [6]. It will highlight the breadth of geological research assisted by spectroscopy studies and the technical progress made over the last two decades such as nanoprobe X-ray fluorescence mapping and HERFD spectroscopy using emission spectrometers.

In addition some examples of the most recent developments, such as oxidation state mapping of uranium using M4-edge HERFD and the nanofocus EXAFS using a sparse acquisition approach, will be outlined.

References:
[1] Schofield PF et al. (2010) Geostand Geoanal Res 34:145-159
[2] Cockell CS et al. (2011) Microb Ecol 61:166-181
[3] Hernández-Herrera C et al. (2025) Minerals 15:333
[4] Burnham AD et al. (2014) Chem Geol 411:248-259
[5] Manceau A et al. (2026) Env Sci Nano 13:1004
[6] Walker JM et al. (2025) Farad Discuss 261:231

Developing U L3 and M4,5 -edge HERFD-XANES to investigate uranium (bio)geochemical processes in radioactive waste disposal and nuclear decommissioning

Waters, C.[1,3], Neill, T.S.[1], Morris, K.[1], Baker, M.L.[2], Alcock, N.M.[2], Mosselmans, J.F.W.[1], Ignatyev, K.[3] and Shaw, S.[1]

[1] Radioactive Waste Disposal and Environmental Remediation Facility, and Williamson Research Facility, Department of Earth & Environmental Sciences, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[2]Department of Chemistry, The University of Manchester, Manchester, M13 9PL, UK
[3] Diamond Light Source, Harwell Science and Innovation Campus, Chilton, Didcot, OX11 0DE, UK

Variations in uranium (U) environmental speciation, including oxidation state and complexation are primary controls on uranium solubility and mobility within engineered and natural environments. This project aims to study environmentally relevant U solids including phosphates, carbonates, oxyhydroxides and silicates using novel spectroscopic methods to develop these techniques in determining actinide speciation in complex environmental matrices. In turn, this will allow their application in environmental actinide research and ultimately gain better understanding of uranium biogeochemical processes in environmental systems. Specifically in this work, we have applied high energy resolution fluorescence detection x-ray absorption near edge spectroscopy (HERFD-XANES) at the U L3 and M4,5 –edges to probe the electronic structure of U in well-characterised, natural and synthetic minerals and explore sensitivities to oxidation state and ligand complexation.1, 2

A suite of environmentally relevant U(VI) phases including key ligands such as carbonates, phosphates and oxyhydroxides were synthesised in the laboratory or obtained from natural samples. Samples were analysed to confirm mineral identity using X-ray Diffraction and characterised at the U L3- and M4,5-edge. Extended x-ray absorption fine structure (EXAFS) was carried out at B18 and U L3 HERFD-XANES at I20 (both Diamond Light Source). M -edge investigations were conducted at the BM20 beamline (ESRF) and I18 beamline (Diamond Light Source).

X-ray absorption spectroscopy (XAS) at the U L3 edge (c.a. 17 keV) is widely applied to characterise U coordination environment and, often, oxidation state in complex environmental media.3, 4 This work focuses on a full systematic study into key environmentally relevant U(VI) phases, thus, extending the current spectroscopy toolkit for characterising U(VI) phases to include updated EXAFS fits to high k values as well as new HERFD-XANES data.3 The increased resolution associated with U L3 edge HERFD-XANES in comparison to standard L3 edge XANES, has been previously found to reveal a distinct pre-edge feature in HERFD-XANES from U(VI) however, analysis of this pre-edge region is yet to be thoroughly investigated.5, 6 Our investigation into the region highlights differences in the intensity of the pre-edge between the HERFD-XANES of the different U(VI) compounds. In particular, the pre-edge area in the HERFD-XANES of compounds with four ligands in the equatorial plane is significantly lower that from the other model phases. We propose that this difference in intensity is related to symmetry surrounding the central U atom.

Probing only the U L3-edge has limitations; for example, identifying the presence and contribution of U(V) is challenging at the L3 -edge even using HERFD-XANES.7 Recent studies focusing on U M4,5 -edge (ca 3.7 keV) HERFD-XANES of uranium samples in complex environmental phases have highlighted the potential for these techniques to enhance characterisation of oxidation state for environmentally relevant U species and coordination environment in ideal systems.8-11 Previous detailed HERFD-XANES studies have often focused on U in highly symmetric uranyl coordination environments. The systematic analysis of environmentally relevant U(VI) minerals/compounds presented here demonstrates that U M4,5 -edge HERFD-XANES varies with U oxidation state and local coordination environment as expected. The U M4,5 -edge HERFD-XANES data presented here also highlight new sensitivity in assessing equatorial ligand coordination number, bond geometries and nearest neighbour atoms.

1. K. O. Kvashnina and S. M. Butorin, Chemical Communications, 2022, 58, 327-342.
2. T. Vitova *et. al.*, Nature Communications, 2017, 8, 16053.
3. J. G. Catalano and G. E. Brown, 2004, 89, 1004-1021.
4. C. Foster *et. al.*, Langmuir, 2022, 38, 2576-2589.
5. R. Bès *et. al.*, Inorganic Chemistry, 2016, 55, 4260-4270.
6. T. Vitova *et. al.*, Physical Review B, 2010, 82, 235118.
7. T. A. Marshall *et. al.*, Mineralogical Magazine, 2015, 79, 1265-1274.
8. G. F. Vettese *et. al.*, Environmental Science & Technology, 2020, 54, 2268-2276.
9. L. Amidani *et. al.*, Inorganic Chemistry, 2021, 60, 16286-16293.
10. I. Pidchenko *et. al.*, Environmental Science & Technology, 2017, 51, 2217-2225.
11. H. E. Roberts *et. al.*, Environmental Science & Technology Letters, 2017, 4, 421-426.

Large-geometry SIMS – analytical capabilities and novel applications in the earth, planetary and environmental sciences

Whitehouse, M.J.[1]

[1]Swedish Museum of Natural History, SE-104 05 Stockholm, Sweden. E-mail: martin.whitehouse@nrm.se

---

High-spatial and -volume resolution analysis of minerals and/or glasses by secondary ion mass spectrometer (SIMS) is the most sensitive method available in the earth, planetary and environmental sciences. The ion optical design of the CAMECA large-geometry (LG-) SIMS provides a unique combination of point analysis (ion microprobe) mode as well as direct (ion microscope) and scanning ion image (SII) modes. Whilst the ion optics has remained largely unchanged for over three decades, advances in source technology, in particular the advent of high-brightness radio frequency plasma sources as well as high-gain Faraday amplifiers, continues to open up new and/or improved approaches to in situ microanalysis (incidentally this is also the case for the broadly similar NanoSIMS instruments).

Ion microprobe mode is most commonly utilized with these instruments, providing high-precision, high-mass resolution geochemical and isotope ratio analysis across most of the periodic table with unparalleled sensitivity, detection limit and at a lateral resolution of ca. 0.5 to >20 μm. Improvements in accuracy and precision in these analyses is to a large degree now limited only by an incomplete understanding of the sputtering process as well as availability of suitable reference materials. Many of the latter comprise natural materials, which have their own inherent limitations with regard to composition and homogeneity.

Ion imaging is increasingly being used both as a reconnaissance method to identify targets of interest for subsequent point analysis (mostly direct image mode), and as a fully quantitative analytical tool (SII) in its own right, using dedicated image processing software to generate accurate, high-precision isotope ratios from user-defined regions of interest in an imaged sample. Spatial resolution in SII is defined by the size of the primary beam, hence higher resolution comes at the cost of lower secondary ion signals and worse detection limits. Despite this limitation, SII has the ability to transcend spot analysis as a means of fully understanding the distribution of elements and their isotopes in a wide range of materials.

This keynote will present a number of case studies from across the earth, planetary and environmental sciences, undertaken using the LG-SIMS instrument at the NordSIMS facility, Stockholm, that illustrate current state-of-the-art in SIMS analysis and indicate the future direction of this method.

Non-destructive SEM-BEX geological sample analysis: a new workflow for high-resolution analysis of unprepared samples

Stavropoulou, A.[1], Stonadge, G.[1] and Rider-Stokes, B.[2]

[1]Oxford Instruments, Halifax Road, High Wycombe, HP12 3SE, UK, alexandra.stavropoulou@oxinst.com
[2]Open University, Milton Keynes, MK7 6AA, UK

Angrites are among the earliest igneous materials in the solar system and hold key clues to early planetary differentiation, yet their extreme rarity often prevents destructive preparation and limits the application of conventional microanalytical techniques. We present a new, non-destructive scanning electron microscopy backscatter & X-ray analytical (SEM-BEX) workflow designed to enable high-resolution elemental mapping of pristine extraterrestrial samples, demonstrating its capability through the first identification of zircon within an unprepared ~4.35 Ga angrite.

SEM-BEX mapping was performed at beam conditions of 15 kV and 4 nA in variable pressure (VP) mode (35 Pa) to mitigate charging on the uncoated angrite surface. To overcome X-ray shadowing from uneven topography and low count rates typical of such conditions (due to absorption by air molecules in the SEM chamber), BEX uses a beneath the pole piece detector geometry (horizontal insertion) that minimises shadowing and maximises X-ray collection efficiency. This approach enabled large-area mapping (>4.5 cm^2) at high resolution (2.5 µm pixel size) to be achieved in 4h.

The dataset revealed ten (10) zircon crystals (<50 µm) dispersed across the sample, representing an exceptionally rare phase at trace abundance. Several crystals were confirmed as zircon through quantitative elemental analysis using EDS (energy dispersive spectrometry). Large area maps now provide a means with which to target individual crystals for localised FIB (Focused Ion Beam) 'lift out' and further analysis with mass spectrometry techniques. As zircon is a key chronometer for U–Pb dating, its presence in angrites opens new avenues for constraining early solar system chronology.

This discovery demonstrates the feasibility of identifying ultra rare minerals in pristine samples without destructive and invasive sample preparation, preserving their integrity for subsequent analysis and enabling different analytical workflows. Beyond the implications for angrite petrogenesis and solar system evolution, this approach demonstrates a powerful pathway for guiding targeted extraction of minerals for geochronology in rare earth and planetary materials.

References:
[1] Rider-Stokes, B.G., Anand, M., White, L.F., Darling, J.R., Tartèse, R., Whitehouse, M.J., Franchi, I., Greenwood, R.C. and Degli-Alessandrini, G., 2024. The impact history and prolonged magmatism of the angrite parent body. Meteoritics & Planetary Science, 59(1), pp.23- 39.
[2] Rider-Stokes, B.G., Greenwood, R.C., Anand, M., White, L.F., Franchi, I.A., Debaille, V., Goderis, S., Pittarello, L., Yamaguchi, A., Mikouchi, T. and Claeys, P., 2023. Impact mixing among rocky planetesimals in the early Solar System from angrite oxygen isotopes. Nature Astronomy, 7(7), pp.836-842.

The calculation of a mineral age from microprobe analyses of U, Th and Pb

Bowles, J.F.W.[1]

[1] 12 chemin de Grand Jean, 24100 Creysse, France john.bowles@UCLmail.net

---

Quantitative electron microprobe analyses of U, Th and Pb within appropriate minerals can provide an age of formation or alteration. This uses the concept of a "chemical age" that was used before isotopic measurements became available [1]. There is the inherent assumption that the mineral contained no Pb when it was formed so that all of the Pb now present is the result of radioactive decay of U and Th. The advantage of this method over whole rock analyses or mineral separation is the ability to distinguish primary and secondary mineralization and relate that information to mineral textures. It is also possible to confirm a result using two or more different minerals. It does not, of course, compete with an ion probe but may serve as a precursor analysis to see if an ion probe study is warranted.

The method was used by this author in two studies of uraninite from Portugal [2] although it was not published until 1990 [3] when the idea was quickly adapted to monazite, zircon and xenotime [4]. Despite a later clarification [5] the necessary calculation has suffered misunderstandings due to the manner by which the calculation is performed. The difficulty arises from the expression for the Pb that is produced by the decay of ^{238}U, ^{235}U and ^{232}Th.

This expression:

$$Pb = {}^{238}U(e^{\lambda U238\, t} - 1) + {}^{235}U(e^{\lambda U235\, t} - 1) + Th(e^{\lambda Th\, t} - 1)$$

is *transcendental* and cannot be reorganised into the form t = some function. (Chambers Dictionary describes *transcendental* as "not capable of being produced or expressed algebraically"). Here Pb, U and Th are the atomic proportions of those elements determined from the microprobe analysis with the U distributed between ^{238}U and ^{235}U using the appropriate ratio, λ is the decay constant for each of the individual isotopes and t is the age. This presentation will show how a result can be obtained.

Clearly the analyses for U, Th and Pb need to be as accurate as possible so it is necessary to perform a full analysis to allow the correction programmes can be applied to those elements. Analysis for U and Th needs extra care because of the large number of X-ray peaks they produce and because the correction procedures are less well calibrated for these elements [6,7]. As Pb is the result of decay of a proportion of the U and Th, the Pb is normally the smallest quantity so the Pb analysis is the most critical to know accurately and it is largely responsible for the error range that can be stated for the age. For young ages the amount of Pb can approach the detection limit and for old minerals the amount of Pb generated can be sufficient for the mineral structure to be disrupted, the host mineral becoming metamict, which allows some Pb to be lost so the method is limited by those considerations.

References:

[1] Holmes A (1965) Principles of Physical Geology Nelson, London rev ed 1288 pp
[2] Basham I et al. (1982) IAEA TC-295/1:279–298 and IAEA TC-295/1:299–309
[3] Bowles J (1990) Chem Geol 83:47–53
[4] Suzuki K and Adachi M (1991) Geochem J 25:357–376
[5] Bowles J (2015) Microsc Microanal 21:1114-1122
[6] Bowles J (1978) Microscope 26:55–67
[7] Matthews M et al. (2021) Microsc Microanal 27:466-483

Integrated analytical workflow for decoding tourmaline-orbicule crystallisation in granitic environments

Ghosh, U.[1,2], Upadhyay, D.[2], Dunkel, K.G.[3], Chandra, D.[4 and] Barnhoorn, A.[5]

[1]The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK, urmi.ghosh@hutton.ac.uk
[2]Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, India
[3]Section for Crustal Processes, Department of Geosciences and The Njord Centre, University of Oslo, P.O. Box 1048 Blindern, 0136 Oslo, Norway
[4]Department of Geoscience (IGV), Norwegian University of Science and Technology, S. P. Andersens veg 15A, 7031 Trondheim, Norway
[5]Department of Geoscience and Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, the Netherlands

---

Quartz-tourmaline orbicules from the Sewariya granites, India, represent spherical aggregates of tourmaline intergrown with quartz and feldspars (along with some minor phases), and surrounded by a leucocratic halo. Although orbicules have been reported in S-type granites before, their formation mechanism remains debated. Diffusion-Limited Aggregation (DLA) has been proposed to explain their dendritic, cluster-like growth; however, textural observations suggest that alternative or additional processes may be involved. This study integrates three-dimensional (3D) structural analysis, crystallographic data, along with geochemical data to evaluate orbicule growth mechanisms.

Electron Backscatter Diffraction was performed on thin sections of the orbicules. Tourmaline within one orbicule exhibits orientation maxima, albeit with significant orientation spread. The boundaries between orientation domains are sharp and no gradational internal misorientations are observed. Combined with a lack of preferred orientation in the surrounding quartz, this negates the possibility of significant recrystallisation or ductile deformation. Thus, the orbicules were formed by primary igneous processes and were not deformed/ recrystallised. The chemical zoning in the tourmaline grains, manifested primarily by variations in Al, Mg, Ti, is not mirrored by crystallographic zoning. Features that appear as discrete grains in 2D are often crystallographically continuous, indicating larger interconnected growth domains.

Using X-ray computed tomography (XCT), we characterised the 3D distribution and internal structure of orbicules within granite samples. The observations confirmed that the orbicules are not connected in 3D, or there are no fractures/ veins connecting them. We also undertook high-resolution scans of extracted orbicules. The XCT successfully distinguished tourmaline from adjacent felsic phases (quartz, feldspar, apatite) and revealed interconnected grain networks and multiple apparent nucleation centres. The 3D architecture supports clustered growth rather than simple concentric crystallisation, consistent with diffusion-limited clustered aggregation.

Together, these multi-scale observations suggest that orbicule formation involved clustered nucleation and growth within a boron-rich magmatic fluid-rich environment, rather than simple radial crystallisation. This integrated approach refines existing DLA-based models and provides new constraints on mineral growth dynamics in late-stage granitic systems, with implications for understanding borosilicate-rich fluid processes using advanced techniques.

The Odyssey of a Ni-phyllosilicate: An adventure of the missing smectite

Mitsis, I.[1], Christidis, G.E.,[2] Gkamaletsos, P.N.,[2] Mocuta, C.[3] and Thiaudiere, D.[3]

[1]National and Kapodistrian University of Athens, Department of Geology and Geoenvironment, 15784 Athens, Greece.
[2]Technical University of Crete, School of Mineral Resources Engineering, 73100 Chania, Greece. E-mail: gchristidis@mred.tuc.gr
[3]DiffAbs beamline, Synchrotron SOLEIL, L'Orme des Merisiers, Départementale 128, 91190 Saint-Aubin, France

---

In December 2006 we reported a new trioctahedral Ni-phyllosilicate belonging to the smectite group, containing up to 36% NiO and 1.3% CoO [1]. The mineral was a Ni-stevensite forming ~100 x 20 mm domains within a Mg-rich/Ni-poorer matrix containing 8-15% NiO. A few weeks later, Ernest Nickel the then Australian representative on the old Commission on New Minerals and Mineral Names (CNMMN/IMA) contacted us suggesting to apply for a new mineral to the CNMMN/IMA. We responded noticing that it would be difficult to provide lattice parameters for the phase. A few years later, capillary XRD experiments in ESRF, Grenoble on bulk clay fractions were not conclusive. In 2012 we sent polished blocks to Steve Guggenheim at Chicago, Illinois, to run a microdiffraction experiment in Argonne National Lab, USA, but the blocks were confiscated by the US customs. One year later, Pete Williams the then chairman of CNMMN/IMA and editor of Min Mag suggested to send him the application file with all data. It was clear that, the file would not be complete unless it contained lattice parameters. We thought that the Ni-stevensite door had been closed for ever, but we were wrong.

Several years later in Euroclay at Paris (2019), Laurent Michot suggested to contact the Soleil light source in France for microdiffraction micro-EXAFS and micro-XRF experiments. Six months later one of the authors was examiner of the PhD Thesis of an Italian student two weeks before the outbreak of Covid epidemic in Europe, who was just beginning her post doc research project in DIFFABS beamline at Soleil! The world is very small, or so it seems! After a rejection, a placement to the reservation list and one postponement due to the invasion in the Ukraine that caused power cuts in France, our proposal was accepted and we were allocated beam-time in mid-September 2023. Yet the adventure was not over. Two weeks before the experiments we were informed that there was a serious vacuum leak in the beamline and the experiment was postponed twice. Finally, on 29 November 2023 the experiment was launched.

The results compensated us for the previous lost years. Ni-XRF mapping confirmed the micro domains that were rich in nickel and micro XRD scans were informative and will allow determination of the lattice parameters of the Ni-stevensite. In addition, it allowed identification of two Co-hosts, the Ni-stevensite and a Co-rich phase. The latter had not been detected on the surface of the polished blocks during routine backscattered SEM analysis, but it was revealed from emission of X-rays under the sample surface, due to the higher energy of the synchrotron radiation. The study will be particularly helpful for similar studies on supergene alteration, especially lateritization. Indeed, after the first report [1], Ni-stevensite has been reported in laterites in Brazil and New Caledonia intergrown with nontronite and/or Ni-kerolite, suggesting that it is a rather common phase in supergene environments during weathering of ultrabasic rocks.

Reference

[1] Christidis GE and Mitsis I (2006) Clays Clay Miner:54 553-566.

Why Automated Mineralogy needed an upgrade

Taylor R.J.M.[1]

[1]ZEISS, Cambridge, CB23 6DW

Automated Mineralogy – the past

The automated classification of mineral phases in rocks has been a mainstay of the Geoscience analytical community for over 40 years. While we have seen great leaps forward in AI in µCT and light microscopy/petrography, the automated capabilities for the SEM have progressed and changed very little in decades, relying heavily on outdated methods that were available at the time.

The technology come with several significant problems moving forward, including excessive hardware-software dependencies, complex mineral libraries and classifications, inconsistent user experience, and difficult workflows outside their intended use.

Recent technological advances

There are two broad shifts that are taking place across a number of microscopy and microanalysis techniques – the acquisition of more quantitative data, and the application of deep learning neural networks. As a general trend this can be thought of as building better datasets, and building bigger datasets.

EDS as a SEM-based technique is fertile territory for both of these shifts. As an analytical technique EDS is commonly applied qualitatively, or as an image based method for distinguishing regions based on chemical maps. In recent years it has become easier than ever before to calibrate systems and detectors for concentration data, meaning the SEM can generate more robust datasets without having to fall back on other techniques.

Deep Learning is a topic that covers a broad range of mathematical applications to everything from the acquisition of microscopy datasets, through to data processing and interpretation across almost all sciences. There are many different flavours of deep learning neural network (DLNN) and each type lends itself to different applications, particularly in the varied data rich environments of microscopy. DLNN are inherently hard to track exactly how they operate, but at their best should be easy to use, and easy to understand how they've been applied to a scientific problem.

Automated Mineralogy – the future

The introduction of both quantitative mineral chemistry and DLNN to automated mineral classification is a huge leap forward, solving many of the problems of traditional software. Detaching data acquisition from processing removes software dependencies and frees users to build their ideal system. An DLNN-driven, unsupervised data processing approach can be data led rather than user led, making it more robust and consistent across instruments and facilities. Quantitative analysis can build on the DLNN approach by allowing a "best fit" classification, removing the need for constant modification of mineral libraries, and simply allowing "textbook" globally consistent mineral compositions to drive the labelling of segmented data.

The evolution of biomining through the lifetime of the Mineralogical Society

Santos, A.[1]

[1]Natural History Museum, Cromwell Road, London, UK, SW7 5BD.

Over the past 150 years, since the founding of the Mineralogical Society, mineral sciences have evolved from largely descriptive studies of minerals and ores to a highly interdisciplinary field integrating geochemistry, microbiology, and biotechnology. During this same period, our understanding of microbe–mineral interactions has transformed from early observations of microbial weathering to the development of biomining technologies now used worldwide for metal extraction. This talk reflects on the evolution of biomining over the lifetime of the Society and considers how these developments mirror broader advances in mineralogical research.

The recognition that microorganisms can catalyse mineral dissolution and influence metal mobility laid the foundations for bioleaching processes that are now used industrially to recover metals such as copper and gold from low-grade ores. Over time, advances in geomicrobiology, molecular biology, and process engineering have deepened our understanding of the microbial communities that drive these transformations and enabled the design of increasingly efficient biohydrometallurgical systems.

Today, the field is entering a new phase. Modern tools in microbiome science, systems biology, and engineering biology are opening opportunities to harness and design microbial consortia for improved metal recovery. These approaches are expanding biomining beyond primary ores to include the re-mining of historical mine wastes, the recovery of critical elements from industrial residues, and the development of hybrid technologies that combine microbial processes with electrochemical and hydrometallurgical methods.

Looking forward, integrating mineralogical knowledge with microbial ecology and biotechnology offers new possibilities for more sustainable and circular resource extraction. As highlighted by the theme of Mineralogical Society at 150: Past Discoveries and Future Frontiers, the next frontier for mineral sciences may lie not only in discovering new minerals, but also in understanding and harnessing the living systems that transform them.

Cyanobacterial influence on carbonate precipitation under varying geochemical conditions revealed by high-throughput correlative imaging and Raman spectromicroscopy

Stigliano, L.[1], Rehmanji, M.[1] and Cosmidis, J.[1]

[1]University of Oxford, Department of Earth Sciences, Oxford, United Kingdom
luca.stigliano@earth.ox.ac.uk

Microorganisms influence mineral formation across a wide range of natural and engineered environments, affecting mineralogy, morphology and growth rates of the mineral products. Microbially mediated minerals often display features that distinguish them from purely abiotic precipitates, including complex morphologies, metastable phases, and close associations with organic matter. These characteristics influence mineral reactivity, stability, and the cycling of elements within biogeochemical systems, and they may also provide potential biosignatures preserved in the geological record. Despite their importance, the mechanisms by which microorganisms mediate mineral nucleation and growth under different geochemical conditions remain poorly constrained.

Microbial biomineralization arises from the complex interplay between microbial metabolism, extracellular polymeric substances (EPS), and surrounding geochemical conditions. Disentangling these controls therefore requires systematic exploration across multiple physicochemical and biological parameters at sufficiently large experimental scale. Conventional low-throughput approaches typically investigate only a limited subset of variables and often rely on sample preparation steps that can introduce mineralogical or morphological artefacts. Resolving mineral–organic–microbe interactions thus requires in situ, non-destructive techniques capable of probing mineral growth directly in aqueous, physiologically relevant environments.

To address this, we developed a high-throughput workflow combining in situ correlative imaging and Raman spectromicroscopy to investigate carbonate precipitation under controlled geochemical conditions. Experiments were performed in multi-well format using two cyanobacterial strains (*Synechococcus* sp. PCC 11901 and *Cyanobacterium aponinum* UTEX 3222) alongside abiotic controls. Carbonate formation was examined across varying temperature, CO_2 concentration, Ca^{2+} availability, Mg/Ca ratios, and bicarbonate concentrations. Mineral growth and spatial relationships with microbial populations were analysed using automated bright-field microscopy, fluorescence imaging leveraging natural cyanobacterial autofluorescence, and targeted Raman-based phase identification.

Results show that across conditions promoting enhanced carbonate mineralization, calcite emerged as the dominant precipitated phase and preferentially forms in spatial proximity to dense cyanobacterial clusters, suggesting that microbial activity modifies local geochemical microenvironments that favour nucleation. Compared to abiotic systems, cyanobacteria-associated precipitates display pronounced anisotropic growth and complex aggregation textures. Time-resolved correlative imaging further reveals a spatial coupling between increases in cyanobacterial autofluorescence and advancing mineral growth fronts, consistent with localized microbial influence on carbonate precipitation.

Adsorption and enzymatic degradation of DNA on goethite in the presence of phosphate and divalent cations

Brijit, A.J.[1,2], Singh, V.V .[1], Klier, P.[1], Kumar, N.[3], Kimber, R.[4], Barthélémy, P.[5], Rose, J.[6] and. Kraemer, S.M.[1,2]

[1]Centre for Microbiology and Environmental Systems Science, University of Vienna, Vienna, Austria, 203060007@iitbb.ac.in
[2]Doctoral School of Microbiology and Environmental Science, University of Vienna, Vienna, Austria
[3]Soil Chemistry, Wageningen University and Research, Wageningen, the Netherlands
[4]Department of Earth and Environmental Sciences, University of Manchester, UK
[5]ChemBioPharm, ARNA, Université de Bordeaux, France
[6]CEREGE, CNRS, Aix Marseille University, Aix- en-Provence, France

---

DNA interactions with mineral surfaces in soil and sediments plays a key role in controlling its environmental persistence. Understanding the mechanisms that contribute towards environmental DNA degradation or protection is important for a range of applications and processes including the recovery of ancient DNA from sediments, biodiversity monitoring, and constraining the role of DNA in biogeochemical cycles. Adsorption to mineral surfaces is known to inhibit DNA degradation by a range of biotic and abiotic pathways. However, in natural systems, mineral surfaces are seldom pristine and a range of (in)organic species may co-exist in solution and compete for adsorption, affecting DNA adsorption processes and persistence. Despite their significance, the geochemical basis and mechanistic understanding of how these competing species affect DNA-mineral interactions remain elusive, highlighting a critical knowledge gap.

In this study, we investigated the impact of phosphate and divalent cations (Ca^{2+} and Mg^{2+}) on DNA adsorption and degradation at goethite surface. Our results show that DNA adsorption to goethite is strongly influenced by DNA length, phosphate concentration, and adsorption time. Phosphate significantly reduced DNA adsorption through competitive surface site occupation. Although the presence of Ca^{2+} and Mg^{2+} enhanced DNA adsorption under phosphate concentrations that were otherwise unfavourable for adsorption, this increased adsorption did not translate into protection against enzymatic hydrolysis. Adsorbed DNA remained susceptible to degradation despite cation mediated enhancement of adsorption. Our study demonstrates that enhanced adsorption alone does not necessarily confer long-term protection of DNA and highlights the complex roles of competing ions and cations in regulating mineral-associated DNA persistence. These findings have implications for ancient DNA preservation, eDNA-based biodiversity monitoring, and the role of DNA in nutrient and mineral cycling within biogeochemical systems.

Iron biogeobatteries, their influence on redox cycling, and their application

Byrne, J. M.[1]

[1]School of Earth Sciences, Wills Memorial Building, University of Bristol, Queens Road, Bristol, BS8 1RJ, United Kingdom james.byrne@bristol.ac.uk

---

Microbe mineral interactions occur across nearly all Earth environments and are especially significant for iron-metabolizing microorganisms. Fe(II)-oxidizing and Fe(III)-reducing bacteria exploit the abundance of iron minerals, using them as electron donors or acceptors to support growth and respiration. Although most previous research has focused on microbial reactions with single valence iron phases Fe(II) and Fe(III), increasing evidence indicates that Fe-metabolizing bacteria can also access mixed-valence (Fe(II)-Fe(III)) minerals, such as magnetite (Fe_3O_4), as sustainable electron sources or sinks without inducing bulk mineral transformation [1]. Through repeated oxidation–reduction cycles, diverse bacteria can continue to draw upon the same magnetite particles to sustain metabolism, leading to the concept of mixed-valence minerals functioning as biogeobatteries [2].

Biogeobatteries comprise minerals containing both Fe(II) and Fe(III), potentially spanning a wide range of phases including iron oxides, iron-bearing clays, sulfides, and green rust [3]. This presentation describes a fundamental understanding of how bacteria interact with biogeobatteries, determines the functions of mixed-valence iron minerals as electron reservoirs, and evaluates their environmental significance. Magnetic measurements combined with spectroscopic analyses reveal the roles of particle size and stoichiometry in governing biogeobattery behaviour. In addition, modifications to the reactive properties of minerals such as magnetite can be used to enhance reactivity toward pollutants including chromium, copper, and cadmium [4]. These insights highlight the importance of mixed-valence minerals as active electron stores, expands the overall understanding of microbial iron cycling and unlocks new possibilities for applying tailored biogeobatteries to pollution mitigation, resource recovery, and engineered redox technologies.

References:

1. Byrne, J.M., et al., Redox cycling of Fe(II) and Fe(III) in magnetite by Fe-metabolizing bacteria. Science, 2015. **347**(6229): p. 1473-1476.
2. Bayer, T., et al., Magnetite nanoparticles are metastable biogeobatteries in consecutive redox cycles driven by microbial Fe oxidation and reduction. Geo-Bio Interfaces, 2024. **1**: p. e3.
3. Biswakarma, J., M. Matthews, and J.M. Byrne, Redox Dynamic Interactions of Arsenic (III) with Green Rust Sulfate in the Presence of Citrate. Environmental Science & Technology Letters, 2024.
4. Bayer, T., et al., Cu (II) and Cd (II) removal efficiency of microbially redox-activated magnetite nanoparticles. ACS Earth and Space Chemistry, 2023. **7**(10): p. 1837-1847.

Nutrient availability dictates microbial ecology in acidic environments

Falagán, C.[1]

[1] School of the Environment and Life Sciences, King Henry Building, University of Portsmouth, Portsmouth, PO1 2DY, UK

Nutrients biochemical cycles have been scarcely studied in acidic environments. Understanding nutrient sources and fluxes in these systems is essential for comprehending microbial dynamics, structure and function in such environments as well as their influence on mineral dissolution during bioleaching. Recent studies have demonstrated that nutrient availability shapes the microbial community composition of acidic metal-mine pit lakes and affects performance during bioleaching at laboratory scale experiments [1–3]. Phosphorus is considered the main limiting nutrient in acidic metal-mine pit lakes while nitrogen is the limiting nutrient in bioleaching. To understand this process; first, we need to examine phosphorus and nitrogen sources and sinks. In both acidic metal-mine pit lakes and bioleaching systems, phosphorus sources are primarily controlled by the host rock composition and the ore being leached; in both cases, phosphorus containing minerals (e.g., apatite, clay) tend to leach due to the acidic conditions. Nitrogen containing minerals are uncommon and while the main source of nitrogen source is biological (e.g., organic matter degradation) or chemical (e.g. atmospheric deposition) in acidic lakes, in bioleaching system nitrogen is added as ammonium sulfate. Examining these nutrient sinks, phosphorus in acidic metal-mine pit lakes is adsorbed in Fe(III)-minerals (schwertmannite, jarosite) in the oxic waters, similarly to what happens in bioleaching systems [1]. Nitrogen sinks in acidic lakes is not well-studied, however, they may be similar to bioleaching systems where ammonium adsorbs to jarosite when the right condition occurs (e.g., high Fe(III) concentration and high temperature). Both nutrients are limiting depending on the environment. Phosphorus is the limiting nutrient in the photic oxic waters where there is high concentration of Fe(III) possibly produced by microbial and chemical activity and sequesters phosphorus as phosphate. While nitrogen is the main limiting nutrient in bioleaching as shown by Falagán et al. [2] and Hubau et al. [3] where limiting ammonium addition affected negatively bioleaching performance. Although we are starting to understand how nutrient availability affect microbial communities in acidic environments there are still gaps that needs to be addressed as this has implications for bioleaching and bioremediation. Falagán et al. [2] suggest that only ammonium is necessary for the bioleaching of mineralogically-rich ores where other nutrients such as phosphate are available. Sánchez-España et al., [1] suggest that phosphorus addition to the metal mine lakes may cause an increase in microalgal growth which serves as organic carbon source for metals sequestering bacterial metabolisms in acidic-metal mine lakes. A better understanding on the nutrient biogeochemical cycles in acidic environments will provide an invaluable knowledge for the improvement of bioleaching systems and for the development bioremediation strategies of acidic metal-polluted waters.

References:

1. Sánchez-España J et al. (2025). Minerals 19;15(11).
2. Falagán C et al. (2024). Front Microbiol 17;15:1359991.
3. Hubau A et al. (2024). Waste Biomass Valor 15(2):2.

Mineralogical and metagenomic evidence for enhanced REE cycling in a granitic saprolite soil microbiome

Moreau, J.W.[1], Voutsinos, M.Y.[2] and Banfield, J.F.[2,3]

[1]School of Geographical and Earth Sciences, University of Glasgow, john.moreau@gla.ac.uk
[2]Department of Microbiology, Monash University
[3]Department of Earth and Planetary Science, University of California-Berkeley

---

Rare earth elements (REEs,'lanthanides') comprise a critical mineral resource for modern "green" technology. Although they are called "rare", REEs actually comprise major constituents of phosphate minerals formed during granite weathering; these phases can provide a source of phosphorus for biological needs. The microbes involved in phosphate mineral dissolution and the role of lanthanides in microbial metabolism have been poorly understood to date. Here we used electron microscopy to characterise I-type, S-type and A-type granites with respect to the weathering state of primary REE- and/or P-bearing minerals [1]. We found evidence for enhanced mobilisation of REE and P in weathered I-type and A-type granites in contrast to S-types, consistent with the higher solubilities of apatite and allanite relative to monazite. Although monazite persisted in highly weathered S-type granites, some alteration textures were still observed. Secondary REE/P-bearing crystals were abundant even in the slightly weathered I-type and A-type granites, yet were not detected in highly weathered samples, indicating that these minerals had been dissolved. We also subsampled weathered granites and associated soils to characterise the soil microbiome for the purpose of identifying phyla potentially involved in REE biogeochemical cycling [2]. From moderately weathered granitic soil, we recovered 136 reasonably high quality genomes from 11 bacterial phyla and detected *xox* biosynthetic gene clusters implicated in lanthanide-based metabolism of methanol [3], including *xoxF3* systems from Verrucomicrobia, Acidobacteria, Gemmatimonadetes and Alphaproteobacteria. These gene clusters include relatively novel conserved hypothetical proteins and transporters. Given the strong chemical affinity required to bind lanthanides, we speculate that putative metallophore biosynthesis systems linked to carbonic acid production may be synergistically enhancing soil formation in granitic terrains.

References:
[1] Voutsinos MY, Banfield JF, Moreau JW., 2021. Secondary lanthanide phosphate mineralisation in weathering profiles of I- S-and A-type granites. Mineralogical Magazine 85(1):82–93.
[2] Voutsinos, M.Y., West-Roberts, J.A., Sachdeva, R., Moreau, J.W. and Banfield, J.F., 2024. Weathered granites and soils harbour microbes with lanthanide-dependent methylotrophic enzymes. BMC Biology, 22(1):41.
[3] Keltjens JT, Pol A, Reimann J, Op den Camp HJM., 2014. PQQ-dependent methanol dehydrogenases: rare-earth elements make a difference. Applied Microbiology and Biotechnology 98:6163–83.

Nanoparticles and bacterial mediation in the mobilisation of toxic critical metals: implications for tellurium and cobalt cycling

Mills, S.J.[1], Missen, O.P.[2], Villalobos-Portillo, E.[3] and Brugger, J.[4]

[1]Gallery of Natural Art, Richardson, TX 75083, USA
[2]Centre for Ore Deposit and Earth Sciences, University of Tasmania, Hobart, Australia.
[3]ALBA, Carrer de la Llum 2-26, 08290 Barcelona, Spain
[4]School of Earth, Atmosphere and Environment, 9 Rainforest Walk, Monash University, Clayton 3800, Victoria, Australia

---

The environmental behaviour of critical raw materials is commonly interpreted through bulk geochemistry, yet our work demonstrates that nanoscale processes fundamentally control the mobility of tellurium (Te) and cobalt (Co) in surface environments. These elements, both toxic in soluble forms and increasingly essential for modern technologies, undergo dynamic cycling mediated by nanoparticle formation and microbial redox transformations.

Field investigation of the outcropping, highly Te-enriched system at Moctezuma, Mexico, shows oxidative dissolution of native tellurium and tellurides coupled with the formation of secondary phases and nanoparticulate Te (Missen *et al.*, 2022a). Elemental Te nanoparticles were detected in regolith using single-particle ICP-MS, including in soils distal to mineralised veins where bulk Te is predominantly present as Te(IV) and Te(VI) associated with Fe (oxyhydr)oxides and clays (Missen *et al.*, 2022b). The presence of reduced Te nanoparticles in oxidised regolith provides direct evidence for active redox cycling and indicates that Te mobility involves repeated transitions between soluble toxic oxyanions and reduced nanoparticulate forms.

Electron microscopy reveals secondary nano-minerals fringing primary hypogene phases, with organic-rich microenvironments hosting abundant Te nanoparticles, consistent with microbially mediated reduction (Missen *et al.*, 2022a). 16S rRNA sequencing demonstrates that Te-enriched soils host diverse bacterial communities including genera capable of metal(loid) tolerance and transformation, supporting a biological driver for Te mobilisation and reprecipitation (Missen *et al.*, 2022a).

Complementary investigation of Co-enriched regolith across multiple Australian deposit types identifies widespread Co–Mn oxide nanoparticles in soils surrounding Co-rich outcrops (Missen *et al.*, 2024). Single-particle ICP-MS and synchrotron analyses demonstrate that cobalt is commonly incorporated into mixed Co-Mn oxide nanoparticles, revealing nanoscale phase formation as a key mechanism governing cobalt dispersion. 16S rRNA sequencing showed *Actinobacteria* rich microbial communities, including heat- and metal-tolerant species were responsible for the mobilization of both Te and Co.

Together, these results show that critical raw metal mobilisation is not governed solely by dissolved speciation, but by bacterially mediated nanoscale phase transitions that create reactive, mobile particulate reservoirs. Since Te and Co are critical components of photovoltaic modules and rechargeable batteries central to the green energy transition, failure to account for nanoparticulate cycling risks underestimating their environmental mobility. The generation and release of reactive metal nanoparticles during weathering of discarded solar panels and battery materials in landfill settings may enhance transport, bioavailability and toxicity, underscoring the need to integrate nanoparticle-scale processes into environmental risk models for critical raw materials.

References:

Missen OP, Etschmann B, Mills SJ et al. (2022a) Geochim Cosmochim Acta 321:265–292
Missen OP, Lausberg ER, Brugger J et al. (2022b) J Hazard Mater Lett 3:100053
Missen OP, Mills SJ, Moro TT et al. (2024) Environ Chem 21:EN23093

Leveraging Microbe-Driven Geochemical Cycles to Enable Sustainable Critical Mineral Recovery

Watkin, E.[1,3], Khaleque, H.[1], Van Alin, A.[2,3]

[1] School of Science, Edith Cowan University, Perth, Australia. E.Watkin@ecu.edu.au
[2] Curtin Medical School, Curtin University, Perth Australia
[3] The Institute for Geoscience Research, School of Earth and Planetary Sciences, Curtin University, Bentley, Western Australia, Australia

---

Rare earth elements (REEs) are essential to modern technologies and the global energy transition, yet their extraction from primary phosphate minerals such as monazite remains environmentally and economically challenging. Biohydrometallurgy offers a sustainable alternative by harnessing **microbially mediated biogeochemical processes** that operate across natural mineral environments and engineered bioleaching systems. The application of phosphate-solubilising microorganisms (PSMs) that release REEs through organic-acid-driven acidolysis, and the complementary mechanism of **complexolysis** has been explored [1].

At the ecosystem scale, the native microbiome of monazite ores, such as those at Mount Weld (Western Australia), interacts dynamically with introduced PSMs, producing synergistic effects on REE mobilisation [2]. These interactions reflect the importance of natural **biogeochemical cycles**, especially those governing phosphate availability: phosphate depletion in solution thermodynamically promotes monazite dissolution, while low phosphate concentrations trigger microbial solubilisation pathways. Such feedback between microbial metabolism, mineral surfaces, and solution chemistry underpin REE cycling in natural ore systems and inform the design of more effective engineered processes.

Parallel developments in genetics, molecular biology, and biochemistry have transformed bioleaching from an empirical practice into a **predictable engineered biogeochemical technology**. Omics-driven studies have elucidated the enzymatic pathways for phosphate solubilisation, acid generation, and stress response, revealing regulatory networks that enable PSMs to function under extreme conditions typical of heaps, reactors, and mine-waste environments [3]. These mechanistic insights now guide microbial selection, and process optimisation, enabling more robust and selective REE extraction across diverse mineral settings.

Collectively, these integrated findings demonstrate that coupling microbial metabolism to **mineral-associated geochemical cycles** provides a powerful and sustainable framework for REE extraction and aligns with circular-economy strategies aimed at reducing the environmental footprint of critical mineral supply chains.

References:
Corbett M et al (2017) Bioprocess and Biosystems Engineering. 40:929-942
Corbett M et al (2018) Research in Microbiology 169:558-568.
Fathollahzadeh H et al (2019) Applied Microbiology and Biotechnology 103:1043-1057

Back to table of contents

GEORGE BROWN LECTURE

Clay-Based Stimuli-Responsive Materials: A Versatile Platform for Smart Functional Systems

Jocelyne Brendlé

Institut de Science des Matériaux de Mulhouse CNRS UMR 7361, Université de Haute-Alsace, Université de Strasbourg, 3b rue A. Werner, Mulhouse Cedex, France

---

Clay-based stimuli-responsive materials constitute a versatile class of hybrid systems designed to undergo controlled physicochemical changes in response to external or internal stimuli, including pH, temperature, ionic strength, redox potential, and light. By combining clay minerals with polymers, surfactants, nanoparticles, or bioactive molecules, hierarchical architectures can be engineered with tailored transport, swelling, degradation, and release properties. The development of such systems relies on a careful balance between composition, interfacial interactions, and microstructural control. Their performance is strongly governed by clay dispersion, surface functionalization, swelling behavior, diffusion pathways, and responsiveness to targeted stimuli. In this context, advanced structural and physicochemical characterization is essential to establish robust relationships between formulation, organization, and functional properties.

Among the most active application domains, drug delivery occupies a central place. Clay-based carriers can enhance drug loading, protect sensitive active compounds, and enable controlled or stimuli-triggered release under specific physiological conditions, particularly for site-specific delivery. In parallel, these materials are gaining increasing interest in environmental applications, including pollutant adsorption, selective contaminant capture, and stimuli-triggered remediation. Their ability to integrate recognition, transport regulation, and adaptive response makes them promising candidates for next-generation treatment systems. Beyond these areas, clay-based stimuli-responsive materials are also being explored in other fields such as agriculture, where they can serve as carriers for fertilizers or pesticides, enabling controlled release and improved resource efficiency while reducing environmental impact. Furthermore, their integration with conductive polymers or nanoparticles opens new perspectives in sensing and soft electronics, contributing to the development of responsive devices capable of real-time environmental monitoring.

Following a general introduction to stimuli-responsive materials and their significance in advanced material design, this lecture will address the main preparative strategies for clay-based hybrid systems, with particular attention to scalability, reproducibility, and environmental sustainability. Emphasis will be placed on the development of eco-friendly and resource-efficient processing routes in line with green chemistry principles. Special focus will be given to elucidating interactions between clay minerals and molecules of interest, as well as the structure–property relationships governing system behavior. The lecture will conclude by highlighting key scientific and technological challenges that must be addressed to enable the sustainable development and practical implementation of these materials.

Evaluating Disposal of Plutonium Wasteforms

Chen, L.[1], Mason, A.[2], Pepper, S.[2], Waters, S.[1], Corkhill, C.L. [1]

[1] School of Earth Science, The University of Bristol, Wills Memorial Building, Queens Road, Bristol, UK, lena.chen@bristol.ac.uk
[2]Department of Materials Science and Engineering, University of Sheffield, Mappin Street, Sheffield, UK

Reprocessing of spent nuclear fuel in the UK has resulted in the production of ~140 tonnes of PuO_2, which, according to current strategy, will be immobilised in a form suitable for a Geological Disposal Facility (GDF) [1]. Understanding the long-term behaviour of this wasteform upon the eventual breach in the engineered barrier system is therefore crucial. This study investigates the leaching behaviour of two candidate ceramic wasteforms for Pu immobilisation: Disposal Mixed Oxide (DMOX) UO_2, zirconolite [(Ca,U,Gd)(Zr,U, Gd,Hf)$(Ti,Fe)_2O_7$]. A semi-dynamic leaching test based on the American Society for Testing and Materials (ASTM) C1308 method [2] was employed to assess their leaching behaviour over the course of one year. The tests were conducted at three different temperatures: 40, 60, and 90°C, and in three distinct solutions: 0.01M HNO_3, 19mM NaCl + 1mM $NaHCO_3$, and 11mM LiCl + 10mM LiOH. Dissolution rates of plutonium, using U and Th as surrogates, and neutron-absorbers, Gd and Hf, were determined. In addition, by assessing trends in other elements (Ca, Fe, Ti) under different temperatures and solutions we gain qualitative insights into the dissolution behaviour of these materials. The activation energies for dissolution were calculated by comparing the dissolution rates at different temperatures, and the experimental data was modelled to further elucidate the mechanisms governing dissolution for each wasteform. Post-leaching surface characterisation of the pellets was carried out using focused ion beam scanning electron microscopy (FIB-SEM), Transmission Kikuchi diffraction (TKD) and X-ray photoelectron spectroscopy (XPS). Overall, this investigation provides key underpinning data of the dissolution behaviour of these ceramic wasteforms under different environmental conditions, offering valuable insights into their long-term stability in a GDF.

References:
[1] Department for Energy Security and Net Zero, Plutonium Disposition Strategy, (2025)
[2] ASTM International, Standard Test Method for Accelerated Leach Test for Measuring Contaminant Releases From Solidified Waste, C1308-21, (2021)

Fate of disposal relevant UO_3 and U_3O_8 in a phosphate cement backfill

Margreiter, R.[1], Neill, T.[1], Shaw, S.[1], Bower, W.[2], Morris, K.[1]

[1]Radioactive waste Disposal and Environmental Remediation National Nuclear User Facility and Williamson Research Facility, Department of Earth and Environmental Sciences, The University of Manchester; Raphael.Margreiter@postgrad.manchester.ac.uk
[2]Nuclear Waste Services (NWS), Harwell, United Kingdom

Deep geological disposal is the internationally favoured option for the safe disposal of high and intermediate level radioactive wastes. In a deep Geological Disposal Facility (GDF), packaged wasteforms will be disposed at depths between 200 - 1000 m and isolated from the environment through a multi-barrier system of natural and engineered barriers. One such engineered barrier is the backfill material, used to fill voids between the waste packages and the host rock. One of the prospective functions of the backfill is limiting the solubility of radionuclides present in the wastes by chemical conditioning [1].

With an estimated 184,000 m³ of packaged depleted, natural and low-enriched uranium (DNLEU) in the UK waste inventory, understanding and optimising the fate of uranium, notably in terms of immobilisation within GDF relevant conditions, is important to underpin DNLEU disposal options. Candidate materials for DNLEU backfill are magnesium potassium phosphate cements (MKPC), novel phosphate cement systems with a crystalline struvite-K ($MgKPO_4 \cdot 6H_2O$) network as the main binder phase. MKPC has promising engineering properties, is expected to generate a lower pH environment compared to typical Portland cement based backfill and will chemically condition the disposal environment with phosphate [2]. Uranium and other radionuclides are known to form highly insoluble phosphate phases that may further retard radionuclide transport in the disposal environment [3].

The research presented here focuses on the effects of leaching on both the cement system and the groundwater, including phase transformations of struvite-K to hazenite ($KNaMg_2(PO_4)_2 \cdot 14H_2O$) and hydroxyapatite ($Ca_5(PO_4)_3OH$), and the equilibrium concentrations of various metals and anions in the leachate. We then explore the precipitation of $U(VI)_{(aq)}$ spiked into the MKPC leachates as both insoluble uranyl silicate and uranyl phosphates phases through a multi-technique approach (e.g. diffraction techniques, electron microscopy and thermodynamic modelling). Finally, we present ongoing research on the fate of disposal relevant uranium oxides (UO_3, U_3O_8) in the MKPC-leachate system, including phase transformations, surface changes, and sorption behaviour.

References:

[1] NDA (2016). Geological Disposal. DSSC/421/01.
[2] Wagh, A.S. (2016). Chemically bonded phosphate ceramics, Elsevier.
[3] Fuller, C.C., et al. (2002). Environ Sci Technol 36, 158–65.

Highly Anisotropic Engineered Minerals – A Treasure Trove of Industrial Applications

Shafran, K.[1]

[1]BYK Additives Ltd., Moorfield Road, Widnes, WA8 3AA, United Kingdom, email: kirill.shafran@altana.com

Highly anisotropic materials, whose chemical and physical properties vary with direction, represent a distinctive and technologically critical class of engineered minerals. Anisotropy may arise from atomic-scale bonding asymmetry or from the external morphology of primary particles. In such materials, mechanical, optical, thermal, and electrical properties depend strongly on crystallographic or structural direction. Platelets, rods, fibres, and other non-equant particle shapes give rise to direction-dependent behaviour that can be exploited in applications ranging from rheology control and polymer reinforcement to surface modification and barrier technologies [1,2].

BYK is a global manufacturer of engineered minerals and additives, with a long history of developing materials exhibiting pronounced one- and two-dimensional anisotropy. Its portfolio includes highly refined and organo-modified clays, acid-activated and synthetic smectites, and mixed minerals designed to combine different anisotropic building blocks within a single engineered structure. Together, these materials enable performance tuning across paints and coatings, adhesives and sealants, polymer composites, cosmetics and personal care, ceramics, and energy-related technologies.

To fully exploit mineral anisotropy, three elements are essential: accurate measurement of anisotropy, mechanistic understanding of anisotropic growth, and process-level control to promote or preserve the desired anisotropic character. At BYK, atomic force microscopy and scanning electron microscopy are used to quantify lateral dimensions, thickness, and aspect ratios of anisotropic particles, allowing direct links between structure and function to be established. Mineral growth pathways can be interpreted through classical nucleation and growth as well as non-classical mechanisms such as oriented and semi-oriented attachment, which are increasingly recognised as key routes to forming high-aspect-ratio particles [3].

These principles are illustrated by examples showing how platelet size in two-dimensional minerals governs application performance. Very small synthetic smectite platelets form transparent colloidal dispersions with exceptional rheological tunability, while mid-sized platelets are particularly effective in clay-polymer composites, promoting intercalation and exfoliation. At the high-aspect-ratio end, large layered silicates exhibit strong platelet alignment, enabling excellent gas-barrier performance in coatings and functional films [4]. Collectively, these examples demonstrate how anisotropy, when intentionally measured, understood, and controlled, becomes a powerful design tool for next-generation engineered minerals.

References

[1] Nye J.F. (1985) Physical Properties of Crystals. Oxford University Press, Oxford.
[2] Bergaya F., Theng B.K.G. and Lagaly G. (2006) Handbook of Clay Science. Elsevier, Amsterdam.
[3] Cölfen H. and Antonietti M. (2005) Angew. Chem. Int. Ed. 44, 5576–5591.
[4] Kalo H. *et. al*. (2012) Nanoscale, 5633-5639.

Can engineered minerals significantly slow global warming? An example where this could be the case

Hochella Jr., M.F.[1], and Babakhani, P.[2]

[1]Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA. hochella@vt.edu
[2]School of Engineering, University of Manchester, Manchester, M13 9PL, UK.
peyman.babakhani@manchester.ac.uk

Since 1850, the 10 warmest years have all occurred in the last decade, and Earth is already at 1.35° C warmer relative to pre-industrial levels. Globally, it is now realized that our dangerously warming planet is far from having these trends reversed without massive and affordable CO_2 removal from the atmosphere in the relatively near future. This is despite important and often successful attempts to begin to reign in CO_2 emissions, to expand solar and wind energy even ahead of expectations, and to greatly improve machine and grid efficiencies. On the other hand, the oceans already absorb between a quarter and a third of the CO_2 that humans put into the atmosphere each year. The CO_2 ends up dissolved in seawater, some taken up by phytoplankton, which is partly stored as biomass in the deep ocean for decades to millennia.

Ocean experiments in the past have already shown that small amounts of iron distributed in parts of the oceans that lack sufficient nutrients, and therefore have low phytoplankton populations, can be stimulated, resulting in more photosynthesis, and therefore more CO_2 uptake [1]. However, these original in situ experiments were rudimentary and many more are needed to refine the process, with the intent to duplicate nature as closely as possible and to keep the oceans in a healthy, balanced state. We describe in this talk ways that, in principle, engineered "mineral" nanoparticles are designed to stimulate efficient phytoplankton population growth and warming ocean tolerance, and to enhance phytoplankton aggregation and sinking so that a significant amount of biomass can reach ocean depths that will result in durable carbon storage [2]. Modern nanotechnology could show the way to making ocean fertilization a reasonable and affordable way to sequester a substantial amount of atmospheric CO_2 per year, significantly and affordably slowing global warming.

The above is a very good example of mineralogists moving well beyond traditional mineralogical studies to pragmatic applications of our science, gaining 21st century relevance and solutions to environmentally and exceptionally challenging problems. This includes applying our knowledge to incidental and engineered materials, including organic and biogeochemical aspects that have global consequences as shown by the example described here. With truly significant applications in these areas, the science of mineralogy could be revitalized.

References:
[1] Buesseler KO, et al. (2024) Frontiers in Climate 6:1430957
[2] Babakhani P., et al. (2022) Nature Nanotechnology https://doi.org/10.1038/s41565-022-01226-w

Mechanical amorphisation of minerals in clay-based mining wastes for the production of low-carbon cements

Dresch, L. [1], Marsh, A.T.M. [2], Bejjarapu, D.S. [2], Neumann, A.[3], Scrivener, K.L. [2], Matos, P.R.[1]

[1] Department of Civil Engineering, Federal University of Santa Catarina, Brazil
[2] Laboratory of Construction Materials, Swiss Federal Institute of Technology Lausanne, Switzerland
[3] Paul Scherrer Institute, Switzerland

Cement is essential for the development and maintenance of our built environment, but the manufacture of cement clinker releases CO_2 from the decomposition of limestone. To reduce the carbon emissions of the sector, cement is increasingly replaced with 'supplementary cementitious materials' to produce blended cements. Supplementary cementitious materials are typically silicate, aluminosilicate or calcium aluminosilicate minerals which can undergo dissolution and participate in hydration product formation, when mixed with cement clinker and water. The faster these minerals undergo dissolution in the alkaline pore solution of a cement mix, the more cement can be replaced. Processing treatments which can increase the reactivity of minerals can therefore help reduce the embodied carbon of cement.

In this study, we investigated intensive grinding as a route to partially amorphise minerals commonly found in clay-based mining wastes in Brazil: kaolinite, quartz, goethite and hematite. Using a variety of characterisation techniques, we tracked the change in physical and structural characteristics after intensive grinding. We then compared this to the change in the ground minerals' dissolution behaviours in a simulated cementitious system, and in a real blended cement paste. The partial amorphization of aluminosilicates and silicates increases their dissolution rate, as expected. Whilst the degree of dissolution of the intensively ground iron oxides/(oxy)hydroxides seemed negligible, they nonetheless exerted a clear influence on the hydration of blended cement pastes. We suggest reasons for this surprising result, and explain the implications for the industrial adoption of this novel processing route in the cement sector.

Towards growing and engineering minerals using bacteria: high-throughput approaches to decoding biomineralization

Cosmidis J[1*], Stigliano L[1], Rehmanji M[1]

[1]Department of Earth Sciences, University of Oxford, South Park Road, Oxford OX1 3AN, UK
*Email: Julie.cosmidis@earth.ox.ac.uk

Biomineralization — the capacity to form minerals — has evolved across a great diversity of bacterial lineages as an adaptation to varied environmental conditions and biological functions. Microbial biominerals often display original properties (e.g., morphology, composition, structure, association with organics) that significantly differ from those of abiotically formed counterparts, altogether defining a unique "mineral phenotype". While it is theoretically possible to leverage microbial biomineralization processes to design and biomanufacture advanced mineral materials for a range of technological applications such as catalysis, battery materials, or sustainable construction, our ability to do so is currently limited by a poor understanding of the underlying molecular and genetic mechanisms controlling these pathways [1]. Our limited understanding of the determinants of the mineral phenotype is preventing us from developing bioengineering strategies aiming at optimizing biomineral properties for different applications.

I will discuss how we are overcoming these limitations through the development of new in-situ, high-throughput mineral characterization techniques based on automated microscopy and Raman spectroscopy. These platforms allow us to rapidly perform and characterize hundreds to thousands of microbial biomineralization experiments simultaneously. I will show how these techniques are deployed to systematically explore the environmental controls of mineral phenotypes. This high-throughput approach also provides a powerful tool for screening mutant libraries of biomineralizing bacteria, enabling the discovery of new genes controlling biomineralization. Altogether, these methodologies provide the necessary framework for the rational design of biosynthesized minerals, moving us closer to a future where advanced mineral materials are grown rather than synthesized.

References:
[1] Cosmidis J (2023) Microbial Biotechnology 16: 1713-1722

Mineralogy of high-temperature aircraft engine deposits

Pawley, A.R.[1], Dowling, J.[1], Ownsworth, E.[1], Liu, Y.[1], Covey-Crump, S.J.[1] and Jones M.A.[1]

[1]Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK
alison.pawley@manchester.ac.uk

The gas turbine engines that power modern civil aeroplanes provide an unexpected setting for a range of interesting high-temperature minerals to form. These high-temperature minerals form when the aircraft fly through dusty air and mineral particles are ingested into the engine. The particles travel with the air flow, either through the hot core of the engine or through the secondary air system (SAS) used to cool the hot components. Particles in the core air are heated to very high temperatures (1400-2000 °C) in the combustor, and then may deposit on the aerofoil of high-pressure turbine (HPT) blades, where gas temperatures are around 1200-1400 °C during routine operation. Particles in the SAS that deposit on cooler surfaces of HPT blades may be heated to temperatures up to 800 °C. Knowledge of the chemical compositions and mineralogy of the deposits from these two locations is important for mitigating the risks of engine component degradation. The mineralogy also provides insights into the chemical and thermal stability of the various minerals that form inside the engine.

We have obtained X-ray diffraction data and scanning- and transmission-electron microscope images and chemical maps for deposits from the SAS (cooler) and from the aerofoil (hotter) of HPT blades from engines that have flown in dusty regions of the world. The dust they ingested is likely to have contained common minerals such as quartz, feldspar, calcite, dolomite, gypsum and clay minerals. Our data shows that the temperatures in the SAS deposits are high enough that no clay or dolomite remains and calcite is rare. Gypsum has dehydrated to anhydrite. New minerals include diopside and melilite, the latter close in composition to alumoakermanite [$(Ca,Na)_2(Mg,Al)Si_2O_7$]. The small number of phases in most SAS deposits, together with the euhedral habit of many of the crystals, suggests that the deposits have mostly equilibrated.

The aerofoil deposits also contain melilite, but in this case it is Na-free, with compositions close to a gehlenite ($Ca_2Al_2SiO_7$)-åkermanite ($Ca_2MgSi_2O_7$) solid solution with a small component of ferrigehlenite ($Ca_2Fe^{3+}{}_2SiO_7$). Melilite is the most abundant phase in most deposits. Other new phases contain metals whose source is abradable material within the engine, including Ti-bearing perovskite and Ni-bearing spinel. Of particular interest, owing to its unusual composition, is a garnet that contains both Ti and Zr, the latter coming from the yttria-stabilised zirconia that forms a thermal barrier coating (TBC) on the HPT blade. This garnet is a solid solution between a schorlomite-group garnet and andradite. The schorlomite group of garnets is distinguished by having Ti^{4+} or Zr^{4+} in the octahedral site instead of the usual Al^{3+}, charge-balanced by Al^{3+} and Fe^{3+} substituting for Si^{4+} in the tetrahedral site. They occur naturally in skarns.

Some of the aerofoil deposits are layered, reflecting both chemical gradients arising from the interaction between deposit and underlying TBC, and thermal gradients arising from the competition between heating from the hot gas above and cooling by SAS air below. Current thermodynamic databases are not able to model the complex reactions that produce the unusual phases that we see. Therefore, experiments will be required to determine their stability as a function of temperature and bulk composition and to investigate reaction kinetics. These will enable us to further understand the chemical and thermal evolution of high-temperature engine deposits. These deposits are becoming more of an issue in the aviation industry as both the drive for greater efficiency leads to hotter-running engines, and climate change leads to changing dust levels in the atmosphere.

Metamorphism – a perspective on progress since the Mineralogical Society centenary

Yardley, B.W.D.

School of Earth, Environment and Sustainability, University of Leeds, Leeds LS2 9JT, UK.
b.w.d.yardley@leeds.ac/uk

Fifty years ago, the study of metamorphism was a growing speciality which was in the process of transitioning from largely observational studies to a quantitative science. The arrival of the electron microprobe in the 1960s had revolutionised mineral analysis and opened the way to determining pressures (P) and temperatures (T) of metamorphism. Experimental petrology had progressed since the 1950s to the point where metamorphic equilibria could be bracketed reproducibly over much of the crustal P-T range. Already, Helgeson's group had produced the first internally consistent thermodynamic data set for metamorphism, so that the stage was set for the emergence of computational geothermometry - geobarometry as we know it today.

Plate tectonics was still a new field, not universally accepted, but as it became obvious that different tectonic settings were characterised by different P/T characteristics, metamorphic petrology was starting to be used to assign tectonic environments to components of orogenic belts. It became apparent that old orogenic belts contained signatures of different settings and ages, but samples for many dating methods were large and the ages often imprecise. Since then, the development of ever more sensitive analytical techniques has revolutionised metamorphic geochronology.

There was also a revolution taking place in the study of metamorphic textures and processes as concepts from materials science were applied to metamorphic rocks. Textures provided relative times of growth of minerals and deformation, but it took a long time to appreciate that the limit to the application of material science to geology is provided by water. There are many mechanisms which are impossible, or absurdly slow, in the dry environment of a materials laboratory, but which become dominant in the presence of water. Geochemists were focussed on fluid composition, which in the 1970s meant where it sat between H_2O and CO_2. Understanding mixed-volatile equilibria revolutionised the study of calc-silicate reactions but ushered in an era when any evidence of deviation from a pure water fluid was interpreted as evidence of the presence of carbon dioxide. Only latterly has the likely presence of salts and their influence on water activity been considered.

Mass transfer in metamorphism was also a concern 50 years ago, and, despite the seminal work of Korzhinski in the middle of the last century, it remains poorly understood. We have failed to integrate principles from hydrogeology into metamorphic studies and as a result "metamorphic fluid flow" has often been contrived to navigate around flawed assumptions, rather than deduced from direct evidence. Even the distinction between diffusion and advection is not well understood in metamorphism and the potential for rock matrix diffusion is not yet appreciated. Similarly, metamorphic kinetics still has potential for significant advances, even though it was already being flagged as the next frontier 50 years ago.

Metamorphic geologists have done a remarkable job over the past 50 years but arguably are victims of their own success. The ability to quantify pressure, temperature and time has had a massive impact on our understanding of orogenic belts, but there is more to metamorphism awaiting investigation. When it comes to understanding metamorphic processes and their rates, there are enough uncertainties and challenges to employ metamorphic petrologists for another half century.

Cratonic serpentinization: new nanoscale insights into the role of spinel and fluids in hydrogen production

Fanesi, E.[1], Brooker, R.A.[1], Clark, S. M.[2], Liu, X.[3], Koemets, E.[3], Kleppe, A. K.[3] and Lord, O. T.[1]

[1] School of Earth Sciences, University of Bristol, Queens Rd, Bristol BS8 1RJ, United Kingdom
[2] School of Engineering, Macquarie University, Rm 236, 3 Management Drive, Macquarie Park, NSW 2109, Australia
[3] Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot OX11 0DE, UK
Corresponding author: Emanuele Fanesi (emanuele.fanesi@bristol.ac.uk)

Natural hydrogen is increasingly recognized as a promising low-carbon fuel for the ongoing energy transition [1]. Surface occurrences of H_2 above cratons suggest that ancient, tectonically stable lithosphere might be hosting hydrogen-producing reactions [2], [3]. Among these, serpentinization is a well-known naturally occurring reaction able to produce molecular hydrogen as a byproduct of the hydrothermal alteration of olivine into serpentine. However, previous studies have mainly characterized serpentinization reactions in oceanic and subducting environments, without addressing cratonic conditions.

We conducted piston-cylinder experiments at 1.3 GPa, 450°C, conditions relevant to the Slave craton [4], reacting olivine ± spinel with alkali-rich brines to investigate how mineralogy, fluid composition, and cratonic P-T conditions control serpentinization kinetics and H_2 generation. Results show slower reaction rates under cratonic P-T conditions compared to oceanic settings, likely due to the inhibitory effect of temperature, with negligible differences between K- and Na-rich fluids. In contrast, spinel dramatically accelerates kinetics, with reaction rates correlating to Al availability from spinel dissolution. Ongoing nano-Fourier transform infrared spectroscopy (nano-FTIR) and transmission electron microscopy (TEM) characterization of reaction interfaces is revealing how olivine hydration, spinel alteration, and fluid-mineral interactions operate at the nanoscale to influence reaction pathways and hydrogen yields.

This multi-scale approach demonstrates that, although cratonic serpentinization proceeds slower than in oceanic environments, it remains extremely rapid on geological timescales, suggesting that where sufficient water is present, cratons can significantly contribute to the continental natural hydrogen budget, potentially linking to surface H_2 occurrences.

References:
[1] International Energy Agency (2023), www.iea.org
[2] O. Maiga et al. (2023), *Sci. Rep.*, 13(11876).
[3] V. Zgonnik (2020), *Earth. Sci. Rev.*, 203(103140).
[4] D. Hasterok and D. S. Chapman (2011), *Earth Planet. Sci. Lett.*, 307(1–2), 59–70.

Komatiite-peridotite interaction and Mg/Si systematics in the Archaean mantle

Tomlinson, E.L.[1], Rodrigues, R.F.[1,2], Melai, C.[1], Kamber, B.S.[3], Kaekane, B.K.[1] and Piazolo, S.[4]

[1] Geology, School of Natural Sciences, Trinity College Dublin, Dublin, Ireland
[2] Research School of Earth Sciences, Australian National University, Canberra, Australia
[3] School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane, Australia
[4] School of Earth and Environment and Sustainability, University of Leeds, Leeds, United Kingdom

---

The cratonic lithospheric mantle is dominated by highly refractory harzburgite and is widely considered to have formed as the residue after extensive mantle melting. Komatiites are ultramafic volcanic rocks that predominantly erupted during the Archaean and require advanced mantle melting, observations that appear to complement the highly refractory nature of the cratonic lithosphere. However, peridotite xenoliths from the cratonic lithosphere have variable MgO/SiO_2, often extending to higher or lower silica contents than those produced by batch melting of fertile peridotite [1]. Komatiites also exhibit MgO/SiO_2 variability, even after accounting for shallow olivine fractionation, and span a wider range of MgO/SiO_2 and Al_2O_3/TiO_2 than ultramafic melts produced by batch melting of fertile komatiite [2]. In addition, Al-undepleted komatiites require garnet in their residues, while their rare earth element (REE) patterns predict the absence of garnet [3]. The picture is further complicated by radiogenic isotopes; cratonic peridotites have non-chondritic Hf isotope compositions that point to a complex and protracted melting history, while komatiites have decoupled Hf-Nd isotope systematics with unexpectedly radiogenic Hf- but near-chondritic Nd-isotope compositions (the komatiite paradox) [4]. These observations bely a simple residue-melt relationship and point to role for open system processes, most notably melt-solid interaction. Indeed, microstructural features preserved in coarse-grained cratonic peridotite xenoliths support melt-solid interaction. My original thermodynamic modelling demonstrated that reaction of ascending komatiite with earlier depleted peridotite of the proto-lithosphere may drive the observed compositional variability in both residue and melt [1].

In this keynote presentation, I combine results from thermodynamic and trace-element modelling of natural harzburgite xenoliths and with new reaction experiments at 3-5 GPa and 1450-1690 °C to investigate the effect of komatiite-peridotite interaction on the mineralogy and composition of the Archaean lithosphere. Our work shows that pyroxene consumption and olivine precipitation in the hotter part of the experimental cell produce dunite and drive the melt towards more silica-rich compositions. This, in turn, leads to the precipitation of orthopyroxene from the melt, producing low MgO/SiO_2 harzburgite that resembles natural silica-rich peridotites. Experimental and thermodynamically modelled melts from ultramafic melt-solid interaction evolve from modified komatiite with variable MgO/SiO_2 to picrite and basalt with decreasing temperature. Assimilation of early-formed harzburgite modifies the REE and Hf isotope compositions of infiltrating komatiite, providing one possible explanation for the komatiite paradox. Ultramafic mantle metasomatism requires high temperatures only seen in the Archaean, the predominant occurrence of komatiites before 2.5 Ga and the highly refractory nature of the Archaean lithosphere both reflect unique geodynamic settings that were common on the early Earth.

References:

[1] Tomlinson EL and Kamber BS (2021) Nature Comms. 12:1082
[2] Herzberg (2016) J Pet 57:2271-2288
[3] Walter M (1998) J Pet 39:29-60
[4] Blichert-Toft et al. (2015) Am Min 100:2396-2411

Interactions between metamorphism and deformation: some key challenges

Wheeler, J.

[1]Dept. Earth, Ocean and Ecological Sciences, University of Liverpool, johnwh@liverpool.ac.uk

---

Understanding interactions between metamorphism and deformation is key for upscaling models for rock strength (e.g. in orogens and subduction zones) and fluid flow in shear zones with its consequences for metamorphic and economic mineral formation. The link between mineralogy and deformation was recognised more than a century ago [1] and many fundamental feedbacks were identified in the 1970s and 1980s [2]. Despite this, other links remain unclear. At the most fundamental level would be useful to have quantitative links between stress (σ, physics) and chemical potential (chemistry) as the basis for model for feedback but these are controversial. For brevity I focus on the effects of deformation on chemical processes, ignoring the reverse feedback.

There is broad agreement that chemical potential has some sort of σV term in a stressed system, analogous to the PV term in a system under uniform pressure. In various circumstances σ may be

the mean stress (average of the three principal stresses), for example in diffusion in stressed garnet [3]

The normal stress at an interface as evidenced by diverse experiments [4]

The pore fluid pressure regardless of stress in the solid part of a porous medium [5]

These approaches look incompatible but are in fact in accord as they address different microscale situations [6]. Unlike pressure, which is uniform at mechanical equilibrium, stress is usually heterogenous which provides much scope for chemical potential gradients and local chemical transport. Normal stress can vary through a grain boundary network even if stress is homogeneous and drives pressure solution and diffusion creep, intimately linked to metamorphism.

Deformation can also affect chemical potential by introducing dislocations which contribute to "plastic strain energy" but I show this is usually a small number relative to the direct effects of stress. Interface curvature affects chemical potential too, but again the effect is relatively small unless curvature is very tight. So, the direct coupling of stress to chemical potential is a major factor in how deformation affects metamorphism.

Other affects include increasing permeability by grain boundary sliding to allow easy fluid ingress which triggers reactions. This is important but not controversial insofar as Darcy's law would surely be a starting point for modelling. Dislocations can provide fast diffusion pathways within lattices and hence speed up reactions. Cataclasis and recrystallisation can make new interfaces again increasing reactivity. In summary stress and deformation can enhance reaction kinetics but also change local equilibria in ways that are still challenging to quantify.

References:

[1] Teall (1885) 41: 133.
[2] Brodie *et al.*, in *Metamorphic reactions: Kinetics, Textures and Deformation*, A.B. Thompson and D.C. Rubie, Editors. p. 138.
[3] Hess *et al.* (2024) 488-489.
[4] Wheeler CMP (2020) 175: Art. 116.
[5] Llana-Funez *et al.* (2012) 164: 69.
[6] Wheeler JMG (2018) 36: 439.

Grain-scale processes during retrograde transformation of eclogite-facies rocks in W Norway: fluid access and deformation are not strongly coupled

Waters, D.J.[1,2]

[1]University Museum of Natural History, Parks Road, Oxford OX1 3PW
[2]Department of Earth Sciences, South Parks Road, Oxford OX1 3AN; dave.waters@earth.ox.ac.uk

---

Deeply-subducted crustal rocks, such as those now seen at the surface in the Western Gneiss Region of Norway, have experienced extreme pressures at eclogite-facies conditions, have undergone retrogression during exhumation, commonly to amphibolite facies conditions, and may now be exposed at the Earth's surface. As seen in outcrop today, some rocks (such as dry granitoids) may show little record of the subduction experience, others (such as metabasic units) may have developed eclogite-facies mineral assemblages, but the majority tend to show partial or complete retrogression to lower-pressure assemblages, commonly of the amphibolite facies.

The transformation of eclogite to amphibolite requires addition of aqueous fluid, and the process is commonly assisted by deformation. This contribution examines the grain-boundary-scale processes at work during these transformations. I shall demonstrate and contrast the processes of fracture permeability relative to fluid access along grain boundaries, and show a variety of microstructures that imply that fluid access and deformation are not strongly coupled in many rock types, revealing a wide range of behaviours.

Most of the examples are taken from outcrop suites studied by Alice L. Wain (d. May 2000, aged 27), at Otnheim and Drage on Stadlandet, West Norway, where mafic, felsic and metasedimentary rocks occur together, and deformation is heterogeneous. The sample collection assembled in the 1990s contains more than 1500 thin sections, and constituted the core of this museum-based petrographic project. The importance of such resources should not be underestimated.

A unique sixty-million-year record of low temperature fluid metasomatism in oceanic lithosphere

Carter, E.J.[1], Burgess, R.[2] Tartèse, R.[2], Coggon, R.M.[3], and Evans, A.D.[3]

[1]School of Life Sciences, Keele University, Newcastle-under-Lyme, UK. *Email: e.carter2@keele.ac.uk*
[2]Department of Earth and Environmental Science, University of Manchester, UK
[3]School of Ocean and Earth Science, National Oceanography Centre, University of Southampton, UK

Low temperature hydrothermal flow through the upper oceanic crust may last for tens of millions of years and represents one of the largest fluxes of matter and energy on Earth. This leads to the incorporation of volatile elements from seawater (carbon, water, halogens) into the oceanic lithosphere, hosted in secondary minerals such as clays and carbonates. However, there is uncertainty over the magnitude and temporal evolution of this chemical exchange [1,2], leading to uncertainty about the feedbacks between global tectonics and climate. Addressing this has been difficult until recently due to a lack of samples from in situ oceanic crust aged 20-100 Ma. The South Atlantic Transect (IODP Expeditions 390/393) recovered a transect of cores from 7–61 Ma upper oceanic crust, along a single crustal flow line [3]. This unique sample set provides an unparalleled opportunity to understand the timing and chemical fluxes associated with progressive low temperature alteration of the crust.

Halogens are hydrophilic and highly concentrated in seawater making them ideal tracers of fluid-rock interactions. Chlorine, bromine and iodine abundances measured by neutron-irradiation noble gas mass spectrometry indicate significant and ongoing chemical exchange between seawater and slow spread oceanic crust, persisting for at least 60 million years. Highly altered samples from the oldest cores yielded the highest bulk iodine concentrations ever measured in altered oceanic crust (61 ppm). Mass-balance calculations suggest that alteration of the oceanic crust may control the iodine content of seawater unless balanced by changes in other sinks such as buried organic matter. This suggests that the iodine content of seawater may offer insight into the balance between seafloor alteration and biomass burial through geological time.

References:
[1] Evans et al. 2025, EPSL, http://doi.org/10.1016/j.epsl.2024.119116
[2] Coogan et al. 2016, Geology https://doi.org/10.1130/G37212.1
[3] Coggon et al. 2024 Proceeding of the IODP http://doi.org/10.14379/iodp.proc.390393.2024

Uranium speciation in reducing environments: from uraninite to U(IV) complexes with minerals and organics

Boyanov, M.I.[1,2], O'Loughlin, E.J.[2], Kemner, K.M.[2]

[1]Institute of Chemical Engineering, Bulgarian Academy of Sciences, Sofia 1113, Bulgaria
[2]Biosciences Division, Argonne National Laboratory, Lemont, IL 60439, USA

Uranium (U) is a contaminant that emerged from enrichment activities during the Cold War and continues to be accumulated to this day at nuclear power plants. Upon accidental release, the dissolved and mobile U(VI) ions will interact with the minerals and bacteria in the subsurface, where U can be (bio)reduced to less-mobile U(IV) species. Risk assessment and remediation designs have historically been informed by transport models that assume U mobility is controlled solely by the formation/dissolution of the mineral uraninite (UO_2). However, work in the last two decades utilizing synchrotron spectroscopy techniques has shown that U(IV) biogeochemistry is significantly more complex, raising questions about the completeness of existing speciation models that guide policy.

We will present our group's journey through this evolution in understanding of U(IV) biogeochemistry, from the observation of nano-UO_2 precipitation when U(VI) is reduced to U(IV) by the mixed-valence Fe mineral green rust [1], to the initial observations of phosphate-complexed U(IV) species during bioreduction of aqueous U(VI) [2]. While these observations were made in simple, reductionist systems, the results prompted an evaluation of the relevant factors that may influence U(IV) speciation in a complex natural environment. Among them are the availability of mineral surfaces where diverse binding sites or inter-layer spaces (e.g., in clay minerals) can bind or occlude U(IV) ions, or the availability of organic ligands that can complex U(IV) and change its partitioning or redox behaviour. Direct x-ray spectroscopy measurements of U(IV) speciation in sediments from the Savannah River or the Oak Ridge nuclear complexes in the USA showed that U(IV) speciation was ubiquitously 'non-uraninite' [3]. These sediments have been contaminated with U for decades, indicating that the adsorbed or complexed state of U(IV) is the long-term source/sink of U in anoxic subsurface environments. Of the many factors potentially leading to such speciation, we have identified ≡TiO surface groups as strong adsorbing sites for U(IV), both in systems with pure TiO_2 or with Ti-substituted magnetite that is a field-relevant mineral at the Hanford nuclear site [4]. Clay minerals appear to be a weaker adsorbent for U(IV), exhibiting a much lower critical surface coverage above which uraninite precipitation is observed [5]. However, when Fe-containing clay minerals are present together with ligands as in natural systems, ternary U-ligand-mineral interactions enable significant U uptake in the clay as U(IV)-EDTA complexes [6]. The combined presence of ligands (citrate or EDTA) and Fe-containing clays (NAu-2) also has a significant effect on the re-oxidation behaviour of U(IV) in air [7].

Although these studies of increasing complexity have greatly improved our knowledge of U(IV) speciation, further work is needed to fully parametrize the major reactions. Their inclusion in more precise U transport models will ultimately lead to better regulatory and remediation decisions.

References:
[1] O'Loughlin E.J. et al. (2003), Environ. Sci. Technol. 37, 721-727
[2] Fletcher K. et al. (2010) Environ. Sci. Technol. 44, 4705- ; Boyanov et al. (2011) ES&T 45, 8336-
[3] Boyanov et al. (2011) "Uranium Dynamics in Biostimulated Field-Site Sediments: Spatial Distribution and Formation of Non-Uraninite U(IV) Phases" Goldschmidt Conference, August 14-19, 2011, Prague, Czech Republic, p.569; Boyanov et al. (2019) "Uranium Speciation and Dynamics in Contaminated Wetland Sediments" Goldschmidt Conference, August 18-23, 2019, Barcelona, Spain, p.363
[4] Latta D.E. et al. (2013) Environ. Sci. Technol. 47, 4121– ; Latta D. E. et al. (2014) ES&T 48, 1683-
[5] Boyanov M.I. et al. (2017) Chemical Geology 464, 110-117
[6] Zhang L. (2021) Environ.Sci.Technol. 55, 9, 5929–5938
[7] Li R. et al. (2026) " Oxidation of Biogenic U(IV) Mediated by Iron-bearing Clay Minerals, Iron-reducing Bacteria, and Organic Ligands", Environ. Sci. Technol. In review.

Geomicrobiological controls on radionuclide speciation and fate during the geodisposal of radioactive waste

Wort, C.T.[1], Lloyd, J.R.[1], Morris, K.[1] and Shaw, S.[1]

[1]Radioactive Waste Disposal and Environmental Remediation National Nuclear User Facility and Williamson Research Facility, Department of Earth and Environmental Sciences, The University of Manchester, Manchester, M13 9PL U.K.
Christopher.wort@postgrad.manchester.ac.uk

The internationally accepted pathway for management of intermediate and high heat generating radioactive wastes is via deep geological disposal. Building on past work that has identified geomicrobiological processes as potentially significant in radioactive waste disposal [1], this project seeks to define how geomicrobial processes will contribute to the long-term biogeochemical evolution of a Geological Disposal Facility (GDF) in conditions relevant to lower strength sedimentary rocks, and how that impacts radionuclide mobility. This is an interdisciplinary research project combining geomicrobiology, microbial genomics, radiochemistry and mineralogy. Research so far has focused on understanding the microbial ecology native to Oxford Clay, a representative lower strength sedimentary rock of international relevance [2]. Preliminary geochemical and nucleic acid extraction data will be presented exploring the stimulated indigenous microbial communities in Oxford Clay samples. Additionally, the methodology for future work expected during the research project will be discussed. Both batch and dynamic flowthrough systems will be used and interrogated using state of the art techniques including microbial analysis (DNA and culture-based), advanced imaging techniques including Confocal Microscopy, Environmental Scanning Electron Microscopy, Transmission Electron Microscopy, X-ray Absorption Spectroscopy and X-ray Refraction Tomography, alongside geochemical, mineralogical and radiochemical characterisation.

References:
[1] Butterworth, S. J., Barton, F., & Lloyd, J. R. (2023). Extremophilic microbial metabolism and radioactive waste disposal. In Extremophiles (Vol. 27, Issue 3). Springer. https://doi.org/10.1007/s00792-023-01312-4
[2] Sellin, P., Livier, O., & Leupin, X. (2013). THE USE OF CLAY AS AN ENGINEERED BARRIER IN RADIOACTIVE-WASTE MANAGEMENT-A REVIEW. https://doi.org/10.1346/CCMN.2013.0610601

Nano-scale interactions of radionuclides with Lower Strength Sedimentary Rock (LSSR)

Robinson, C.[1], Kravvi, K.[1], Hao, J.[2], Morris, K.[1], Gomez Gonzalez, M.[3] and Shaw, S.[1]

[1]Radioactive Waste Disposal and Environmental Remediation National Nuclear User Facility and Williamson Research Facility, Department of Earth and Environmental Sciences, The University of Manchester, Manchester, M13 9PL, U.K
[2]Depatment of Chemical Engineering, The University of Manchester, M13 9PL, U.K
[3]Diamond Light Source, Diamond House, Harwell Science and Innovation Campus, Didcot OX11 0DE, UK.

Globally, electricity from nuclear power has been generated for over seventy years and this has consequently generated intermediate and high-level radioactive wastes. The internationally accepted solution for this radioactive waste is to dispose of it in a deep Geological Disposal Facility (GDF) emplaced 200 – 1000 m deep in a host rock.[1] Potential candidate rock types for GDF emplacement are Lower Strength Sedimentary Rocks (LSSRs) including both the Oxford Clay (OXC) and Mercia Mudstone Group (MMG) formations are of relevance. To explore the potential for GDF siting within LSSR formations, quantitative understanding of both the radionuclide interactions, and (geo)chemical and mineralogical properties of the host rocks are necessary. Currently, knowledge gaps exist relating to radionuclide interactions with these LSSRs which can have associated high salinity groundwaters. In particular, the mechanistic understanding of radionuclide retention and transport at a range of length scales and under relevant conditions is poorly constrained. This fundamental study is part of NERC and Nuclear Waste Services (NSW) funded 'Towards Safe Geological Disposal of Radioactive Waste in LSSRs (GeoSafe)' project, the objective of which is to understand the potential for radioactive waste disposal in representative LSSRs, building new experimental capability and characterising key processes (e.g. sorption and diffusion) controlling radionuclide transport in these complex systems.

Key processes controlling radionuclide speciation, include sorption to high surface area phases, including clay minerals (e.g. illite) and reduction on the surfaces of redox active phases including sulphides (e.g. pyrite). These processes will occur at the nanoscale within the LSSR pores at the mineral/solution interface. In this study, we used petrographic thin sections to study LSSR-radionuclide interactions at the nanoscale. Thin sections were exposed to synthetic groundwaters[2] doped with ^{238}U/Se and reacted under anaerobic and oxic conditions. The high salinities in the experiments present analytical challenges compared to conventional techniques (e.g. ICP-MS) which we have addressed by methodology development. This includes both advances in analytical method development and developing radiotracer experiments (e.g. ^{233}U) conducted parallel to higher concentration active (e.g. ^{238}U) and stable isotope experiments (e.g. Se). After 2 weeks of exposure the thin sections were analysed using nano-focus X-ray absorption spectroscopy/X-Ray fluorescence (XAS/XRF) at beamline I14 Diamond Light Source, UK. Here, the high-resolution X-ray beam (~50 nm resolution), enabled characterisation of U and Se distribution on OXC and MMG, determining association with the key mineral phases (e.g. pyrite, illite), and speciation of U and Se (nano-XANES mapping). High resolution XRF maps of each thin section were collected to determine the distribution of U/Se, and their association with the other key chemical constituents e.g. Fe, S, Si/Al, Ca and Mg (Figure 1). Analysis of nano-focus X-ray Absorption Near Edge Spectra (XANES) from select regions were subject to principal component (PCA) and linear combination analysis (LCA) against known standards to quantify the oxidation state of the U and Se adsorbed to the LSSR. This nano-scale information will be combined with additional datasets related to the uptake and transport of U and Se within the LSSR, including information from other microanalysis techniques (e.g. electron microscopy and μ-focus XANES), aqueous analyses and adsorption data (e.g. distribution coefficients). This multi-technique state of the art approach will then be synthesised to determine the key reactions (*e.g.,* adsorption, redox, precipitation) and geochemical factors that control U and

Se transport in the LSSR. Finally, this information will be used to develop larger scale reactive transport models as part of the wider NERC GeoSafe consortium.

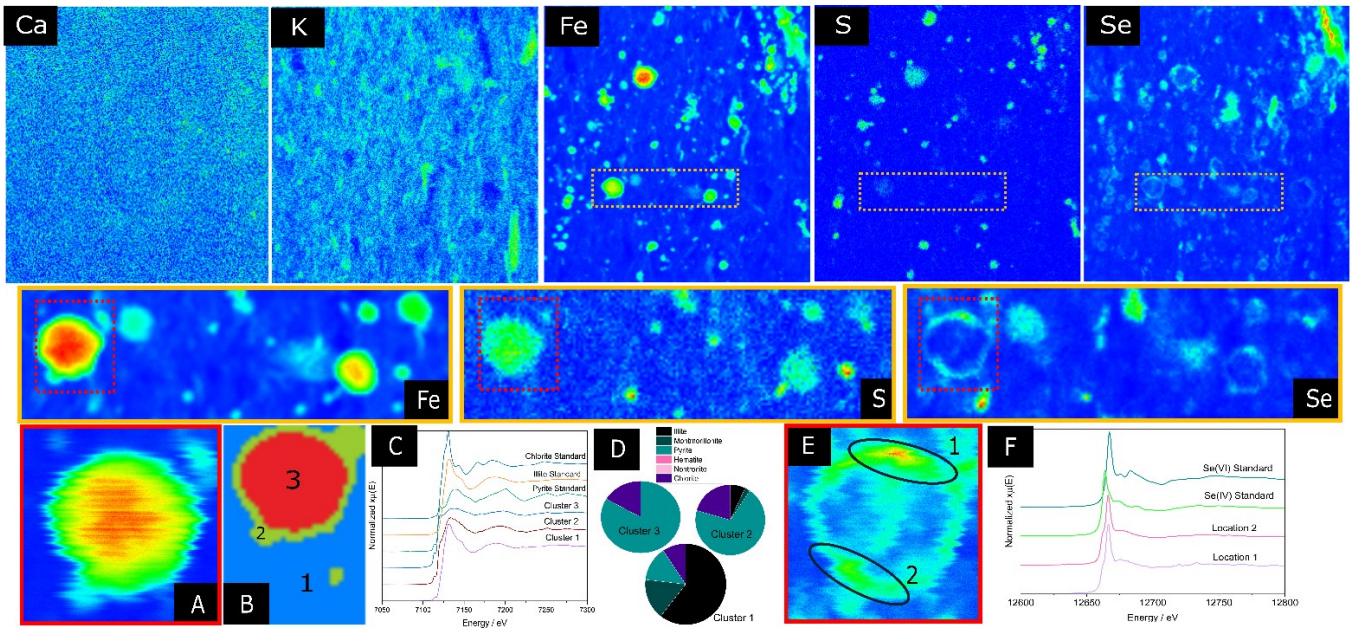


Figure 1. Nano-XAS analysis of Oxford clay thin section exposed to Se doped groundwater. Top and middle panel; Nano-focus (~50 nm beam size) XRF chemical maps of OXC petrographic thin sections (top 200 µm x 200 µm and middle 50 µm x 100 µm sized map). Bottom panel; (A) High-resolution XRF Fe map of pyrite grain (~20 µm x 20 µm), (B) PCA cluster analysis with Fe XANES regions shown (1-3), (C) corresponding XANES spectra with Fe standards, (D) LCA analysis of Fe XANES regions, (E) High-resolution XRF Se map with Se XANES regions (1 and 2) and (F) corresponding Se XANES spectra with Se standards.

References

(1) Department of Energy & Climate Change. Implementing Geological Disposal. **2014**.
(2) Smedley, P. Guide to Reference Groundwater and Porewater Compositions in Support of the UK GDF Programme. **2023**,

Mechanistic Roles of Minerals in Radionuclide Behaviour at the Department of Energy's Hanford Site

Pearce, C.I.[1], Jay LaVerne[2], Hilary Emerson[1], Amanda Lawter[1], James Szecsody[1], Rob Mackley[1], Xin Zhang[1], Zheming Wang[1], Kevin Rosso[1], Gregory Schenter[1], Linda Young[3], Thomas Orlando[4], Aurora Clark[5], Xiaosong Li[1,6], Lynn Francesconi[7]

[1] Pacific Northwest National Laboratory, Richland, WA, E-mail: carolyn.pearce@pnnl.gov; [2] University of Notre Dame, Notre Dame, IN; [3] Argonne National Laboratory, Lemont, IL; [4] Georgia Institute of Technology, Atlanta, GA; [5] University of Utah, Salt Lake City, Utah; [6] University of Washington, Seattle, WA; [7] Hunter College, City University of New York, New York, NY

Plutonium production for the US weapons program at Department of Energy's Hanford Site has resulted in one of the most challenging environmental cleanups in history. Retrieval of 200 million litres of waste, containing 6,300,000 terabecquerels of radioactivity and 218,000 metric tons of complex chemicals, from 177 underground storage tanks, is ongoing and will take decades of time, costing hundreds of billions of dollars. To gain a holistic understanding of the cleanup mission, it is important to consider the sources and sinks for radioactivity in the environment, including: (i) characterizing the chemistry of radioactive waste in the tanks; and (ii) understanding contaminant transport and reactivity in the subsurface. The Ion Dynamics in Radioactive Environments and Materials (IDREAM) Energy Frontier Research Center has uncovered new fundamental insights into precipitation and dissolution processes that are a grand challenge for processing radioactive tank waste at Hanford. Hanford tank waste is complex and contains "sludge," a mix of water-insoluble oxides/hydroxides of aluminum. IDREAM has elucidated the molecular mechanisms governing aluminum (oxy)hydroxide nucleation and crystal growth over a range of conditions and examined radiolytic water generation at their interfaces. Although gibbsite ($Al(OH)_3$) is known as the solubility-limiting phase across a wide pH range, its nucleation mechanism has been debated for decades. IDREAM examined dissolution of gibbsite in sodium hydroxide solutions using fast-scanning atomic force microscopy (AFM) and revealed that, in contrast to classical terrace-ledge-kink notions of monomer detachment, dissolution occurs by release of aluminate dimers that subsequently dissociate into monomeric species, which are the dominant species in solution. The continuous production of transient reactive species by ionizing radiation from radionuclides in the waste drives chemistry far from equilibrium. IDREAM investigated radiation effects with unprecedented spatial resolution using a unique AFM with an integrated X-ray source to directly monitor radiolytically driven interfacial chemistry. Using these new capabilities, IDREAM has developed a foundation for understanding radiolytic products in Hanford solids and roles of adsorbed water and impurities at interfaces. We have shown that simple carboxylates or chromium adsorbed on boehmite (AlOOH) nanoplates significantly slowed boehmite dissolution in alkaline solutions, despite incomplete surface coverage. The liquid waste was initially stored in 149 stainless steel single-shell tanks (SSTs), of which one third are suspected of having leaked waste into the environment. In addition to the tanks, liquid waste from chemical separations to extract plutonium from irradiated uranium fuel rods was also deposited into engineered cribs and trenches, resulting in groundwater plumes and a large vadose zone contaminant inventory. These residual sources of contamination in the vadose zone continue to impact groundwater. Targeted treatment scenarios include source treatment of a perched water zone and development of a permeable reactive barrier at the groundwater table. Primary contaminants of interest in the groundwater include technetium-99 (as highly mobile pertechnetate $Tc(VII)O_4^-$) and uranium. Several promising remediation technologies are being evaluated, including: (i) tin apatite particles, (ii) sulfur modified iron particles, (iii) bismuth subnitrate particles, (iv) liquid calcium polysulfide, and (v) liquid polyphosphate. The proposed immobilization mechanisms are: (i) reduction (tin apatite particles, sulfur modified iron particles, and liquid calcium polysulfide); (ii) adsorption (bismuth particles); (iii) incorporation (liquid apatite forming solutions and bismuth particles); and (iv) in-situ precipitation and mineral coating (liquid apatite forming solutions). The effectiveness of these remediation technologies for immobilization of U and Tc-99, with and without co-contaminants, is continuing to be investigated in a series of batch and column experiments using site-specific sediments. Ultimately, the risks associated with this unprecedented task of retrieving, processing, and disposing of the radioactive waste at Hanford can be mitigated by: (i) characterizing waste chemistry; and (ii) understanding contaminant reactions both in the waste form and with environment.

Redox-active iron (nano)minerals and their impact on contaminant behaviour in natural and engineered environments

Perez, J.P.H.[1,2,3]

[1]GFZ Helmholtz Centre for Geosciences, Potsdam, Germany. Email: jpperez@gfz.de
[2]Technische Universität Berlin, Berlin, Germany
[3]Aarhus University, Roskilde, Denmark

Iron is central to biogeochemical cycling and strongly influences nutrient availability and contaminant behaviour through ubiquitous Fe-bearing minerals in Earth's surface, including (oxyhydr)oxides and clays. Redox-active Fe (nano)minerals are particularly important because they can act as both reductants and oxidants for a wide range of inorganic and organic contaminants in both natural and engineered environments. Yet, the kinetics, reaction pathways, and molecular-scale mechanisms, especially those involving metastable Fe phases, remain poorly constrained. Resolving these controls is critical for understanding how mineral-contaminant interactions govern contaminant speciation, mobility, and toxicity while driving mineral formation and transformation. More importantly, closing these gaps is essential for reliably predicting contaminant fate and advancing mineral-based remediation strategies.

Using recent advances in conventional and synchrotron-based X-ray and electron-based characterisation, we elucidate these coupled processes from the molecular to the nanoscale to (i) resolve the formation and transformation of redox-active (nano)minerals that control the speciation and immobilisation of toxic oxyanions such as arsenic and chromium, and (ii) inform the design and field-relevant application of (nano)mineral-based technologies for treating groundwaters contaminated with arsenic and chlorinated solvents. Together, these studies demonstrate how redox-active iron (nano)minerals act as both drivers and tools for contaminant control across natural and engineered systems, and how mechanistic insight can be leveraged to deliver more predictable, robust, and effective remediation strategies.

Adsorption and stability of double-stranded RNA at goethite surfaces

Reid, F.[1], Singh, V. V.[2], Krämer, S. M.[2], Coker, V. S.[1], and Kimber, R. L.[1]

[1] Department of Earth and Environmental Sciences, School of Natural Sciences, Faculty of Science and Engineering, The University of Manchester, Manchester, M13 9PL, UK
Email: flora.reid@postgrad.manchester.ac.uk
[2] Department of Environmental Geosciences, Centre for Microbiology and Environmental Systems Science, University of Vienna, 1090 Vienna, Austria

---

RNA interference (RNAi) biopesticides are pest control products that use double-stranded RNA (dsRNA) designed to target specific organisms. This dsRNA induces a genetic response in the target, leading to developmental disruption and increased mortality. The potential benefits of RNAi biopesticides over traditional chemical pesticides include increased specificity for target pests as well as presumed rapid biodegradation in soil systems through microbial uptake and enzymatic degradation. However, abiotic factors can also influence dsRNA stability in the environment. For example, while metal-catalysed hydrolysis of dsRNA in solution is limited [1], adsorption at iron (oxyhydr-)oxide mineral surfaces can greatly enhance dsRNA hydrolysis [2]. It is therefore likely that geochemical processes play a key role in controlling the environmental fate of dsRNA, but the mechanisms involved and their relative contributions are not well understood. Uncovering these processes is crucial to accurately assess environmental risk and develop guidance for safe and sustainable use of RNAi biopesticides.

In this work, batch equilibrium tests were used to assess how pH and the presence of environmentally relevant metal cations impacted dsRNA adsorption to goethite, an iron oxyhydroxide mineral commonly found in soils. Stability of dsRNA at the surface of goethite was also assessed through analysis of dsRNA fragment size by automated gel electrophoresis. Adsorption of dsRNA to goethite was found to decrease with increasing pH but an increase in adsorption was observed with increasing metal cation concentration at all pH levels tested. Despite evidence of some goethite-catalysed hydrolysis occurring over the experimental period, a broad size distribution of dsRNA was found to persist even after 2 weeks, suggesting that hydrolysis may induce fragmentation but not complete degradation of dsRNA polymers.

Our results indicate that dsRNA may exhibit greater persistence under a range of geochemical conditions than previously recognised, offering a foundation for mechanistic understanding of the factors regulating its environmental fate in soils.

References:
[1] Chatterjee et al. (2022) Environ Sci Technol 56(6):3564-3574
[2] Zhang et al. (2023) Environ Sci Technol 57(22):8280-8288

Performance of Fe-modified Biochars and Carbo-Iron in Remediating Arsenic in Groundwater

Feng, M.[1], Richards, L.A.[1], Polya, D.A.[1], and Lloyd, J.R.[1]

[1]Department of Earth and Environmental Sciences, The University of Manchester, Manchester, UK
E-mail: mingyu.feng@postgrad.manchester.ac.uk

Geogenic arsenic (As) mobilisation in aquifers, sometimes influenced by anthropogenic activities, can give rise to a widespread and serious hazard, leading to human health and ecological risks that can require mitigation. Here, we investigate the efficiency of Fe-modified biochars and Carbo-Iron (CI) in remediating As in groundwaters, focusing on their adsorption capacities and long-term performance under varying biogeochemical conditions.

Batch adsorption experiments demonstrated that Fe-modified biochars and CI significantly enhanced As (both As(V) and As(III)) removal compared to pristine biochar, primarily through surface complexation and co-precipitation. Among the tested materials, CI exhibited stable and high removal capacity across various pH levels, whereas magnetite-containing biochar (M+BC) and ferrihydrite-containing biochar (FH+BC) was more prone to pH changes and showed reduced performance under alkaline conditions. Extended six-month incubations in circumneutral pH conditions confirmed that both M+BC and CI effectively sustained As retention in As-containing water environments.

Anaerobic microcosm incubations containing high As aquifer sediments showed that microbial interactions influenced As fate in groundwater environments and further highlighted the effectiveness of M+BC and CI in controlling As mobility. While the presence of lactate and acetate stimulated microbially mediated Fe(III)/As(V) reduction, leading to As release, the addition of remediation materials nevertheless effectively inhibited As mobilization. Notably, CI maintained consistently low As concentrations throughout the incubation, demonstrating its potential for long-term groundwater remediation.

We acknowledge support from a China Scholarship Council-The University of Manchester joint scholarship (CSC-UoM, 202208440009) to M.F., the Natural Environment Research Council (NERC; NE/X010813/1 to L.A.R. and D.A.P.) and a UKRI Future Leaders Fellowship (MR/Y016327/1 to L.A.R et al; see www.aquaroad.org).

A Sustainable and Cost-effective Method of Uranium and Arsenic Removal using Biogenic Iron Minerals

Attfield, S.S.[1], Bryce, C.[1], Bostick, B.[2] and Byrne, J.M.[1]
[1] School of Earth Sciences, University of Bristol, UK. sara.attfield.2020@bristol.ac.uk
[2] Lamont-Doherty Earth Observatory, Columbia University, USA

Uranium (U) and arsenic (As) contamination disproportionately affects rural communities that rely on groundwater wells, such as Native American communities living in the Northern Plains, US. Alarmingly, higher-than-average rates of cancer and chronic cardiovascular diseases are observed in the Oglala Sioux Tribal lands (OST), emphasizing the need for an effective water treatment [1]. A promising approach involves utilizing natural iron (Fe) cycling for bioremediation [2]. In collaboration with Native American research groups, our goal is to design a water treatment that harnesses microbial Fe cycling which is economical, safe, and sustainable. The Fe cycle is driven by groundwater geochemistry and the activity of Fe(II)-oxidizing and Fe(III)-reducing bacteria, which are ubiquitous in most aquatic environments [3]. Of particular interest are phototrophic Fe-oxidizing bacteria, such as *Rhodobacter ferroxidans.* Photoferrotrophs require sunlight for photosynthesis and produce biogenic Fe minerals like ferrihydrite, which is known to effectively sorb heavy metalloids such as U and As [4]

This study combines laboratory experiments, such as U sorption experiments, with field data from the OST, including microbial DNA extractions, to test whether exploiting Fe biominerals as a type of treatment is viable for the target site. To our knowledge, this represents the first microbial survey conducted in this region. 16S rRNA amplicon sequencing and metagenomic analyses were performed to determine whether native microbes are suitable for bioremediation. Reassuringly, results indicate the presence of Fe-oxidizing taxa and key marker genes for both Fe-oxidation and photosynthesis across most of the sites. U(VI)-sorption experiments were conducted to investigate the sorption capacity of Fe biominerals, and mineral phases were characterized using Transmission Electron Microscopy (TEM), Fourier Transmission Infrared Radiation (FTIR), and Mössbauer Spectroscopy. Together, these results will help inform the design of a light-based bioreactors system that utilises natural microbial Fe cycling, to remove U and As from groundwater wells in rural communities.

References:

[1] Sobel M, et al.(2021) Environmental Pollution. **287**.
[2] Byrne JM and A Kappler (2017) Microbial Biotechnology. **10**(5): p. 1098-1101.
[3] Kappler A, et al.(2021) Nature Reviews Microbiology. **19**(6): p. 360-374.
[4] Bryce C, et al.(2018) Environmental Microbiology. **20**(10): p. 3462-3483.

Developing (bio)remediation options for high pH radionuclide contaminated land and water

Shaughnessy, L.[1], Shaw, S.[1], Morris, K.[1], Graham, J.[2], Abrahamsen-Mills, L.[2], Lloyd, J.R.[1]

[1] The University of Manchester (UoM)
[2] United Kingdom National Nuclear Laboratory (UKNNL)
Email: lea.shaughnessy@manchester.ac.uk

The subsurface of many nuclear sites have been contaminated with radioactivity. To date, research on injectable bioremediation approaches have focused on groundwater systems at circumneutral pH; however in several cases alkaline pH's are known to be present. The long-term effectiveness of these remediation techniques at elevated pH therefore remains poorly understood.

This project is building upon recent advances in bioremediation of circumneutral pH radionuclide contamination, including the use of novel stimulants for radionuclide biomineralisation undertaken at the University of Manchester and aims to underpin the development of low cost, minimally invasive (bio)remediation options for high pH impacted contaminated land and water, suitable for both site interim and end-state scenarios.

Two alkaline leachate solutions (ALS) have been developed to simulate a high pH leak to subsurface from the Magnox Swarf Storage Silo (MSSS), a legacy waste storage facility at Sellafield. In initial experiments ALS was incubated with site-relevant sediments and a spike of either stable Sr or Cs to better understand the natural attenuation of Sr and Cs in the shallow subsurface under high pH conditions. Following these 'baseline' experiments, batch microcosms were used to test promising bioremediation treatments including injectable phosphates and CarboIron™. Planning of column experiments is now underway for the more promising treatment options. These offer an opportunity to examine the performance of the amendments under dynamic environments, which can better simulate natural groundwater flow, as well as potential chemical perturbations that may be encountered in the future, such as seawater ingress and nitrate influx.

This presentation will summarise work completed to date on (1) natural attenuation processes under elevated pH conditions highlighting retention of Cs and Sr, and (2) remediation treatments that can enhance radionuclide retention, including the biostimulation of indigenous microbial consortia with growth substrates and nanomaterials.

Mechanistic Insights into the Reductive Incorporation of Tc(IV) in Fe(II)-Doped Layered Double Hydroxide (LDH)

Cai, H.[1], Neill, T.S.[1], Morris, K.[1], Stockdale, A.[1], and Shaw, S.*[1].

[1]Radioactive Waste Disposal and Environmental Remediation (RADER) National Nuclear User Facility and Williamson Research Facility for Molecular Environmental Science, Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, Manchester M13 9PL, U.K.
samuel.shaw@manchester.ac.uk

The treatment of radioactive effluents is a significant challenge for the nuclear industry, especially within the decommissioning sector. A key radionuclide of concern is technenium-99 (^{99}Tc), which is a β-emitting high yield (6.06%) fission product with a long-life (2.11×10^5 years). In oxic, aqueous conditions Tc is present predominantly as the $Tc(VII)O_4^-$ species, which is highly soluble and mobile due to the poor sorption onto mineral surfaces. In reducing environments, however, Tc(IV) dominates (e.g. $TcO_2{\cdot}xH_2O$) which is insoluble. Therefore, the reduction of Tc(VII) to Tc(IV) is an effective strategy to facilitate sequestration. In addition, incorporation of Tc(IV) into synthetic mineral phases (e.g. magnetite) phases has been shown to be an effective method to prevent reoxidation of immobilized Tc(IV)[1,2]. In this study, Fe(II), as a well-known reductant for Tc(VII), is doped into a Ni(II)-Al(III)-CO_3 Layered Double Hydroxide (LDH) and applied to the removal of $Tc(VII)O_4^-$ from solution. In-situ co-precipitation experiments during the synthesis of LDH are performed:

- LDH was synthesized following a co-precipitation process,
- $Tc(VII)O_4^-$ was added into the initial precursor solution,
- The yield of Tc removal along with the synthesis process was analyzed
- The resulting Tc-containing solid was analyzed by X-ray absorption spectroscopy (XAS)

The results show that the removal of Tc under both high and low initial concentrations could reach a high yield of >99% by pH 9 where LDH formed. The XAS results show that Tc(VII) was reduced to Tc(IV) and has provided a detailed insight into the sequestration mechanism. These results suggest that the in-situ co-precipitation of LDH can immobilize Tc(VII) with high efficiency via reductive incorporation mechanism.

References:
[1] Marshall, T. A. et al. (2014) Environmental Science & Technology 48 (20): 11853–11862.
[2] Rodríguez, D. M. et al. (2020) Environmental Science & Technology 54 (5): 2678–2687.

Experimental investigation of toxic metal behaviour during laterite mine waste formation

Delina-Agillon, R.E.[1], Bateman, K.[1], Lacinska, A.M.[1], Vosper, M.[1], Perez, J.P.H.[2,3,4], and Benning, L.G.[2,5]

[1] British Geological Survey, Natural Environment Research Council, Keyworth, Nottingham NG12 5GG, UK; ragil@bgs.ac.uk
[2] GFZ Helmholtz Centre for Geosciences, Telegrafenberg, Potsdam 14473, Germany
[3] Technische Universität Berlin, Berlin 10623, Germany
[4] Aarhus University, Roskilde, Denmark
[5] Department of Earth Sciences, Freie Universität Berlin, Berlin 12249, Germany

---

Nickel laterites distributed worldwide are an important source of many critical metals that drive our technological development (e.g., Ni, Co, Sc). However, these deposits may also contain potentially toxic components (e.g., hexavalent Cr, asbestos) that can negatively impact communities and ecosystems. In the case of Cr, it primarily exists as Cr(III) in Ni laterites, but concentrations exceeding the global drinking water regulatory limits for the more toxic and carcinogenic Cr(VI) species have been documented in waters associated with such mines [1]. Interestingly, no Cr(VI) was found in mine tailings generated after high-pressure acid leaching (HPAL) of Ni laterites, raising questions on the detoxification pathways for Cr. To address this, we have investigated the fate of Cr during HPAL processing and explored the geochemical mechanisms controlling its mobility and sequestration in the mine wastes.

High temperature and pressure batch experiments at 250°C, with laterite ores reacted with sulfuric acid, were conducted to simulate industrial extraction processes. The leach solutions and solid residues were characterized for the Cr speciation and mineralogical transformations using a suite of cross-correlated mineralogical and geochemical methods. Leaching of Cr within the first 30 minutes of HPAL treatment was followed by a decline in dissolved Cr concentrations up to 120 minutes. This coincided with the dissolution-precipitation of Fe phases, specifically of goethite from the initial limonite and the precipitation of secondary hematite. Our data also confirmed the structural incorporation of Cr into hematite, supporting the hypothesis that Cr becomes immobilized via coprecipitation with Fe oxides during HPAL processing.

These findings provide critical insights into the environmental stability of HPAL tailings, suggesting that hematite formation acts as an important sequestration mechanism for Cr. This potentially mitigates the risk of Cr(VI) contamination in surrounding waters, offering a more sustainable pathway for tailings management. Field validation confirmed our experimental findings [2], reinforcing the role of iron oxides in the immobilization of Cr in these systems.

References:
[1] Delina et al. (2020), Chemical Geology 558, 119863.
[2] Delina et al. (2025), Environmental Science & Technology 59 (11), 5683-5692

Natural Attenuation of Cobalt and Nickel in mine waste

Bowell, R.J.[1,2], Jamieson, H.E.[2] and Dobosz, A[2]

[1]SRK Consulting, Churchill House, Churchill Way, Cardiff CF102HH, Wales, UK.
[2]Department of Geological Sciences and Geological Engineering, Miller Hall, 36 Union Street, Queen's University, Kingston, ON, Canada K7L 3N6

Cobalt and Nickel occur in many mineral deposits as mixed sulfide or arsenide minerals and even when they are in separate discrete phases show common paragenetic relationship. Despite similarities in the two metals in the supergene environment they appear to form discrete and independent mineral phases with only a partial solid solution existing between similar forms of the metals.

Mine waste at the former copper-uranium mine of South Terras, Cornwall and from Nipping and Kelsey mines in the Cobalt mining district of Ontario, Canada have been evaluated for primary, secondary and tertiary mineralogy to provide an insight into the supergene geochemistry of both metals.

In the South Terras historical mine waste Co and Ni are present in unweathered clasts of quartz vein as gersdorffite and skutterudite although volumetrically pyrite appears to be the main host of both elements in trace amounts. By contrast in the supergene environment complexation with arsenic seems to account for the majority of both metals with annabergite and erythrite being relatively common phases[1]. Both minerals are relatively pure with few trace elements. In addition, poorly crystallized phases Asbolane is present in the mine dumps that contains both metals. Nickel is also present in iron ochres formed on site and is generally present in higher concentrations in seepage water from the mine waste.

In the mine waste of the silver mines of Cobalt, Ontario, cobalt and nickel occur as cobaltite, gersdorffite, nickeline, safflorite and skutterudite [2,3]. In the supergene environment both annabergite and erythrite are formed and produce relatively pure forms in the mine waste and in historic specimens. However, in mine tailings there is a much greater solid solution between them and hornesite (Mg-arsenate) indicating tertiary formation of the arsenates. In addition, chlorite can host appreciable amounts of Co (up to 4%) but negligible amounts of Ni. By contrast Ni is a common trace element in Fe-oxides and carbonate minerals. Although both elements occur in similar concentrations in the ore Ni is generally higher in tailings pore water and in seepage chemistry.

In both sites supergene and tertiary attenuation of cobalt and nickel occurs through binding with arsenic as arsenate minerals in historic mine waste and in some surface tailings. However, these phases appear to be only partially stable, and mobilization occurs. Differences in the geological weathering cycles of Ni and Co is reflected in the distinct secondary mineral composition formed that appears not to be as strong when these phases are weathered and tertiary, post mining, phases are formed but continued weathering and mobilization has led to different fate for the two elements. Nickel appears more dispersed and Co more concentrated in sediments around both sites. Possibly this reflects preferential biogeochemical uptake of Co compared to Ni. Sequestration of Co by clay minerals and organic matter may represent a geological sink for the metal that may be a target for future resource recovery or make any extraction unfeasible.

References:
[1] Tindle 2008. Minerals of Great Britain and Ireland. Terra Publishing. 616p
[2] Petruk, 1971, Can Mineral., 11, 108-139.
[3] Turcotte et al 2025, Applied Geochemistry, 181, 106296

Weathering of minerals of tungsten and its environmental mobility

Majzlan, J.[1], Jurkovič, Ľ.[2], Faragó, T.[2], Koděra, P.[2] and Števko M.[3]

[1]Friedrich-Schiller-University Jena, Germany; Juraj.Majzlan@uni-jena.de
[2]Comenius University, Bratislava, Slovakia
[3]Slovak Academy of Sciences, Bratislava, Slovakia

Environmental mobility of tungsten is judged to be limited [1,2] based on the few studies available. The increasing demand and associated mining and processing can be taken as an indication that the amount of W released into the environment will grow. For this reason, we investigated weathering of W ores at the W-Mo porphyry deposit Ochtiná-Rochovce in eastern Slovakia. This deposit offers a unique combination of chances to explore both natural, long-term weathering, and man-induced processing that operates at much shorter time scales.

The deposit consists of ores hosted in quartz veins with muscovite, devoid of carbonates. The main ore minerals are scheelite, wolframite, and molybdenite, accompanied by copious pyrite. The abundance of pyrite is unusual for this deposit type and causes generation of acidic weathering fluids. The deposit features a well-developed oxidation zone that locally reaches almost 30 meters below the current surface. Small-scale mining in the past created dumps, covered today by technogenic soils.

In the upper parts, the primary ores are completely weathered. They were converted to two mineral assemblages. One of them is dominated by goethite, either massive or vuggy. This goethite contains little W (< 3 wt.% WO_3), even though some parts thereof were produced by weathering of wolframite. Locally, schwertmannite-like morphology was observed. If relics of wolframite are present, they are replaced by iron oxides with up to 10 wt.% WO_3. X-ray absorption spectroscopy proved that W is adsorbed to the surface of the iron oxides. The presence of goethite and schwertmannite suggests mildly acidic conditions. The second assemblage consists of W oxides (tungstite, hydrotungstite), together with jarosite and baryte. This assemblage formed under acidic conditions, as evidenced by the consistent spatial association of jarosite (or similar minerals, such as goyazite), with the W oxides.

The deeper parts of the oxidation zone feature weathering of scheelite. The mineral weathers faster than wolframite and is replaced along fractures by W oxides with little to no Ca, attesting to the mobility of Ca in the weathering process. Wolframite and pyrite remain largely unweathered here. The deepest manifestations of the oxidation are fine-grained aggregates of hematite dispersed in the ores.

Soils and sediments in the area of the W-Mo deposit contain 139 ppm to 0.17 wt.% W in soils and up to 0.2 wt.% W in Fe ochres. The primitive soils on the mining dumps are acidic (pH ~4.4). Elevated W concentrations were detected also in riverine sediments downstream from the dumps (up to 125 ppm). Relative mobility (as $W_{leachate}/W_{total}$) is lower in more acidic initial soils on the dumps relative to the more alkaline native soils.

This study documents well that tungsten is mobile under environmental conditions but only under specific conditions. In mildly acidic to neutral solutions, tungsten is highly mobile and is released into surface or ground water; ferric iron is highly insoluble. Such conditions are documented in our samples by Fe oxides with little W. In strongly acidic solutions, W oxides are insoluble but the solubility of Fe^{3+} increases. In our samples, such conditions are documented by W oxides + jarosite. These observations are supported by geochemical modelling that documents the opposite behaviour of Fe and W oxides as a function of pH.

Acknowledgement: This work was financially supported by the grant APVV-22-0134.

References:
[1] Kazamel BG et al. (2023) Econ Geol 118: 659–674
[2] Jamieson HE et al. (2025) Facets 10: 1–11

Intelligence, strategy, and the shifting landscape of critical raw materials in the UK: the role of CMIC in bridging policy and practice

Josso, P.[1]

[1]British Geological Survey, UK Critical Minerals Intelligence Centre – piesso@bgs.ac.uk

---

The UK Critical Minerals Intelligence Centre (CMIC), hosted by the British Geological Survey and funded by the Department for Business and Trade, provides independent, evidence-based intelligence on critical raw material (CRM) supply chains to inform government and industry decision-making. Its work sits at the heart of the *Vision 2035: Critical Minerals Strategy* [1], embedded as a foundational pillar of the *UK Industrial Strategy* (IS-8) [2], which identifies CRMs as a cross-cutting enabler of eight high-growth sectors. The 2025 Strategy sets ambitious, though not-binding targets: 10% of annual UK demand met through domestic production, 20% through recycling, and a 60% cap on reliance on any single supplier country, all by 2035.

Despite its ambition, the strategy has attracted substantive critique. While more tangible than its 2022 predecessor, several targets remain poorly calibrated to delivery capacity. The £50 million committed by DBT, whilst a welcome signal, is widely regarded as modest against comparable programmes in the US, Canada, and EU, and key implementation details have been deferred, leaving a material gap between strategic intent and operational roadmap.

The support architecture draws on the National Wealth Fund (NWF), UK Export Finance (UKEF), and the British Business Bank as primary instruments. NWF has committed over £80 million in equity to domestic projects including Cornish Lithium and Cornish Metals, while UKEF's new Critical Goods Export Development Guarantee and expanded growth minerals eligibility are designed as catalytic capital to de-risk projects and attract private investment.

Strategically, the emphasis has shifted decisively toward midstream and downstream segments, where the UK retains genuine competitive advantage in processing and refining with ambitions towards its advanced manufacturing sector. The midstream 'gap', illustrated by Cornish tin exported for overseas refining before return, is both a vulnerability and an investment opportunity. The circular economy is similarly foregrounded, with a 20% recycling target anchoring domestic ambitions.

CMIC's research outputs directly support this reorientation. Its report on *Waste and Scrap Flows* found that UK copper waste exports [3] are significantly undervalued relative to contained metal value, identifying the case for new secondary refining infrastructure. Domestic supply chain mapping work is providing granular visibility into industrial demand concentrations and strategic bottlenecks, while the *Future of Digital* report examines future demand for key technology metals for the next information and communication Technology revolution.

These contributions sharpen a broader question for the UK's CRM and geology research landscape: where does the frontier now lie? The pivot toward midstream processing, secondary materials, and circular metrics creates new demand for metallurgy, materials recovery, and supply chain analytics alongside, rather than instead of, traditional exploration geology. For the research community, Vision 2035 represents both a mandate and a challenge: to deliver the integrated, supply-chain-literate, and digitally informed intelligence that policy and industry now require.

[1] https://www.gov.uk/government/publications/uk-critical-minerals-strategy/vision-2035-critical-minerals-strategy
[2] https://www.gov.uk/government/publications/industrial-strategy
[3] https://ukcmic.org/reports/cmic.html

Thinking about the connections between minerals research and the responsible sourcing of critical raw materials

Wall, F.

Camborne School of Mines, University of Exeter, Penryn Campus, Penryn, Cornwall, TR10 9FE, UK.
f.wall@exeter.ac.uk

Demand for minerals is increasing rapidly; a low carbon world is an age of metals and low carbon and digital technologies seem to need most of the elements in the Periodic Table for their manufacture. In addition, there are now many global security of supply concerns regarding critical minerals that are driving the search for new and alternative local sources. Mineralogists can make significant contributions not only to securing sufficient supplies of the minerals we need but also to the responsible sourcing and stewardship of these minerals. Here are some points to discuss about that contribution.

Finding new supplies – this is the 'business of usual' application of geoscience, understanding how mineral deposits form, and making models that help exploration. Better understanding of potential co- and by-products from early on in exploration, production of additional raw materials from existing mines and use of legacy waste, tailings and slags are now also important research areas.

Process mineralogy and minerals processing – this is an area of science that is much less well known but essential in improving resource efficiency and environmental performance.

Secondary anthropogenic supplies – might seem out of scope for geoscience but many mineralogical skills and principles can be applied to manufactured materials so that they can be remanufactured and recycled. Better integration between primary and secondary sources of materials is likely to become common.

Creating real sustainable development from critical minerals production – requires wider transdisciplinary links but integrates many mineralogy skills. These include links to socioeconomic issues, environmental monitoring, creating conditions for biodiversity net gain, mine remediation and post-mining activities, health and welfare and contributing to good economic governance.

Decarbonising materials – is an area where raw materials production has a key part to play, using techniques like life cycle assessment that manufacturers need for their reporting.

Supply chain and materials tracking and tracing – may use paper chains, blockchains or other clever technology but only mineral-based technologies can actually track the materials.

Leading by our own actions - many of us buy fairtrade coffee, tea or bananas, but the long and complex supply chains leading to products such cars and electronic devices make the connections much less visible. As consumers with some of the best knowledge about supply chains, the mineralogy community are important advocates of responsible sourcing. If we don't ask the questions who will?

Acknowledgement: Colleagues including teams on UKRI Met4Tech grant EP/V011855/1 and the Critical Minerals Challenge Centre (UKRI grant 5052188).

Don’t dig it up! In situ reprocessing and remediation of Cu mine tailings

Jenkin, G.T.R.[1], Gibaga, C.R.L.[1,2,4], Mubaira, S.[1], Symons, J.[1], Tanciongco, A.[1,4], Swift, R.[2], Chambers, J.[2], Yan, Y.[3], Crane, R.[3], Gervasio, J.H.[4], Tungpalan, K.[5], De Oliveira, V.[6], Tibbett, M.[6], Samaniego, J.O.[4], Arcilla, J.A.[4] and the PROMT consortium

[1]Centre for Sustainable Resource Extraction, University of Leicester, LE1 7RH, UK
[2]British Geological Survey, Nicker Hill, Keyworth, Nottingham, NG12 5GG, UK
[3]Camborne School of Mines, University of Exeter, Penryn Campus, Cornwall, TR10 9FE, UK
[4]Philippine Nuclear Research Institute
[5]University of the Philippines, Diliman
[6]University of Reading, United Kingdom

Tailings storage facilities pose environmental hazards, and failure could cause contaminated materials to be released affecting people and ecosystems. Conversely, tailings are significant resources of unrecovered metals, especially in older facilities produced using less efficient mineral processing, and many initiatives are underway to recover metals, including those previously discarded but now classed as critical metals. Removal of toxic metals also serves to remediate the tailings and promote revegetation. The already finely ground material makes remining and reprocessing of tailings appealing but challenges include the risk of damaging the structural integrity of the tailings, handling costs, and the potential for release of contaminants. Reprocessing *in situ* is a potential alternative [1].

The PROMT project involved over 40 UK and Philippine researchers working together with mining companies to develop new science and sustainable technologies for *in situ* reprocessing and remediation of mine tailings, to recover metals, to develop soils and promote plant growth, and to allow the land to be reused. Here we describe a case study on a Cu-porphyry tailings facility at the Philex Padcal Mine in Benguet Province, the Philippines.

Using mesocosm experiments in the natural environment we have demonstrated how we can leach copper using an environmentally benign solvent combined with monitoring solvent infiltration using electrical resistivity tomography (ERT). These show a high proportion of the theoretically leachable copper can be leached in 8 days and demonstrate the use of ERT to monitor the leaching process itself. We also describe the outcome of mesocosm experiments that use applied electric fields to accelerate copper leaching by electrokinetics. The mineralogical host of the leachable copper is identified as iron oxyhydroxide rims on primary chalcopyrite, with decades of weathering necessary to make the tailings amenable to leaching in a weathering profile.

References:
[1] Jenkin GRT (2024) Mine Closure 2024 Australian Centre for Geomechanics:30-43
doi:10.36487/ACG_repo/2415_0.03

Legacy Slags as Critical Metal Resources: Geochemical Insights from a Cornish Historic Copper Smelting Site

Tanciongco, A., Jenkin, G.R.T., Bird, P.

Centre for Sustainable Resource Extraction, University of Leicester, Leicester, United Kingdom, corresponding author email: at657@leicester.ac.uk

---

Legacy metallurgical slags are increasingly recognised as potential secondary resources for critical and base metals [1,2], particularly as demand rises for low-carbon technologies [3]. This study investigates historic copper-tin slags from Hayle, Cornwall, United Kingdom, to evaluate the geochemical characteristics, mineralogy, and potential for sustainable metal recovery.

Microtextural observations show that the Cornish copper slags are composed of fayalite and Fe-Al spinel set in an amorphous silica-rich matrix with scattered Cu-bearing phases in sulfides and in entrained metal prills, which are broadly similar with other copper slags worldwide. However, the difference is that the copper slags in this study contain uncommon Cu-Sn alloy phases locally containing bismuth and also secondary Cu-Cl alteration products due to the long-term coastal exposure. Bulk composition analysis reveals elevated concentrations of economically relevant metals, including Cu (up to 2.7 wt.%), Zn (up to 4.3 wt.%), Sn (up to 2.92 wt.%), In (up to >400 ppm), and Bi (up to >50 ppm). Relative to the composition of other copper slags and of bulk continental crust, the samples are depleted in major oxides yet strongly enriched in several base and critical elements, particularly In, Cu, Sn, Pb, and Bi. The presence of Cu-Sn alloy prills is notable since these are rarely reported in copper slags derived from copper ores and reflect the Sn-rich character of Cornish mineralisation [4].

Given the broadly similar phase assemblages observed in historic copper slags worldwide, these findings support re-evaluating legacy smelting wastes as potential secondary critical metal resources. Rather than relying on high-temperature re-smelting or strong mineral-acid systems, there is a need to evaluate selective, and environmentally benign hydrometallurgical routes to determine whether Cu and associated critical metals can be recovered via lower-impact processing routes. Such approaches may contribute to future circular resource strategies and long-term metal supply security.

References:
[1] Shen H and Forssberg E (2003) Waste Manag 23(10): 933-949. 10.1016/S0956-053X(02)00164-2
[2] Cempa M et al (2024) Minerals 14(10): 1050. 10.3390/min14101050
[3] ICSG (2025) World Copper Factbook 2025
[4] Dines (1956). The metalliferous mining region of south-west England. BGS, London

Using Appinite Geochemistry to Understand Critical Metal Mineralisation in the Scottish Highlands: A Mineral Systems Approach

Bronziet, J., Hartley, M.E., Neave, D.A. and Covey-Crump, S.

Department of Earth Science, University of Manchester, UK, M13 9PL

Within the last 20 years, exploration for critical metals has shifted from pattern matching towards a mineral systems approach that focuses on the physical processes driving ore formation. The Scottish Highlands host long-recognised mineralisation in critical chalcophile elements (e.g. Pb, Cu, Ag, Au), which continue to be mined today. Recent sulfur isotope work [1] indicates that at least part of this mineralisation is magmatic in origin, implying a direct contribution from mantle-derived magmas rather than solely crustal or hydrothermal sources. Our study focuses on the Grampian and the Northwest Highlands. These tectonostratigraphic terranes are separated by the late Caledonian (Scandian) Great Glen Fault, interpreted to record large sinistral displacement on the order of hundreds of kilometres [2]. Most known mineralisation occurs in the Grampian terrane, whereas the Northwest Highlands remain comparatively barren, presenting a key exploration and geodynamic question.

In this study, we use the geochemistry of appinites to investigate the origin of the disparity in mineralisation between the Grampian and Northwest Highlands terranes. Appinites are hydrous, mantle-derived, largely mafic intrusions dominated by amphibole phenocrysts, and are widely developed across the Caledonian orogen. Appinite emplacement in both terranes occurred during the Scandian event c.430 Ma [e.g. 3], when collision between Baltica and Laurentia closed the Iapetus Ocean and led to slab failure beneath the orogen. We have analysed major and trace elements in 30 appinite samples from the Grampian terrane and 21 from the Northwest Highlands terrane. We combine these data with amphibole-only thermobarometry to constrain magma evolution, storage and ascent pathways on either side of the Great Glen Fault. We aim to constrain mantle melting conditions and to clarify how metasomatised mantle sources, magmatic sulfur, and evolving crustal structures controlled the transport and deposition of chalcophile elements. Our goal is to refine regional models for critical metal fertility in the Scottish Highlands, and to link these processes via a mineral systems framework to provide transferable criteria for assessing critical metal potential in other ancient convergent margins worldwide, where similar metasomatised mantle sources and slab failure tectonics may localise globally significant metal resources.

[1] Graham, S.D. Et Al., (2017) Scotland: Ore Geology Reviews, v. 80, p. 961–984,
[2] Prave, A.R., Et Al., (2024) Geol Soc, v. 181, p. jgs2024- 085
[3] Rogers, G., and Dunning, G., (1991) Geol Soc, v. 148, p. 17–27,

Trace elements and REE behaviours in nepheline syenite and related weathering materials in tropical climatic conditions: case study of Eboundja nepheline syenite (Southern Cameroon)

Kwanang, K.K.[1], Santoro, L.[2], Li, M.Y.H. [3], Ngo Bidjeck, L.M.[1] and Ndjigui, P.-D.

[1]Department of Earth Sciences, Faculty of Science, University of Yaounde I, P.O. Box 812, Yaounde, Cameroon Kwanang.k@yahoo.com.
[2]Department of Earth Sciences, University of Turin, Via Valperga Caluso 35, 10125, To, Italy
[3]Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, United Kingdom

---

Rare earth elements (REEs) are critical metals for green technologies and high-tech industries. They can be extracted from both primary deposits (e.g., those associated with agpaitic rocks, such as the Ilímaussaq complex in Greenland) and regolith-hosted deposits (e.g., the Zudong deposit in China) [1]. Among these, regolith-hosted REE deposits offer the advantage of low-cost extraction. They form through chemical weathering of REE-rich rocks under favourable climatic conditions and are most abundant in subtropical regions (China, Madagascar [1]). In contrast, few discoveries have been reported in tropical equatorial areas, despite climatic conditions that also promote intense chemical weathering [2]. A key process in the formation of these deposits is the enrichment of REEs in the regolith relative to their concentration in the parent rock. Although numerous studies have shown that REEs can be enriched in weathered materials from tropical equatorial climates [3], the mechanisms of REE concentration in regoliths from these regions remain poorly understood. Investigating these mechanisms could provide valuable insights for the exploration of new deposits.

To address this gap, geochemical and mineralogical studies were conducted on two weathering profiles developed over metaluminous nepheline syenite at Eboundja, Cameroon, to evaluate the factors controlling REE enrichment in tropical equatorial regoliths. The two profiles, referred to as EB2 and EB6, exhibit similar morphological horizons (bedrock, saprolite, mottled, nodular, loose clayey, and organo-mineral). EB2 is characterised by high REE content in the parent rock (~600 ppm) and enrichment in the saprolite horizon. REEs are hosted primarily in allanite, whose susceptibility to weathering was enhanced by prior hydrothermal alteration. Enrichment in the lower saprolite is attributed to clay adsorption, accounting for ~60% of bulk REEs excluding Ce (~131 ppm), while in the upper horizons, REEs are adsorbed onto Fe-Mn oxyhydroxides. In contrast, EB6's bedrock contains low REE concentrations (~5 ppm), likely due to the combined effects of limited magmatic differentiation and hydrothermal alteration. This profile shows REE enrichment mainly through the accumulation of relic zircons. In tropical regions, intense leaching generates a REE-depleted zone from the surface to the upper saprolite, with enrichment occurring at deeper horizons than those typically observed in subtropical regions. Excessive leaching shifts the dominant enrichment mechanism from adsorption onto supergene minerals to the preservation of relic minerals, as demonstrated by the comparison between EB2 and EB6.

References:
[1] Li MYH and Zhou MF (2024) Econ Geol 113 (3):645–673
[2] Kwanang KK et al. (2026) J. Afr. Earth Sci. 237 10590
[3] Ntomb YD et al. (2024) J. Afr. Earth Sci. 216 105315

Macro- to nanoscale mineralogical controls on the genesis of deep weathered carbonatite REE deposits

Smith, M.P.[1], Maciag, B. [1], Broom-Fendley, S. [2], Li, M.Y.H.[3], Wall, F.[2], Kumar, P.[1], Rooks, C.[1], Grasten, T.[4], Geraki, K.[5]

[1]School of Applied Sciences, University of Brighton, U.K.
[2]Camborne School of Mines, University of Exeter, Falmouth, U.K.
[3]Department of Earth Science and Engineering, Imperial College, London, U.K.
[4] Sokli Oy, Savukoski, Finland.
[5]Diamond Light Source, Harwell Campus, Oxford, U.K.

Carbonatite-hosted rare earth element (REE) deposits, alongside granitoid regolith hosted ion adsorption deposits, form one of the key resources to meet REE supply for decarbonisation and high technology industry [1]. Despite a huge increase in exploration and research into carbonatite-hosted REE resources, only four deposits are currently mined (as of end 2025), and one of these (Mount Weld, Australia [2]) is hosted in deep weathered laterite rather than bedrock carbonatite. It is therefore important to understand the supergene processes controlling enrichment and depletion of the REE during carbonatite weathering, and how their mineralogical hosts evolve. The former influences the resource potential of carbonatites through supergene enrichment, whilst the latter is critical in controlling geometallurgy and ultimately the potential for processing of the weathered zone. As part of the NERC funded SCREED (Supergene enrichment of carbonatite hosted REE deposits) project we have studied the geochemistry and mineralogy of deep weathered carbonatites from macro-scale genetic processes and elemental distribution, down to their mico-scale mineralogy and the nano-scale crystallographic sites of the REE. Study sites include the palaeo-weathering profile at Sokli, Finland, and actively weathering carbonatite at Longonjo, Angola.

Rare earth redistribution processes in weathering can include residual enrichment of primary minerals, dissolution and active supergene enrichment in secondary phosphates and fluorcarbonates, and adsorption on to clays and oxyhydroxides, alongside mechanical transport through karst collapse, fluvial and eluvial processes. At Sokli bulk rock geochemistry and sequential leaching studies indicate that residual enrichment is the dominant process, but dissolution-reprecipitation as authigenic phosphates resulting in the formation of anomalous REE patterns is also a significant process. Adsorption onto clays is limited by the high pH of the local carbonatite interacting groundwater, but oxides can host a significant portion of the REE content. These interpretations are supported by individual mineral chemistry, with cerium anomalies indicating oxidation and dissolution-reprecipitation developed in secondary monazite, rhabdophane and crandallite-group minerals. Pyrochlore may be a significant source of mobile REE as the B-site cations remain immobile but REE on the A-site are leached during weathering and replaced by K and Ba, or by the development of A-site vacancies.

X-ray adsorption spectroscopy (XAS) conducted at the Diamond Light Source confirms the oxidation of CeIII to CeIV, and the modification of the aluminophosphate lattice through development of crandallite group minerals from crandallite-goyazite-gorceixite (Ca-Sr-Ba) to florencite-(Ce), the precipitation of secondary monazite and rhabdophane and the leaching and replacement of pyrochlore. Overall, textural, mineralogical and spectroscopic data support genetic models whereby the lateritic profile is not the product of a single continuous weathering event. REE-enriched profiles form through a repeated cycle of dissolution and collapse, accompanied by residual enrichment and dissolution-reprecipitation processes which control the final mineralogy and the potential for inter-element fractionations. Further work from this project aims to constrain the time scales of palaeo-profile development (see Broom-Fendley et al., - this meeting), the role of the soil microbiome in mineral breakdown and element mobilisation, and the controls on contrasting deposit characteristics from the geological, tectonic and climatic environment.

References:

[1] Mudd et al. (2024) British Geological Survey Open report, OR/24/047. 235pp.
[2] Lottermoser, B.G. (1990) Lithos, 24, 151-167.

Dating carbonatite weathering using U–Pb in apatite

Broom-Fendley, S.[1], Littler, K.[1], Evenstar, L.[2], Chen, W.[3], Li, M.Y-H.[4,5], Yang F.[3], Smith M.[5], and Wall F[1].

[1]Camborne School of Mines, University of Exeter, Cornwall, UK; s.l.broom-fendley@ex.ac.uk
[2]Department of Geography, Earth and Environmental Sciences, University of Plymouth, UK
[3]State Key Laboratory of Geological Processes and Mineral Resources, Collaborative Innovation Center for Exploration of Strategic Mineral Resources, China University of Geosciences, Wuhan, China
[4]Department of Earth Science and Engineering, Imperial College London, UK
[5]School of Applied Sciences, University of Brighton, BN2 4GJ, UK

Carbonatites host major high-grade rare earth element (REE), niobium, and phosphate deposits. Weathering can enrich these elements as carbonate dissolves and immobile components remain, forming thick profiles typically associated with tropical climates. However, some deposits occur in low-weathering environments (e.g., the Arctic), where the timing and duration of weathering remain unclear, hampering prospectivity analysis for further exploration. Here we present the first successful dating of supergene carbonate-bearing fluorapatite ("francolite") from the Sokli carbonatite, Finland.

The Sokli weathering profile comprises saprolith and remnants of the lower pedolith containing residual vermiculite, magnetite, baddeleyite, and apatite, variably cemented by carbonate-bearing fluorapatite [1]. This mineral occurs only in the lower pedolith as discontinuous crusts interlayered with lateritic material. Textures follow a typical weathered-carbonatite paragenesis: early massive phosphate cement replacing carbonates, followed by later colloform apatite along fractures and cavities, often in multiple generations [2].

In situ U–Pb dating of apatite from 13 samples across six boreholes yielded ages mainly between 7 and 40 Ma, with peaks at ~11, 22, and 50 Ma. Within samples, apatite generations follow the observed paragenetic sequence, but ages show no clear depth dependence. These patterns support a model of continuous karstic collapse, where calcite dissolution outpaces new apatite formation. Massive apatite forms at the saprolite–pedolith interface, while colloform apatite reflects dissolution and reprecipitation of phosphate during collapse.

These results provide the first U–Pb apatite dates for carbonatite weathering, indicating that Sokli weathering mainly occurred during the mid-Miocene, consistent with evidence for Arctic warming at that time [3].

References:
[1] Li M Y-H et al (in review) Econ Geol
[2] Broom-Fendley S et al. (2020) Min Dep 56:863–884
[3] Hall AM et al. (2024) Palaeogeography, Palaeoclimatology, Palaeoecology 634:111927

Understanding Lithium Leaching from Lithium-Bearing Granite and Polylithionite: Implications for Lithium Extraction from Geothermal Brines,

Evans, A.J.M.[1,2], Tibble-Howlings, J.[3], Littleton, J.A.H.[1], Farrell, N.J.C.[2], Neave, D.A.[2], Hartley, M.E.[2] and Hunt, S.A.[1]

[1]Department of Materials, The University of Manchester, Oxford Road, M13 9PL
[2]Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, M13 9PY
[3]Department of Chemical Engineering, The University of Manchester, Oxford Road, M13 9PL

The global transition towards decarbonisation and renewable energy systems has driven unprecedented demand for a broad range of raw materials. The uneven geological distribution of mineral resources, compounded by geopolitical constraints, creates significant supply vulnerabilities. To address these risks, critical raw materials—defined as materials of high economic importance and high supply risk—are periodically identified to inform policy and resource security strategies. Within these lists, strategic raw materials comprise a subset considered essential for the green, digital, defence, and space industries.

Lithium is classified as a strategic raw materials due to its central role in battery technologies that underpin many green technologies and applications. Currently, Li production is dominated by pegmatites – mainly in Australia – and continental brines in Chile, Argentina, Bolivia and China, resulting in limited geographic diversity in supply chains. With Li demand projected to exceed supply by 2030, previously uneconomical resources are being evaluated to secure future Li supply. Among these are Li-bearing granites and associated geothermal brines, which are under investigation in several regions, including Cínovec on the Germany-Czechia border and Cornwall, UK.

Lithium is hosted within the micaceous phase of granite, with polylithionite representing the Li-rich end member. In this study, we investigate how aqueous solvents of varying composition influence the liberation of Li^+ and other cations from powdered samples of pure polylithionite mica and a typical Li-rich granite from the St. Austell granite pluton within the Cornubian Batholith. Preliminary experiments indicate that NaCl solutions, a major constituent of geothermal brines, are insufficient to leach usable quantities of lithium, whereas both strong and weak acids promote lithium leaching proportional to the pH.

Mineralogical transformations during extraction of lithium from spodumene

Oskierski, H.C.[1], Ncube, T.[1], Alhadad, M.[1], Chischi, J.[1], Abdullah, A.A.[1], Senanayake G.[2] and Dlugogorski B.Z.[3]

[1]Sustainable Geochemistry and Mineral Sciences (GeMS), School of Mathematics, Statistics, Chemistry and Physics, Murdoch University
[2]School of Mathematics, Statistics, Chemistry and Physics, Murdoch University
[3]Energy and Resources Institute, Charles Darwin University

About half of global lithium supply is derived from lithium-bearing minerals, with spodumene representing the most important commercial source [1]. Extraction of lithium from spodumene concentrates involves a sequence of high-temperature and chemical processing steps, including calcination, roasting, leaching, purification, and crystallisation to produce lithium hydroxide or lithium carbonate. Mineralogical transformations during calcination and acid, alkaline or sulphation roasting control lithium recovery, leaching selectivity and by-product value but are poorly understood. Here, we present ex-situ and in-situ observations of these mineralogical transformations by thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), laboratory and synchrotron X-ray diffraction (XRD) and scanning electron microscopy (SEM) that document the reaction sequences and mechanisms underpinning different lithium extraction processes.

In the conventional sulfuric acid process calcination at temperatures above 1050 °C converts naturally occurring, monoclinic α-spodumene into more reactive, tetragonal β-spodumene [2], from which lithium can be extracted by exchange of Li^+ with H^+ in hot concentrated sulfuric acid. Subsequent water leaching results in a delithiated β-spodumene (DBS) by-product that is currently investigated as a supplementary cementitious material (SCM) [3]. Gangue minerals resulting from spodumene alteration melt during calcination, leading to formation of glass that encapsulates spodumene and degrades lithium extraction [4].

As an alternative to the conventional process, lithium can be efficiently extracted from β-spodumene by alkaline pressure leaching with NaCl and NaOH. The conditions of this extraction process can be adjusted to produce different by-products, one of which is analcime, a zeolite mineral that has cementitious properties and can absorb radioactive elements by ion exchange [5]. Roasting of α-spodumene with K_2SO4 results in the formation of leucite, a slow-release fertiliser. This extraction process progresses through ion exchange and reconstructive transformation of α-spodumene to leucite and is mediated through a K-Li-bearing sulfate melt [6]. The presented work demonstrates that understanding of the above mineralogical transformations is critical for efficient rejection of impurities and high lithium recoveries into leach liquors but also for the manufacturing of by-products with various functional properties, uses and markets.

[1] USGS Mineral Commodity Summary 2026 Lithium
[2] Abdullah et al. (2019) Mineral Engineering 140, 105883.
[3] Jin et al. (2026) Cement Concrete Composites 169, 106549.
[4] Chischi et al. (2022) GSA Connects meeting paper no. 257-8.
[5] Alhadad et al. (2022) Hydrometallurgy 105985.
[6] Ncube et al. (2021) Inorganic Chemistry 60, 3620-3625.

Volatiles and the Many Types of Melt: Why Critical Metals Aren't Always Where Expected In Ore Deposits

McFall, K.A.[1], McDonald, I.[2], Hanley, J.J.[3], Kerr, M.[3], Yudovskaya, M.A.[4], Kinnaird, J.[4], and Tattitch, B.[5]

[1]Department of Earth Sciences, University College London, London, UK, k.mcfall@ucl.ac.uk
[2]School of Earth and Environmental Science, Cardiff University, Cardiff, UK.
[3]Department of Geology, Saint Mary's University, Halifax, Canada.
[4] School of Geosciences, University of the Witwatersrand, Johannesberg, South Africa.
[5]Centre College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, USA.

Ore formation models in magmatic-hydrothermal deposits have traditionally focused on interactions between volatiles and silicate melts. However, sulphide melts, semi-metal melts, and salt melts (carbonate, sulphate and chloride) can all carry metals. In particular, the interaction of volatiles with semi-metal melts and salt melts can have a profound affect on metal distribution and geometallurgy in magmatic and magmatic-hydrothermal ore deposits. However, evidence for the presence of these more unusual melts is often cryptic or not preserved.

Potential critical metal by-products in porphyry Cu deposits (PCDs) such as Pd, Te and Bi, are predominately hosted in microscopic Bi-Te accessory minerals which are found as melt inclusions in hydrothermally-precipitated silicates as well as sulphides [1]. Under certain conditions an immiscible semi-metal melt may exsolve from a hydrothermal fluid, 'collecting' and concentrating precious metals. Critical metal rich PCDs are often also enriched in semi-metals [2] and this semi-metal collector mechanism may control critical metal endowment and geometallurgy in these deposits. A similar mechanism may also occur in some skarn, greisen Sn, and epithermal Au deposits [e.g. 3].

Salt melts have been shown to transport metals in many high temperature magmatic-hydrothermal systems, such as sulfide-bearing carbonatites [4], IOA, and IOCG deposits [5]. The Northern Limb of the Bushveld Complex, South Africa is one of the most important magmatic sulfide Ni-Cu-PGE provinces in the world. A systematic fluid inclusion survey of all ore deposits in the Limb observed carbonate-dominated hypersaline brine inclusions in cumulate magmatic silicates across all deposits. These homogenise >820°C, above solidus temperatures, and are interpreted to represent a hydrous salt melt. Evidence of brine-sulfide melt interaction was observed in all deposits, implying this was a common factor during their development. Hydrous carbonate salt melts may therefore play an important role in critical metal transport in high temperature magmatic-hydrothermal systems generally, and the Northern Limb of the Bushveld Complex in particular.

References:
[1] McFall et al. (2018) Ore Geo Rev 99:344-364
[2] McFall et al. (2021) SEG 24:277-295
[3] Cook and Ciobanu (2004) Min Mag 68:301-321
[4] Walter et al. (2021) Earth Sci Rev 215:103-509
[5] Xu et al. (2024) Geology 52:417-422

Critical Metal Enrichment in Sphalerite from Zn–Pb–F–(Ba–Sr) Deposits, Northern Tunisia: Implications for Mississippi Valley-type Systems

Jemmali, N.[1,2], Bertrandsson Erlandsson, V.[3], Melcher, F.[3], Rddad, L.[4], Souissi, F.[2,5]

[1] University of Gafsa, Faculty of Sciences of Gafsa, Sidi Ahmed Zarroug, 2112 Gafsa, Tunisia.
[2] Laboratory of Useful Materials, Nationa Institute of Research and Physicochemical analysis, 2026 Technopole de Sidi Thabet, Tunisia.
[3] Department of Geosciences and Applied Geophysics, Technical University of Leoben, Leoben, Austria.
[4] Earth and Planetary Division, Department of Physical Sciences, 2001 Oriental Boulevard, Kingsborough Community College of the City University of New York, NY 11235-2398 Brooklyn, New York, USA.
[5] University of Tunis El Manar, Faculty of Sciences, 2092 El Manar, Tunis, Tunisia.

Trace element signatures in sphalerite provide key insights into metal sources and ore-forming processes in carbonate-hosted Zn–Pb–F–(Ba–Sr) deposits of northern Tunisia. This study focuses on five representative deposits (El Akhouat, Sakiet Koucha, Jebel Trozza, Hammam Zriba, and Jebel Mecella) to evaluate the distribution of critical metals, particularly germanium (Ge) and cadmium (Cd), across different sphalerite generations.

Results reveal significant variability in trace element contents among deposits and between paragenetic stages. Germanium enrichment is particularly pronounced in Hammam Zriba, Jebel Trozza, and Jebel Mecella, whereas El Akhouat shows comparatively low concentrations. Cadmium is consistently enriched across all deposits. Ge- and Cd-rich sphalerite occurs in both colloform and crystalline textures but is preferentially associated with late-stage mineralization linked to Cu–Ag–Hg–As–Sb–Pb sulfosalt assemblages.

These findings suggest that critical metal enrichment is controlled by evolving physicochemical conditions during ore formation, with late, low-temperature fluids playing a key role. The results highlight the strong potential of selected Tunisian deposits as targets for Ge and Cd critical metals and provide new constraints on trace element incorporation in sphalerite within MVT systems.

Critical Mineral Enrichment in the Carboniferous Carbonate-hosted Deposits of the Pb-Zn-F Orefields of Northern England and Wales

Ryczek, D.J.[1], Farrell, N.J.C.[1], Hollis, C.[1], Healy, D.[2] and McClenaghan, S.H.[3]

[1]Department of Earth and Environmental Sciences, The University of Manchester, Manchester, M13 9PY, UK
daniel.ryczek@postgrad.manchester.ac.uk
[2]Geosolutions Leeds, School of Earth, Environment, and Sustainability, University of Leeds, Leeds, LS2 9JT, UK
[3]Department of Geology, Trinity College Dublin, Dublin, 2, Republic of Ireland

---

Globally significant sources of base metal resources, such as Zn, Pb, and Cu, occur in low temperature (80-280°C) carbonate replacement deposits (CRDs) or carbonate-hosted deposits, such as Mississippi valley type (MVT), Sedimentary Exhalative (Sedex), and Irish-type [1]. Carbonate-hosted deposits also have the potential to contain economic quantities of trace metals, such as Cd, Ge, Ga, and In as secondary resources. These metals are now classified as critical minerals (CMs) or critical raw materials (CRMs), essential for the development of new technologies and pushing forward the green transition [2]. CRMs are most commonly associated with the sphalerite ((Zn, Fe)S) mineralization from these deposits via various styles of coupled substitution into the mineral crystal lattice [3].

In the north of England and Wales there are four main lower Carboniferous (Asbian-Pendleian) carbonate-hosted Pb-Zn-F orefields in an area of over 7000 km^2, separated by as much as 200 km and containing more than 750 small to moderate sized historical surface and shallow (<300 m) works. The base metal deposits from these areas of mineralization are historically classified as MVTs and were targeted mainly for their widespread lead, fluorite, and baryte mineralization dating back to at least the Roman era [4,5]. More modern commercial production for either Pb or fluorite across the region ceased for the most part during the 1980s-90s, with the last operational fluorspar mine producing sporadically until 2023. In a few instances, historical secondary production of Ag and Zn were reported from some of these orefields, but for the most part, the potential for Zn and CRM resources of the region have historically been ignored, underreported, and understudied.

This ongoing project is focused on the potential for CRM enrichment within Carboniferous carbonate-hosted deposits in the UK by studying the factors responsible for their enrichment through a combination of geospatial, petrological, geochemical, and field based methods. Initial phases of the project have been focused on the databasing and geospatial interpretation of large amounts of open-source data and the collection, organization, and detailed petrological study of representative samples of variable sphalerite textures and other associated sulphide mineralization from across each of the main orefields. Preliminary geochemical results, particularly from *in situ* laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), have highlighted varying but highly anomalous amounts of CRM enrichment from some of the sampled occurrences, such as up to 3723 ppm Cd, 862 ppm Ge and 33 ppm In (18600x, 507x and 660x avg. crustal abundances respectively). In addition to determining the CRM potential of base metal deposits in the exposed shallow portions of the UK orefields and gaining a better understanding of the processes responsible for their enrichment, our work could have major implications for the overall district-scale mineralizing system of the region and the potential for more significant deposits of base metal mineralization further at depth.

References:
[1] Leech DL et al. (2005) SEG 100th Anniversary Vol: 561-608
[2] Luo K et al. (2022) Min Dep 57: 1343-1365
[3] Cook NJ et al. (2009) Geo et Cosmo 73: 4761-4791
[4] Cann JR and Banks DA (2001) Proceedings Yorkshire Geo Soc 53: 187-196
[5] Bouch JE et al. (2008) BGS Research Report RR/08/06

Evidence for mechanochemical CO_2 trapping as silicon carbonates and mineral lattice cages by comminution of silicate rocks in CO_2

Stillings, M.S.[1], Stevenson, S. [1] , Donagueda Suso, B.[1] Hope, M. [2], Head, A[3]. and, Lunn, R.J.[1]

[1]Universtity of Strathclyde, Department of Civl and Environmental Engineering mark.stillings@strath.ac.ukand
[2]University of Warwick Department of Chemistry.
[3]Brookhaven National Laboratory Centre for Functional Nanomaterials

---

Historically, CO_2 capture into rocks and minerals has been achieved either through high-temperature direct carbonation or via an aqueous route, both forming metal carbonates[1]. In this work, we demonstrate a distinct mechanochemical route that forms stable silicon carbonate within silicate rocks and minerals through their comminution under a CO2 atmosphere.

Silicon and carbon, both group IV elements, form oxides (SiO_2 and CO_2) that are ubiquitous across chemistry, materials science, and planetary science. Under ambient conditions, these oxides are typically unreactive, although metastable silicon carbonates have been shown to form at high pressures and temperatures, then decomposing within 24 hours as conditions return to ambient [2]. We show that mechanochemical processing, where mechanical energy drives chemical reactions, can instead induce stable bonding between CO_2 and silica at ambient temperature and low pressure (0.4 MPa). Using high-energy ball milling in a CO_2 atmosphere, we find that polymineralic silicate rocks, including basalt and granite, can trap up to 15.3 g/kg and 13.9 g/kg of CO_2, respectively,without process optimisation. The trapped CO_2 is retained in a thermally stable (up to 300°C) and water-insoluble form [3].

To isolate the role of mineral chemistry in mechanochemical CO_2 capture, we milled quartz and quartzite (99.9% SiO2) under CO_2, and both exhibited the same stable CO_2-trapping behaviour. In contrast, milling individual minerals in CO_2 (olivine, biotite and pyroxene) also captured CO_2, but predominantly in water-soluble forms. CO_2-milled rocks and minerals additionally released significantly higher concentrations of Mg and Ca, and other group I and II metals into aqueous solution relative to air-milled controls, suggesting that surface-bound CO_2 weakens or alters the bonding environment of coordinating cations in the silicate lattice.

To characterise the bonding environment, we conducted X-ray Photoelectron Spectroscopy (XPS), Infrared (IR) spectroscopy, and solid-state ^{13}C-NMR on CO_2- and air-milled samples before and after water exposure. XPS spectra confirm the presence of single and double carbon-oxygen bonds concurrent with CO_2 and carbonate species, while IR spectra reveal clear signatures of silicon carbonate groups (including unidentate, bidentate, and bridging carbonates) along with evidence for lattice-bound CO_2. Solid-state ^{13}C NMR of CO_2-milled quartzite and basalt confirms the presence of silicon carbonate and bound CO_2. In situ heating experiments (25–700°C) reveal that silicon carbonates thermally decompose between 350°C and 700°C (depending on the substrate), whereas lattice-bound CO_2 molecules remain insoluble and trapped within the lattice above 700°C in all samples. These results demonstrate that mechanochemical CO_2 mineralisation provides a promising low-energy pathway for carbon capture and offers a new synthesis mechanism for producing stable silicon carbonates and caged CO_2 within silicate minerals, with important implications for climate mitigation and resource recovery technologies.

References

[1] Lackner, K.S., et al., (1995).Energy 20 1153-1170.
[2] Santoro, M., et al., (2011). Proc. Natl. Acad. Sci. U.S.A. 108 (19).
[3] Stillings, M., Shipton, Z.K. & Lunn, R.J. (2023). Nat Sustain 6, 780–788 (2023).

NEUMAN MEDALLIST

Research on the Edge

Berry, A.J.[1]

[1]Research School Earth Sciences, Australian National University, Canberra, ACT 2601, Australia

In the Earth sciences, processes are often interpreted and inferred from the concentrations and/or isotopic ratios of trace elements. An impressive arsenal of analytical instruments have been developed to measure very low concentrations and tiny differences. However, the oxidation state and coordination environment of an element, i.e., the speciation, are often poorly understood but are integral to understanding geochemical behaviour. For example, two different oxidation states of the same element behave geochemically as if they are different elements (e.g., the Eu anomaly in igneous rocks). The oxidation state ratio is dependent on the oxygen fugacity, which is one of the key variables that controls mineral assemblages, but quantification is challenging. Indeed, the oxidation state of Fe in mid-ocean ridge basalt (the most common rock on the surface of the Earth) is still argued about today.

The most widely used method for determining the speciation of elements is X-ray Absorption Spectroscopy (XAS) carried out at a synchrotron light source. However, to use XAS to understand how the oxidation state of an element varies as a function of geological variables requires experimental petrology. Using a gas mixing furnace, which provides continuous control of temperature and oxygen fugacity at atmospheric pressure, and a piston-cylinder, which provides continuous control of temperature and pressure at discrete values of oxygen fugacity, the oxidation state of an element can be investigated as a function of composition, temperature, pressure and oxygen fugacity. The oxygen fugacity range over which an element changes from fully oxidised to fully reduced depends on the number of electrons involved and is ~16 log units for a single electron reduction (e.g., Fe^{3+} to Fe^{2+}) and ~2 log units for eight electrons (e.g., S^{6+} to S^{2-}). We can experimentally access ~25 log units of oxygen fugacity. Our approach is to prepare samples over a much larger oxygen fugacity range than seen in nature to allow the function describing the dependence of oxidation state on oxygen fugacity to be defined accurately. Systematic changes in X-ray Absorption Near Edge Structure (XANES) spectra can then be correlated with changes in oxidation state and referenced to the thermodynamically expected function. The result is an ability to quantify redox states in quenched melts with an accuracy of better than 2%. Melts can also be studied in situ. Results will be presented for the quantification of Cr, Fe, Eu, Ti and U in glasses.

For minerals, the approach is more challenging because of the role of crystal chemistry. For example, the anomalous concentrations of Ce and Eu relative to the other rare earth elements in zircon are a result of site preference for different oxidation states. These anomalies are an indicator of the oxygen fugacity of the melt from which the zircon crystallised, which is of particular interest for rocks where zircon is all that remains (such as those from the Hadean). In recent work we have shown how the magnitude of the anomaly is strongly dependent on sector zoning and hence the orientation of the zircon crystal. For other trace elements the site can dictate how the concentration is interpreted. For example, the Ti content of zircon is widely used as a geothermometer, but assumes Ti occupies the Si site, which requires estimates of the silica activity. While Ti does occupy the Si site at low pressures, we have found that at pressures corresponding to the lower crust it occupies the Zr site. Our approach was to prepare a series of samples as a function of pressure and then determine the Ti site by XANES spectroscopy. The result is a recalibration of the Ti-in-zircon thermometer that improves the accuracy of temperature estimates for ultra-high pressure metamorphic rocks by up to 100 ˚C.

Kyanite-muscovite-dumortierite vein mineralisation mechanisms from advanced microstructural analysis using EBSD.

Mariani, E.[1,4*], Dandekar, S.[2], Dandekar, T.R.[3], Khatirkar, R.K.[2], Pande, K.[2,5], Gardner, J.[1,4], Bagshaw, H.[4], Randive, K.[6] and Peshwe, D.[2]

[1]Department of Earth, Ocean, and Ecological Sciences, University of Liverpool, Liverpool, L69 3GP, UK
[2]Department of Metallurgical and Materials Engineering, VNIT, Nagpur, Maharashtra, India-440010
[3]School of Mechanical and Design Engineering, University of Portsmouth, Portsmouth, PO1 3DJ, UK.
[4]Scanning Electron Microscopy Shared Research Facility (SEM SRF), University of Liverpool, Liverpool, L69 3GL, UK
[5]G. H. Raisoni College of Engineering, Nagpur, Maharashtra, India-440001
[6]Post Graduate Department of Geology, RTMNU, Nagpur, Maharashtra, India-440001

Dumortierite, an aluminous borosilicate mineral, is relatively rare in Earth's crust, but it is the second most abundant aluminous borosilicate after tourmaline. Boron is an element with many uses in modern societies worldwide, from health products to wind turbine blades for clean energy, but of limited availability and at future risk of supply. Only a limited number of studies have been published on dumortierite mineralization processes and the factors that control its abundance and distribution remain poorly understood.

Here we present the first comprehensive electron backscatter diffraction (EBSD) study of dumortierite mineralization mechanisms in kyanite-muscovite-dumortierite veins occurring in the metapelites of the Amgaon Gneiss Supracrustals, in the Girola hill area, Sakoli region, Central India. Advanced microstructural and chemical analyses show that mixed-mode brittle-viscous deformation in kyanite, by fracturing and easy glide on (100)[001], facilitates fluid-rock interactions with reactive hydrothermal fluids rich in B, F, and K and containing Na, Ti, Mg, Fe and Pt. These interactions cause the dissolution of kyanite along fracture and cleavage surfaces and the precipitation of muscovite (F = 0.32 wt%) and topaz (F = 16.48 wt%). The motion of ripplocation defects in muscovite facilitates fluid migration along cleavage surfaces and crystallisation of dumortierite needles within these surfaces. Fluid flux removes silica in solution from the system, so reactions may continue. The observed mineral assemblage, the microstructural signature of kyanite and muscovite, the moderate fluorine content of topaz, and low fluorine content of muscovite, together suggest that dumortierite mineralization results from hydrothermal activity, possibly in a transitional magmatic-hydrothermal environment, possibly at $P > 2.5$ kbar and $400° < T < 550°$, that could be linked with granite intrusions in the area.

Using EBSD we demonstrate that dumortierite mineralization is focussed along muscovite basal cleavage surfaces and dumortierite needle elongation is likely controlled by the fluid flux direction. These new results advance our understanding of dumortierite mineralization mechanisms and conditions and have important implications for our understanding of the distribution of this aluminous borosilicate mineral in muscovite-rich rocks.

Tracing Paleoproterozoic fluid events using Apatite from the Dharwar Craton and adjoining Granulite Terrane boundary

Pandey, R.*[1], Kumar Singh, N.[1], Debnath, S.[1], Giuliani, A.[2,3], Lorenzo, T.[2], Belyatsky, B.[4], Chalapathi Rao, N.V.[1,5], Chew, D.[6], Amal Dev, J.[5] and Tomson, J.K.[5]

[1]Mantle Petrology Laboratory, Department of Geology, Institute of Science, Banaras Hindu University, Varanasi-221005, India. *Presenting Author E mail: rohit.pandey1@bhu.ac.in; rhtgeo@gmail.com
[2]Institute of Geochemistry and Petrology, Department of Earth and Planetary Sciences, ETH Zurich, 8092 Zürich, Switzerland
[3]Earth and Planets Laboratory, Carnegie Institution for Science, Washington, 20015 DC, United States.
[4]Centre for Isotope Research, A.P. Karpinsky All Russian Geological Research Institute (FSBE "Karpinsky Institute"), St. Petersburg 199034, Russia
[5]ESSO-National Centre for Earth Science Studies, MoES, Akkulam, Thiruvananthapuram 695011, India
[6]Department of Geology, Trinity College Dublin, Dublin

Plutonic complexes in cratonic lithosphere preserve records of prolonged magmatism and later tectono-thermal modification, providing insights into continental crust evolution. The accessory mineral apatite is particularly sensitive to fluid-mediated disturbance and can record post-magmatic thermal events not always preserved in more robust chronometers. This study investigates apatite U-Pb systematics from two Alkaline-Carbonatitic complexes of the Dharwar Craton: the Neoarchean Koppal Alkaline Complex (KAC) in Central Dharwar Craton (CDC) and the Gundlupete Carbonatite-Syenite Complex in Western Dharwar Craton (WDC), in order to evaluate the role of fluid-assisted processes in resetting apatite geochronometers and recording Paleo-proterozoic tectono-thermal activity across both the craton interior and its tectonically reactivated margins. In the KAC, in-situ LA-ICP-MS U-Pb dating of apatite from syenites and associated mafic-ultramafic intrusives (MUIs) yields ages ranging from ca. 2366 ± 70 Ma and 2393 ± 38 Ma for the syenites, and 2306 ± 33 Ma and 2438 ± 29 Ma for the MUIs, significantly younger than the previously reported zircon emplacement age of 2528 ± 9 Ma. Apatite occurs as fluorapatite enriched in Sr and rare earth elements with high F contents (~1.1-3.5 wt.%), consistent with primary magmatic crystallization and the absence of pervasive metasomatic alteration. The younger and dispersed apatite ages therefore reflect partial resetting of the U-Pb system rather than primary crystallization ages. These disturbances are interpreted to result from episodic hydro-(carbo)thermal fluid activity associated with Paleoproterozoic metamorphic breakdown of calc-silicate minerals within the structurally deformed KAC and possibly fluid release during multiple pulses of mafic dyke emplacement within the craton interior, promoting localized Pb loss and isotopic exchange along grain boundaries.

In contrast, apatite from the Gundlupete carbonatite occurs as euhedral to subhedral prismatic grains within calcite-dominated matrices and preserves primary magmatic textures. The magmatic emplacement age of the carbonatite has previously been constrained at ~2474 Ma based on U-Pb geochronology of Monazite. However, apatite U-Pb systematics define a coherent lower-intercept age of 2001 ± 69 Ma, indicating a significant Paleoproterozoic Pb-loss event and complete resetting of the apatite U-Pb chronometer. Textural evidence and trace element variability, including low chondrite normalised REE rations $(La/Sm)_N$ <2, further indicates chemical re-equilibration during fluid-rock interaction. This resetting likely stem from fluid-assisted thermal overprinting related to regional tectono-metamorphic activity along the nearby Salem-Attur Shear Zone or to contemporaneous large-scale magmatic pulses capable of generating transient heat and fluid fluxes along the craton-granulite terrane boundary. Together, these results demonstrate that apatite U-Pb chronometry in alkaline and carbonatitic systems provides a sensitive record of fluid-mediated post-magmatic processes. The combined datasets reveal spatially variable but temporally significant Paleoproterozoic hydrothermal events that modified primary magmatic signatures across both the interior and tectonically reactivated margins of the Dharwar Craton, highlighting the utility of apatite geochronology for reconstructing cryptic fluid-rock interaction and the protracted thermal evolution of cratonic lithosphere.

Deep-Time Mineralogical Metaphors: Arrows, Cycles, Trees, and Networks

Hazen, R. M.[1]

[1]Earth and Planets Laboratory, Carnegie Institution for Science, Washington DC, USA; rhazen@ciw.edu

Since the seminal contributions of James Hutton (1726-1797) and his description of the "rock cycle," metaphors have played a key role in the scientific conceptualization and public understanding of Earth's mineral evolution. The 4.6-billion-year history of changes in Earth's mineral diversity and distribution provides a robust, comprehensively documented example of an abiotic evolving system. As in evolution of other domains, including elements, organic molecules, life, and social and technological systems, minerals began simply—in that instance with a score of stellar minerals. New minerals emerged through a sequence of physical, chemical, and ultimately biological processes. Stage by stage, minerals diversified through a congruent path, each stage adding complexity to what came before—a history that has led to today's inventory of more than 6200 approved mineral species.

Concepts of mineral and rock evolution have been framed using a range of metaphors, each of which captures an aspect of change through time. The uni-directional increase in diversity of Earth's minerals through geological history suggests an "arrow of time"—a characteristic of many evolving systems that begin simply and exhibit an inexorable increase in structural and chemical complexity. Rocks and minerals also display cycles in time as they evolve—a metaphor championed by James Hutton in his transformational *Theory of the Earth* [*1*]. From daily hot/cold and wet/dry cycles to longer-term effects of gradual glaciation/deglaciation, episodic bolide impacts, and plate tectonics, many minerals form, degrade, and form anew.

Superimposed on the arrows and cycles of mineral evolution is a tree-like organization of diversifying mineral species—a hierarchical framing based on chemistry and structure that is embedded in the Dana system of classification. In the recently proposed "Evolutionary System of Mineralogy" [*1*] network analyses of the evolution and co-occurrence of minerals provide multi-dimensional visual metaphors that incorporate arrows, cycles, and trees.

[1] Hutton J (1795) Theory of the Earth with Proofs and Illustrations. Edinburgh: Creech
[2] Hazen RM et al. (2023) In: L Bindi & G Cruciani, Celebrating the International Year of Mineralogy. NY: Springer, 15-37

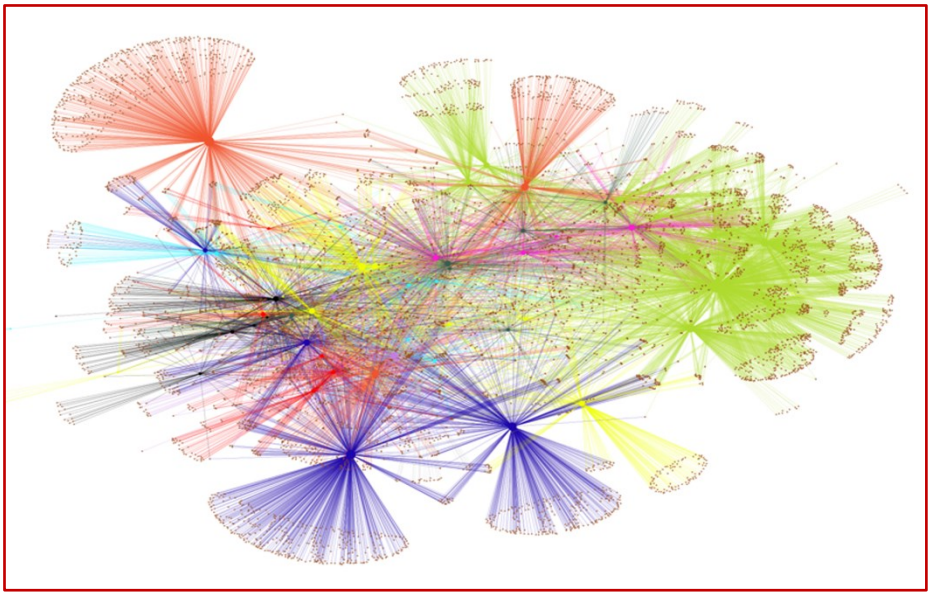


Figure 1. A bipartite network links 57 nodes that represent different modes of mineral formation to ~6000 nodes representing different IMA-approved mineral species. This graph thus is a visual metaphor for all of Earth's near-surface mineralogy.

Wangxibinite, TiFe: a new mineral with implications for the interpretation of an enigmatic coesite-bearing fragment from the Luobusa ophiolite, Tibet, China

Xiong, F.[1], Mugnaioli, E.[2], Xu, X.[1], Yang, J.[3], Wirth, R.[4], Grew, E.S.[5*] and Yates, M.G.[5]
(*presented by R.M. Hazen*)

[1]Center for Advanced Research on the Mantle (CARMA), Key Laboratory of Continental Dynamics of Ministry of Natural Resources, State Key Laboratory of Deep Earth and Mineral Exploration, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China
[2]Department of Earth Sciences, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy
[3]School of Earth Sciences and Engineering, Nanjing University, Nanjing, 210023, China
[4]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section 3.5 Interface Geochemistry, Telegrafenberg, C 120, D-14473 Potsdam, Germany
[5]School of Earth and Climate Sciences, University of Maine, Orono, Maine 04469 USA
*E-mail: esgrew@maine.edu. In-person oral presentation preferred. Session: Evolving mineralogy of the Earth system: interactions within the crust, mantle and core

---

The mineral assemblage in one of the fragments extracted from chromitite ore body #31 in the Luobusa ophiolite, sample M11843, is uniquely diverse in containing 11 confirmed species, including wangxibinite, TiFe, which was approved in 2025. The fragment, with dimensions of 0.80 × 0.45 mm, comprises 3 zones: (1) an alloy core consisting of Ti, paulrobinsonite, maurogemmiite, and a symplectic intergrowth of wangxibinite and osbornite, (2) a continuous rim of Ti with a margin of wenjiite, and (3) a partial outer rim of aluminosilicate consisting of ~15% kyanite. ~45% coesite and ~40% amorphous aluminosilicate, traces of osbornite, iron, rutile-II unidentified Ti-Al-Si-O phases.

Electron-dispersive spectroscopic analysis (EDS) of the structure crystal gave (in wt%) N 0.05, O 0.77, Al 0.50, Si 0.43, Ti 47.95, Fe 48.25, Ni 0.25 Sum 100, and an empirical formula calculated for sum cations = 1 $(Ti_{1.036}Fe_{0.894}Ni_{0.036}Al_{0.020}Si_{0.016})_{\Sigma 2.000}(O_{0.050}N_{0.004})_{\Sigma 0.054}$ (Z = 1).

Wangxibinite is cubic, space group: *Pm*-3*m* (# 221), with a = 3.162(2) Å and V = 31.61(3) Å^3 for Z = 1. Its crystal structure was determined by 3-dimensional electron diffraction with the TEM; R_{all} = 0.0689. Reflections with *hkl*: $h + k + l = 2n$ are very weak and it is difficult to distinguish them from the background. If these weak reflections were interpreted as extinctions, the cell becomes body-centred cubic (*Im*-3*m*). However, lattice extinctions should not be overprinted by dynamical effects, and therefore the space group was eventually determined as *Pm*-3*m*. The cell parameter for wangxibinite is ~6% greater than that of synthetic TiFe, 2.979 Å; this difference may be related to the interstitial presence of O and N. The difference Fourier map shows extra-potentials at (0, ½, ½).

Wangxibinite forms a vermicular intergrowth with osbornite that occupies areas tens of µm across interstitial to paulrobinsonite. Individual vermicules range 0.3-1 µm in width. Three-dimensional electron diffraction revealed the presence in osbornite of weak reflections giving an apparent periodicity of 7Å. Attempts to correlate with other forms of TiN were not successful, and consequently the weak reflections are most likely reflections from neighboring crystals.

Our preferred scenario for M11843 is that the outer rim of coesite+kyanite+qingsongite+rutile-II of crustal origin was brought into contact with the inner rim and alloy core of mantle material after subduction of the crustal material to mid-mantle depths (~400 km)[1][2].

References

[1] Xiong et al. (2025) Mineral Magazine 89:855-871
[2] Dobrzhinetskaya LF (2014) Amer Mineral 99:764–772

The stishovite to post-stishovite transition under cyclic loading in the dynamic diamond anvil cell

Ledoux, E. E. [1], Buchen, J. [1,2], Wang, B. [1,3], Satta, N. [1,4], Trautner, V. [1,5], Criniti, G. [6,7], Méndez, A. S. J. [8], Liermann, H.-P. [8], Marquardt, H. [1]

[1] Department of Earth Sciences, University of Oxford, Oxford, UK, estelle.ledoux@earth.ox.ac.uk
[2] Bayerisches Geoinstitut, Universität Bayreuth, Bayreuth, Germany
[3] Department of Earth and Environmental Sciences, Michigan State University, East Lansing, USA
[4] Institut für Mineralogie, Universität Münster, Münster, Germany
[5] The Njord Centre, Department of Physics, University of Oslo, Oslo, Norway
[6] Earth and Planets Laboratory, Carnegie Institution for Science, Washington DC, USA
[7] Department für Geo- und Umweltwissenschaften, Ludwig-Maximilians-Universität München, München, Germany
[8] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Stishovite, a high-pressure polymorph of SiO_2, is expected to be present in the deep Earth, in particular in the crustal part of subducted slabs. It has also been proposed that SiO_2 can exsolve from Earth's core as it crystallises, and/or that silica-rich regions have remained in the lower mantle after crystallisation of the magma ocean. In the mid-mantle tetragonal stishovite undergoes a displacive phase transition to post-stishovite with an orthorhombic $CaCl_2$-type structure. Determining stishovite properties at high pressures, as well as changes across the stishovite to post-stishovite transition, is crucial to interpret seismic signals from the mantle and understand geodynamic processes.

Previous studies have determined the elastic properties of stishovite and post-stishovite at high pressure, but its response to an imposed oscillating stress, such as induced by a passing seismic wave, has not been investigated.

Here, we employed the dynamic diamond anvil cell (dDAC) to impose stress oscillations on stishovite and post-stishovite at high pressures. Polycrystalline stishovite samples were first pressurised manually to different starting pressures of about 10 GPa, 40 GPa and 70 GPa. For each sample, we then used the dDAC setup available at the P02.2 beamline at PETRA III (DESY) to apply cyclic loadings to the dDAC using a piezoactuator. An X-ray diffraction pattern of the sample was acquired in radial scattering geometry every second during the loading cycles. This allows us to follow in-situ the evolution of crystal structure, unit cell volume, as well as lattice strains in the sample.

We will present a detailed analysis of lattice strains and unit cell volume behaviour throughout the cycles and discuss them with respect to the physical properties of SiO_2 across the stishovite to post-stishovite transition.

Compositional signatures of (Fe,Al)OOH and their implications for the lowermost mantle

Sharma, S.[1*] and Shukla, G.[1,2]

[1] Department of Earth Sciences, IISER Kolkata, India
[2] National Center for High Pressure Studies, IISER Kolkata, India

---

Recent studies have proposed a crucial role of hydrous oxyhydroxides like FeOOH and AlOOH in being potential hydrogen carriers into the Earth's deep mantle. In addition, individual studies have sug-gested the presence of high-pressure FeOOH and AlOOH phases at the depths of the lowermost mantle. However, their relevance to realistic mantle compositions remains poorly constrained. In particular, FeOOH and AlOOH form extensive solid solutions, and the role of Al incorporation in governing the phase stability and thermoelastic properties of Fe-bearing high-pressure oxyhydroxides is yet to be systematically explored. In our study, we investigate the thermoelastic properties and phase stability of (Fe,Al)OOH solid solutions across ε/δ-type and pyrite-type (Py) structures at lower-mantle pressures and temperatures, with a focus on cold-slab geotherms. Our results demonstrate that Al incorporation substantially modifies the ε-(Fe,Al)OOH to Py-(Fe,Al)OOH phase boundary, shifting transition depths and stabilizing solid oxyhydroxide phases over an expanded pressure-temperature range compared to pure FeOOH. Along cold slab geotherms, (Fe,Al)OOH solid solutions exhibit pronounced contrasts in density and seismic velocities relative to surrounding mantle assemblages. These findings indicate that Al can act as a key compositional control on the depth distribution and physical properties of hydrous Fe-bearing phases in the lower mantle. We propose that such composi-tional filtering may contribute to the spatially heterogeneous occurrence of seismic velocity anomalies in the deep mantle, particularly in regions influenced by long-lived, cold subducted slabs. Our study highlights the importance of considering realistic solid solutions when assessing the role of hydrous phases in deep Earth structure and dynamics.

Structural evolution of the hydroxyperovskite $MgSi(OH)_6$ up to 23 GPa: implications for water storage in cold subduction zones

Najorka, J.[1], Collings, I.E.[1], Kleppe, A.K.[2], Koemets, E.[2] and Welch M.D.[1]

[1]Natural History Museum, Cromwell Road, London SW7 5BD, United Kingdom; j.najorka@nhm.ac.uk
[2]Diamond Light Source, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0DE, United Kingdom

---

Hydrous high-pressure phases play a key role in transporting water into the mantle and in the mineralogical evolution of subducted lithosphere. The hydroxyperovskite $MgSi(OH)_6$ ("3.65 Å phase") forms at P > 9 GPa through the pressure-induced breakdown of layered hydrous magnesium silicates (talc → "10 Å phase" → $MgSi(OH)_6$) [1]. It is the most water-rich dense hydrous magnesium silicate and has been proposed as a potential host for water in "cold" subduction zones.

In contrast to perovskites, $MgSi(OH)_6$ contains a vacant *A*-site and a strongly hydrogen-bonded framework of corner-sharing MgO_6 and SiO_6 octahedra, resulting in higher compressibility and pronounced elastic anisotropy [2,3,4]. A previous single-crystal X-ray diffraction study [2] constrained its structure to 8.4 GPa, just outside its stability field, and revealed contrasting compressional responses of the MgO_6 and SiO_6 octahedra.

Here we extend single-crystal X-ray diffraction measurements to 23.5 GPa at 300 K and provide the first detailed structural dataset within the stability field of $MgSi(OH)_6$. Compression is smooth, with no evidence of a phase transition. A second-order Birch–Murnaghan equation of state yields K_0 = 86.1(7) GPa (K' = 4), consistent with powder diffraction results [3] and confirming that $MgSi(OH)_6$ is significantly more compressible than perovskites. Compression is accommodated by coupled octahedral tilting and bond length shortening; the SiO_6 octahedron shows markedly reduced compressibility > 20 GPa. Axial moduli (K_{a0} = 72.5(9) GPa; K_{b0} = 88.1(5) GPa; K_{c0} = 99(2) GPa) reveal pronounced anisotropic compressibility, highlighting the influence of hydrogen-bond topology and vacant-site framework flexibility on the pressure-driven structural evolution of $MgSi(OH)_6$.

[1] Rashchenko et al. (2016) Am Min, 101, 2564-2569
[2] Welch et al. (2024) Am Min, 109, 255-264
[3] Mookherjee et al. (2015) Am Min, 100, 2199-2208
[4] Zhao et al. (2004) Phys Chem Min, 31: 299-305

A MED study of nanometric mineral inclusions in fluid-rich diamonds

Cámara, F.[1], Day, M.C.[2], Wang, Y.[2,3], Innocenzi, F.[2], Ardit, M.[2], Luth, R.W.[4], Pearson, D.G.[4], Weiss, Y.[5], Timmerman, S.[6], Pamato, M.G.[2], Novella, D.[2], Rotiroti, N.[1], Grässlin, J.[7], Schüermann, C.J.[7], Barbaro, A.[2], Qu, K.[8], and Hou Z.[3] and Nestola, F.[2]

[1]Università degli Studi di Milano, Dipartimento di Scienze della Terra 'A. Desio', Milan, Italy, fernando.camara@unimi.it
[2]Dipartimento di Geoscienze, Università degli Studi di Padova, Padova, Italy
[3]State Key Laboratory of Deep Earth and Mineral Exploration, Chinese Academy of Geological Sciences, Beijing, China
[4]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada
[5]Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel
[6]Institute of Geological Sciences, University of Bern, Bern, Switzerland.
[7]Rigaku Europe SE, Neu-Isenburg, Germany
[8]Tianjin Centre, China Geological Survey, Tianjin, China

Fluid-rich (cloudy/fibrous) diamonds are a particularly interesting type of diamond. They host nanometric fluid and mineral inclusions that can reveal the nature of diamond-forming media. Yet, the nanometric size of such inclusions makes rigorous structural and chemical characterization exceedingly difficult. As a consequence, formation conditions are challenging to unveil. In order to attempt to solve this problem, the MADAM research group (ERC Advanced Grant - 2025) through the use of micro-electron diffractometry (MED) has been able to identify and refine the structure of nanometric mineral inclusions hosted in a fluid-rich diamond from the Kaapvaal craton (Kimberley region, South Africa). In this diamond, the MED study revealed nanometric inclusions of the Ca-Mg silicate åkermanite ($Ca_2MgSi_2O_7$), unusual carbonates (norsethite, a Sr-carbonate with a Calcite II monoclinic structure and nyerereite), sellaite (CaF_2) and anatase (TiO_2). A full anisotropic crystal structure refinement was obtained in MED data from one åkermanite crystal (100 × 40 × 10 nm), thus becoming the first complete structural characterization of a nanometric mineral inclusion from a diamond. In addition, this is the first time that åkermanite and Sr-rich calcite II have been observed as inclusions in diamonds. MED data, together with FTIR data from fluid inclusions, suggest this diamond formed from an alkali-silico-carbonatitic parental melt, possibly related to recycling of crustal material into the lithospheric mantle beneath the Kaapvaal Craton. N-aggregation thermochronometry, and the available information on the experimental formation temperatures of synthetic åkermanite, was used to constrain the minimum diamond formation temperature to 1000 °C, at ≈140 km depth (≈4.6 GPa).

The authors acknowledge funding from the Chinese Academy of Geological Sciences Basal Research Fund (JKYDM2025205), the Nest_Contratti_Ric_BIRD24_01, Department of Geosciences, University of Padova, the ERC Advanced Grant MADAM (grant agreement n. 101199315) and the ERC Starting Grant INHERIT (grant agreement n. 101041620).

Diamond ages from the Premier kimberlite

O'Sullivan, G.J[1], Tomlinson, E.T.[1] and Hoare, B.C.[3]

[1]School of Natural Sciences, Trinity College Dublin, Ireland
[2]Shool of Earth and Environmental Sciences, University of St Andrews, UK
[3]King Abdullah University of Science and Technology, Saudi Arabia

---

Archaean and Palaeoproterozoic Sm–Nd dates and model ages have long been reported from inclusions in diamonds globally [1]. Understood as sampling palaeo-geotherms, these inclusions in diamond purportedly reveal widespread modern cold lithosphere conditions very early in Earth's history and are invoked to require craton assembly by lateral terrane accretion and early subduction [2]. However, there are causes for doubt. Foremost is the fact that xenocrysts of garnet entrained in kimberlites also commonly yield ancient dates [3] and similar $^{87}Sr/^{86}Sr$ ratios. Additionally, unequivocal Archean deposits containing macro-diamonds of mantle origin are rare [4] and ancient lithospheric diamond ages are only reported from pipes from the Neoproterozoic onwards [5]. Lastly, within individual kimberlite fields diamond-productive mines are restricted to specific time windows [4], which is inconsistent with random sampling of old diamonds in the lithosphere.

Using developments in U–Pb dating of low-U garnet we find contrary evidence. We have analysed both inclusions of peridotitic and eclogitic garnet inclusions in diamond and unshielded garnet xenocrysts in the host kimberlite kimberlite from the ~1.15 Ga Premier Kimberlite where previously reported Sm-Nd dates and model ages from inclusions of garnet in diamond range from close to the age of emplacement at 1.2 Ga (eclogitic garnet), to 1.6-1.9 Ga (lherzolitic garnet) and >3 Ga (harzburgitic garnet) [1]. Our U–Pb garnet xenocryst data yield an emplacement age for the kimberlite of 1,193 +/- 16 Ma (MSWD = 3.96); while inclusions of mostly harzburgitic garnet in diamond yield two dates: a dominant population at 1,269 +/- 22.8 Ma (MSWD = 1.36) and a small population at 1,582 +/- 88 Ma (MSWD = 2.44), with no age difference between eclogitic and peridotitic inclusions.

Our interpretation is that U-Pb garnet ages must be maximum ages of entrapment (diamond formation). Firstly, because the dates recorded by inclusions of garnet in diamond are older than those recorded by xenocrysts, and secondly because data from Ni-in-Grt thermometry confirms that all garnet were sampled well above the closure temperature of the U–Pb system. Our interpretation is that most diamonds at Premier formed at ~1.25 Ga, with a minor growth event at 1.6 Ga. This suggests that diamond formation was related to proto-kimberlite metasomatism and older reported ages based on REE-radioisotope systems are refractory and record events unrelated to diamond growth. Importantly, diamonds at Premier do not thus offer snapshots of the thermal state of the Archaean and Palaeoproterozoic lithosphere. The fact that diamonds often yield surprisingly 'modern' (i.e. cold) geotherms may be because diamonds do not entrap the thermal conditions of the Archean mantle. In fact, the paucity of ancient diamonds could suggest that the early lithospheric mantle was too hot to form widespread diamond.

References:
[1] Richardson et al., 1984, 1986, Nature
[2] Pearson et al., 2024, IKC abstacts
[3] Lazarov et al., 2009, EPSL
[4] Kjarsgaard et al., 2022, Rev. in Min. and Geochem.
[5] Gurney et al., 2010, Economic Geology

Predicting the strength of the lithosphere: a new microphysical model of semibrittle

Breithaupt, T.[1] and Wallis, D.[1]

[1]Department of Earth Sciences, University of Cambridge

The strength of Earth's lithosphere is controlled by a combination of ductile and brittle deformation processes, with peak strength occurring at the brittle–ductile transition. Although these endmember processes are well understood in isolation, we lack a microphysical model that encapsulates the interplay between them, which results in a distinct deformation mechanism termed semibrittle deformation. This deformation process is usually neglected, resulting in substantial overestimation of the strength of the lithospheric relative to that inferred from geophysical observations.

A key challenge in the development of a quantitative model of semibrittle deformation is describing the nature of the elastic interactions between defects associated with brittle and ductile processes (i.e., cracks and dislocations, respectively). We upend classic approaches, which focus on the emission of dislocations from cracks, to focus instead on the absorption of dislocations into cracks. This approach allows us to characterise the relationships between crack characteristics (crack length and crack density) and dislocation properties (dislocation density and backstress). By integrating these insights into a microphysical framework for dislocation-mediated deformation, we obtain a mathematically simple model of semi-brittle deformation.

The predictions of our model match experimental observations of the increase in steady-state strength of olivine and calcite aggregates with pressure. Extrapolated to natural rates of deformation, the model predicts that semi-brittle deformation exerts the primary control on the strength of Earth's lithosphere, bringing predictions of rock strength into alignment with inferences from geophysical observations.

Reassessing the Onset and Effects of Dynamic Recrystallization in Metals at High Pressure

McElhinney, T.R.[1], Heinen, B.J., Walker, A.M., Rogmann, E.-M., Fanesi, E., Vlasov, K., Pamato, M.G., Ezad, I.S., Daisenberger, D. Lord, O.T., Hunt, S.A.[1]

[1]Department of Materials, University of Manchester, Oxford Road, Manchester, UK, M13 9PL
[2]School of Earth Sciences, University of Bristol, Queens Road, Bristol, UK, B58 IRJ
[3]Department of Earth Sciences, University of Oxford, South Park Road, Oxford, UK, OX1 3AN
[4]Department of Geosciences, University of Padova, Via Giovanni Gradenigo, Padova, Italy, 6, 35131
[5]School of Earth and Ocean Sciences, University of Western Australia, Stirling Highway, Crawley, Perth, Western Australia, 6009
[6]Diamond Light Source, Harwell Science and Innovation Campus, Didcot, Oxfordshire, UK, OX11 0AE

Seismic observations indicate that Earth's inner core exhibits anomalously low shear wave velocities and complex elastic behaviour. Interpreting these signatures requires an understanding of how metals deform near their melting temperatures at high pressure; however, experimental constraints on the high homologous temperature behaviour of metals remain limited.

Here we present two complementary high-pressure experimental datasets that probe mechanical and microstructural evolution in metals approaching melting. Internally resistive-heated diamond anvil cell experiments on titanium at 18–40 GPa were conducted with in-situ synchrotron X-ray diffraction. Changes in grain-size during heating were inferred from changes in intensity distributions of Debye–Scherrer ring were show onset of dynamic recrystallization at ~0.6% T/T_M. In parallel, finite-frequency Young's modulus was measured in copper and zinc during cyclic deformation at seismic frequencies (0.1–0.3 Hz) using multi-anvil experiments at 3–4 GPa. Above homologous temperatures of ~0.8 T/T_M both metals exhibit sustained softening despite constant stress amplitudes, indicating a transition in accommodation mechanisms.

Both datasets indicate the onset of substantial dynamic recrystallization (DRX) at low homologous temperatures (~0.6–0.85 T/T_M). In Ti, this microstructural transition precedes coincides with temperatures where previous studies reported apparent melting using laser speckle diagnostics. The onset of accommodation softening in Cu and Zn is closely alighed with the onset of dynamic recrystallisation. Our results highlight the complexity of high-temperature deformation and anelasticity in metals and suggest that frequency-dependent softening and recrystallization may play an important role in governing the mechanical behaviour of planetary core materials.

Isotopic fractionation during core formation on terrestrial planets

Kubik, E.[1,2], Makhatadze, G.V.[3], Zhu, D.[2] and Schulze M.[2]

[1]School of Earth Sciences, University College Dublin, edith.kubik@ucd.ie
[2]Bayerisches Geoinstitut, University of Bayreuth
[3]Institut de Physique du Globe de Paris, Université Paris Cité

Accretion and core formation are major events that led to the present-day structure and composition of the terrestrial planets. Knowledge of the distribution of core-forming elements and their isotopes during core formation has the potential to make headway on questions such as (1) the physical and chemical conditions of core formation, (2) planetary source materials and genetics and (3) accretion scenarios. Nickel is a well-suited tracer of core formation given its strong affinity for the core and insensitivity to volatile processes. Thus, mantle Ni isotope signatures in terrestrial planets ought to be mainly established by core formation. The Ni isotopic composition of the Earth ($\delta^{60/58}Ni_{BSE}$=0.11±0.06‰) is slightly lighter than the average of chondrites ($\delta^{60/58}Ni_{BSE}$=0.23±0.07‰) [1], which could not be inherited from volatilisation processes. Core formation is therefore a good candidate as a process generating these signatures. This study aims to determine both experimentally and via ab initio simulations the direction and magnitude of Ni isotopic fractionation between metal and silicate at conditions relevant to core formation on large terrestrial planets. Experiments were performed in a 5000-ton multianvil press from 8 to 14 GPa at superliquidus conditions in order to reproduce the metal–silicate equilibrium occurring during core formation. Quenched equilibrated metal and silicate samples were carefully selected and prepared for Ni isotopic ratio characterisation via MC-ICPMS. Molecular dynamic simulations were computed at conditions matching that of the experiments. These results yield new information on the adequacy of Ni isotopic fractionation as a tracer of core formation and accretion on large terrestrial planets.

References:

[1] Klaver et al., 2020. GCA 268, 405–421.

A spatiotemporal approach to melting investigations: A spotlight on Earth's core-mantle boundary

Jackson, J.M.[1], Zhou, C.[1], Dobrosavljevic, V.V.[2], Zhang, D.[3], Sturhahn, W.[1], Toellner, T.S.[4], Zhao, J.[4], Hu, M.[1], Chariton, S.[5] and Prakapenka V.B.[5]

[1]Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA (jacksonj@caltech.edu)
[2]Earth and Planets Laboratory, Carnegie Institution for Science, Washington, D.C., USA
[3]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa,Honolulu, HI, USA
[4]Advanced Photon Source, Argonne National Laboratory, Lemont, IL, USA
[5]Center for Advanced Radiation Sources, The University of Chicago, Chicago, IL, USA

The boundary layer separating the liquid outer core from the mantle is a region of great complexity, where extreme contrasts in material properties promote the persistence of multi-scale structural heterogeneities, as evidenced through seismic observations. Thermochemical variations at the base of Earth's mantle play a critical role in the evolutionary history of the Earth through regulation of heat flow, influencing the dynamics of both the mantle and the core. Despite the significance of this region for Earth's evolution, many open questions remain regarding its thermal state, as well as the characteristics, origins, and dynamic interactions of seismically-distinct structures, such as large thermochemical piles, regions of ultralow seismic velocities, and subducted former oceanic material [1,2]. As observational studies of such features continue to develop, a synthesis of results involving geodynamic modeling and mineral physics is providing new insights into this complex region.

We highlight new developments in mineral physics that investigate melting at high-pressures. By pairing independent *in-situ* techniques, different time and length scales of the involved spatiotemporal atomic arrangements are emphasized: x-ray diffraction, sensitive to the loss of long-range crystalline order due to melting, and time-domain Mössbauer spectroscopy, sensitive exclusively to the dynamics of solid-bound iron nuclei. Our recent applications of this approach offer a comprehensive understanding of phase relations and melting of key materials in or proximal to planetary cores: an iron-nickel-silicon alloy [3,4] and FeO wüstite [5]. Our discussion will be on the thermal state of Earth's core and core-mantle boundary, with mineralogical implications for lowermost mantle plume roots, such as beneath Hawai'i [6,7].

References:
[1] Jackson JM and Thomas C (2021) AGU Monograph: 10.1002/9781119528609.ch8
[2] Hu M et al. (2025) Geophys J Int: 10.1093/gji/ggaf457
[3] Dobrosavljevic VV et al. (2022) Earth Planet Sci Lett 584: 117358
[4] Zhou C et al. (2026) J Geophys Res Solid Earth, under review
[5] Dobrosavljevic VV et al. (2023) Nat Commun: 10.1038/s41467-023-43154-w
[6] Lai VH et al. (2022) Geochem Geophys Geosyst: 10.1029/2021GC010020
[7] Wilding JD et al. (2022) Science: 10.1126/science.ade575

POSTERS

Goethite alteration in sulphate-rich brines on Mars: Implications for organic molecule preservation

Gasimov, N.[1,3], Hamzayeva, T.[2] and **Abdullayev, E.**[3]

1 French-Azerbaijani University, Azerbaijan State Oil and Industry University, Baku, Azerbaijan
2 Institute of Geology and Geophysics, Baku, Azerbaijan
3 Geoscience and Georesource Research Group, Azerbaijan State Oil and Industry University, Baku Azerbaijan/elshan.abdullayev@asoiu.edu.az

---

From Earth, it is known that reactive iron minerals play an important role in the preservation of organic molecules in sediments [1]. On Mars, iron minerals have also been identified in sediments [2,3], and these minerals can play a significant role in the long-term preservation of organic molecules [4]. Both goethite and lepidocrocite are iron oxyhydroxide minerals; however, goethite has a higher adsorption capacity [5]. Its transformation to lepidocrocite may release adsorbed organic molecules, increasing their vulnerability to decomposition and potentially reducing long-term preservation. Thus, studying the stability of iron minerals in sediments is important.

In this study, we investigate the fate of goethite (α-FeO(OH)) during its interaction with sulphate-rich brines, given the widespread distribution of sulphur-rich brines on Mars [6–8], in order to better understand its stability under such conditions. To achieve this, batch experiments were conducted at 75 °C, in which goethite was reacted with a simulated brine solution composed of 1 M $MgCl_2$, 0.5 M Na_2SO_4, and 0.5 M $CaCl_2$ under acidic (pH 3.0 to 3.5) and alkaline (pH 8.0 to 8.5) conditions. Both oxidizing and reducing environments were tested, with reducing conditions established by the addition of 0.025 mg of sodium dithionite ($Na_2S_2O_4$). The experiments carried out for up to 7 days with triplicate samples taken after 1, 3, 7 days.

The X-ray diffraction results indicate that goethite was altered after interaction with the simulated brine. A new peak at approximately 6.0 Å appeared after 7 days of reaction. This peak was observed under alkaline conditions in the reducing experiment and under acidic conditions in both oxidizing and reducing experiments, suggesting the formation of a new phase during the reaction. We interpret this peak as evidence for the presence of lepidocrocite (γ-FeO(OH)). It suggests that goethite undergoes more marked alteration under acidic conditions. This indicates that goethite may be particularly suitable for the preservation of organic matter under alkaline environmental conditions in sediments.

References:

1. Lalonde K et al. (2012) Nature 483: 198–200
2. Rampe E.B et al. (2020) Geochemistry 80: 1–31
3. Rampe E.B et al (2017) Earth Planet. Sci. Lett 471: 172–185
4. Schröder C et al. (2016) Hyperfine Interact 237: 85
5. Bowell R.J (1994) Applied Geochemistry 9: 279-286
6. Bristow, T.F et al. (2021) Science 373: 198–204
7. Vaniman, D et al. (2024) Minerals, 14: 815
8. Vaniman, D.T et al. (2004) Nature 431: 663–665

Layers of Discovery: Clay Mineralogy at the James Hutton Institute

Pendlowski, H.A.

The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland.
helen.pendlowski@hutton.ac.uk

Mineralogy, including clay mineralogy, has played a significant role in soil, environmental, and geological research carried out at the James Hutton Institute and its predecessor organisations for many decades, and continues to do so today. This poster traces the development of clay mineralogical research at the Institute, highlighting key scientific advances, analytical techniques, and the researchers who have contributed to establishing its international reputation in clay science.

The poster will also highlight key links between researchers at the Institute and the Mineralogical Society of the United Kingdom and Ireland, and in particular, the Institute's link with the Clay Minerals Group (CMG). This link with the CMG is routed from the groups very beginning in 1947 with both its 'founders', Robert Mackenzie and Douglas MacEwan [1], being researchers at the Institute, which at that time was called the Macaulay Institute for Soil Research.

The Institute also maintains an extensive mineral collection that has supported research and commercial activities for many years. This collection includes a variety of clay minerals, non-clay minerals, synthetic minerals and reference standards, sourced from a wide range of national and international localities. The collection reflects the long-standing tradition of mineralogical investigation within the Institute.

Reference:

[1] Kemp, S., 2023, *The Clay Minerals Group (CMG): 1947–2022,* Clay Minerals, 58 (1): 38–56.

Non-Ambient Raman Spectroscopy of Olivine-Type Lithium Battery Cathodes: $LiMPO_4$ (M = Fe, Mn, Ni, Co)

Wang, B.[1], Xu, Z.[2], Hunt, S.A.[3]

[1]Oxford Road, Manchester, M13 9PL beining.wang-5@postgrad.manchester.ac.uk
[2]Oxford Road, Manchester, M13 9PL zhen.xu@manchester.ac.uk
[3]Oxford Road, Manchester, M13 9PL simon.hunt@manchester.ac.uk

---

Lithium phosphates with olivine structures, including $LiFePO_4$, $LiMnPO_4$, $LiNiPO_4$, and $LiCoPO_4$, have been widely studied and used as cathode materials for lithium-ion batteries due to their structural stability, relatively low toxicity, and good electrochemical performance[1]. These compounds are structurally similar to natural olivine minerals, thus attracting widespread attention from materials science and mineral physics communities. Understanding their thermophysical behaviour over a wide temperature range is helpful not only for battery performance and safety but also for a broader understanding of the stability and lattice dynamics of olivine structures. However, previous studies have largely focused on ambient temperature and pressure, with relatively little research on the behaviour of these materials at extremely high temperatures.

This study investigates the temperature-dependent behaviour of $LiMPO_4$ (M = Fe, Mn, Ni, Co) olivine-structured cathode materials using extremely high-temperature Raman spectroscopy and X-ray diffraction. We will collect Raman spectra from low temperatures to high temperatures, as well as X-ray diffraction measurements between -180 °C and 600 °C. These measurements enable comparison between the thermophysical properties and to constrain the effect of different cations (M) on the vibrational and lattice behaviour of the phases.

References:
[1] [2] Padhi et al. (1997) J. Electrochem. Soc., 144, 1188–1194

Impact of biomolecules on iron (oxyhydr)oxide transformations

Barclay, M.[1], Coker, V.S.[1] and Kimber, R.[1]

[1] Department of Earth and Environmental Sciences, School of Natural Sciences, Faculty of Science and Engineering, University of Manchester, Manchester, M13 9PL, UK.
Email: max.barclay@manchester.ac.uk

Ferrihydrite, an iron oxyhydroxide, is a widely occurring environmental mineral that plays a key role in controlling pollutant and nutrient mobility through surface binding. However, as a metastable phase, ferrihydrite readily transforms into a variety of secondary mineral phases via processes including recrystallization, topotactic nucleation, and dissolution-reprecipitation, often altering its surface reactivity and sorption capacity. These transformation processes are heavily influenced by the presence of adsorbed organic and inorganic species including phosphate and organic acids. However, the role and impact of biomolecules, including ubiquitous nucleic acids, on these processes is not known.

This work aims to identify the impact of nucleic acids (DNA) on the structural evolution and phase development of ferrihydrite during Fe(II)-catalysed transformation. The effect of DNA polymer length, DNA loading, and aqueous Fe(II) concentration on ferrihydrite transformation was quantitatively assessed with X-Ray Diffraction (XRD). Quantitative Phase Analysis (QPA) was performed by assigning 'crystallinity' to ferrihydrite via the Partial or Not Known Crystal Structure (PONKCS) method, followed by assigning phase % weighting using Rietveld Refinement. DNA adsorption was found to impact the extent of ferrihydrite transformation as well as the secondary minerals formed, relative to systems lacking DNA or containing adsorbed phosphate. These effects were further influenced by DNA polymer length and starting aqueous Fe(II) concentration. Differences observed in lattice plane diffraction peaks may also indicate preferential orientation when secondary mineral nucleation is occurring in the presence of DNA, potentially influencing the stability and reactivity of the transformation products.

Alongside QPA, transformation products were also characterised using transmission electron microscopy (TEM). TEM confirmed the presence of phases identified via QPA but may suggest an overestimation of the remaining ferrihydrite component by QPA. This could be explained by XRD's inability to distinguish between amorphous minerals and secondary nanophases that may be present. For resolving these initial conclusions, further work and in-depth analysis, such as Mossbauer and 4D-STEM, is planned. These results suggest that the presence of nucleic acids can strongly influence secondary crystal nucleation processes, such as preferential orientation, transformation pathways, and resulting phase composition. These effects may drive downstream differences in nutrient and pollutant binding, with consequences for mineral reactivity and biogeochemical cycling.

Using Engineering Biology to Understand and Enhance Uranium Biomineralisation.

Byrd, N.[1], Felgate, H.[2], Egan-Morriss, C.[1], Robinson,. C.[1], Nunn, E.J.[3], Morris, K.[1], Natrajan, L.[3], Webber, M.[2] and Lloyd, J.R.[1]

[1] Research Centre for Radwaste Disposal and Williamson Research Centre for Molecular Environmental Science, Department of Earth and Environmental Sciences, The University of Manchester, U.K., natalie.byrd@manchester.ac.uk
[2] Quadram Institute BioScience, Norwich Research Park, NR4 7UQ
[3] Department of Chemistry, The University of Manchester, Manchester, M13 9QQ UK

Radioactively contaminated sites, such as Sellafield in the UK, are often congested and characterised by extreme in-situ conditions, including high pH, radionuclide concentrations and radioactivity, making remediation an expensive and substantial challenge. In this context, microbial bioremediation has great potential to facilitate the immobilization of soluble radionuclides (e.g., Sr, U, Tc) from contaminated effluents and land. Amendments that stimulate microbial communities, can easily be administered on space-restricted sites to facilitate targeted enzymatic reduction (e.g. for U(VI), Tc(VII), Np(V)) and biomineral precipitation (e.g. for ^{90}Sr). As part of a UK based multi-institutional Engineering Biology ("ELEMENTAL") Hub[1] we aim to employ a suite of engineering biology techniques to enhance existing bio-based radionuclide immobilization technologies. This initial research has focussed on understanding the response of model geomicrobiological organism, *Shewanella oneidensis* MR-1 to uranium exposure, as a widespread radioactive contaminant. Work here is intended to develop an experimental workflow for identifying target genes for bioengineering, to enhance bioremediation/biomineralisation efficacy; future applications will focus on other radionuclides/conditions of relevance to radioactively contaminated environments. To do this we have paired transposon mutagenesis (TraDIS-Xpress; 'Transposon Directed Insertion-site Sequencing – with eXpression'), a powerful high-throughput functional genomics tool, with conventional transcriptomic and geomicrobiological techniques. TraDIS-Xpress experiments were performed to identify genes important for (a) surviving under U(VI) stress (up to 10 mM) and (b) uranium biomineralisation (including bioreduction). A *S. oneidensis* MR-1 transposon library was grown in the presence of U(VI) at various concentrations (0.01, 0.1, 1, 5 and 10 mM), in bacterial growth medium containing bicarbonate (50 mM), at pH 8.5 or pH 7, and with high (4.4 mM) or low phosphate (0.5 mM). Growth, U(VI) bioreduction and biomineral precipitation was observed in all systems, including at U levels as high as 10 mM. The bulk biomineral phase was characterised as nano-UO_2 (associated with extracellular polymeric substances) with the other major phase present characterised as U-phosphate (associated with the cell membrane). Key genes identified as important in these systems can be linked to biofilming activity, EPS production or lipopolysaccharide structure [cell surface composition]; which supports the biomineral characterisation indicating that EPS and cell surfaces are likely important sites for biomineral nucleation. In terms of U(VI) bioreduction, both *c*-type cytochrome and flavin biosynthesis were identified as important, and only 1 out of a potential 41 *c*-type cytochromes was identified as important, suggesting a key role for this cytochrome under our experimental conditions. Findings presented will include those from TraDIS-Xpress and transcriptomic analysis alongside solid and aqueous characterisation of these systems (cryo-luminescence spectroscopy, NIR-UV-Vis, IC, ICP-MS, S/TEM-EDS, XRD and XANES). These experiments not only inform future bioengineering approaches to generate optimized strains for U(VI)/radionuclide immobilisation but also reveal new fundamental knowledge regarding U(VI) bioreduction mechanisms in *S. oneidensis* MR-1.

[1] ELEMENTAL engineering Biology Hub [online: https://elementalhub.org/] accessed: 06/03/2026]

Characterisation of ochreous mining waste in the UK to optimise sustainable bioprocessing of iron oxyhydroxides

Stott, L.[1]*, Kimber, R. L[1], Coker, V. S [1], Lloyd, J. R[1]

[1]Department of Earth and Environmental Sciences, University of Manchester, Manchester, M13 9PL, UK
*Correspondence address Lucy.Stott@postgrad.manchester.ac.uk

Thousands of tonnes of iron ochre waste are generated every year as a byproduct of mine water treatment plants in the UK, most of which ends up in landfill [1]. This project is focusing on developing novel processes of repurposing this waste including recovering valuable metal constituents and re-using of the resource to revalorise the material. This aims of this project are to explore the potential of using iron-reducing bacteria to convert the ochre waste into functional nanomaterials.

The initial stages of this project involve extensive characterisation of the mine wastes kindly provided by the Mining Remediation Authority (MRA) using a range of techniques such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS), X-Ray Diffraction (XRD), X-Ray Florescence (XRF), Scanning Electron Microscopy (SEM), Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR), and Ferrozine Assay to analyse the crystalline and geochemical properties, as well as iron speciation of the ochre. Six legacy mine sites have been sampled and analysed for this preliminary research, 2 from copper mines in North Wales, 1 from a coal mine in Greater Manchester, and 3 from MRA treatment sites. An analogous sample from a site of naturally occurring acid rock drainage has also been included for comparison.

The later work packages aim to sustainably bioprocess this waste using dissimilatory iron-reducing bacteria, such as *Shewanella oneidensis*, to transform the iron minerals through reduction of Fe^{3+} into Fe^{2+}, leading to precipitation of mixed valence iron oxyhydroxides nanomaterials, including magnetite. These nanomaterials can be used in a range of catalytic processes from industrial reactions to biomedical treatments [2]. These products will be characterised using the aforementioned analytical techniques to assess the properties of the transformed minerals.

References:
[1] Mayes, W., Potter, H. & Jarvis, A. 2010. Inventory of aquatic contaminant flux arising from historical metal mining in England and Wales. Science of the Total Environment, 408, 3576-3583.
[2] Lucía Gandarias, Richard L. Kimber, Georges Ona-Nguema; Environmental, Biomedical, and Industrial Applications of Biogenic Magnetite Nanoparticles. Elements 2023; 19 (4): 228–233. doi: https://doi.org/10.2138/gselements.19.4.228

Acknowledgements: Thanks to Sulaiman Mulroy, Paul Scattergood, and James White of the MRA for providing samples.

Biogeochemical activity in highly saline environments relevant to candidate host-rocks for geological disposal of radioactive waste

Rose, M. N.[1], Morris, K.[1], Shaw, S.[1], Lloyd, J.R.[1]

[1]RAdioactive waste Disposal and Environmental Remediation (RADER) National Nuclear User Facility and Williamson Research Facility for Molecular Environmental Science, Department of Earth and Environmental Sciences, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK

Worldwide nuclear power generation and other nuclear fission related activities have generated high- and intermediate-level radioactive waste and spent nuclear fuel. Globally, the accepted route for disposal of these wastes is deep geological disposal in a geological disposal facility (GDF). Microbial/mineral interactions are ubiquitous in engineered and natural environments in the presence of suitable electron donors and acceptors. Low-strength sedimentary rock (LSSR) formations are appropriate candidates for geological disposal of radioactive waste. Representative LSSRs may feature groundwaters with elevated salinity, often due to the presence of evaporate minerals, in turn these extreme salinity conditions may present energetic constraints to microbial metabolism. Previous work has demonstrated that microbial communities adapted to high salinity conditions (e.g., soda lakes, brine pools) are able to reduce electron acceptors including nitrate, ferric iron (e.g. ferrihydrite), and sulfate in-situ [1]. The capacity for such high salinity tolerant microbial communities to reduce priority radionuclides including uranium has also been demonstrated [2]. Here, we examine the fundamental biogeochemical processes associated with core samples from the Mercia Mudstone Group (MMG) and its microbial communities in relevant high-salinity conditions, as well as communities from an analogous high salinity environment (Cheshire Brine Springs). Microcosm experiments were undertaken containing disaggregated rock samples and high salinity groundwaters relevant to MMG formations, incubated over timescales of up to 1 year. The experiments included suitable electron donors for microbial activity, and where applicable added nitrate and ferrihydrite, to probe terminal electron accepting processes and their impacts on radionuclide fate (e.g., U) in conditions relevant to the MMG lithology.

[1] Foti et al. (2007) Appl. Environ. Microbiol. 73(7): 2093-2100
[2] Nevin et al. (2003) Appl. Environ. Microbiol. 69(6): 3672-3675

Criticality safety: Investigating the co-mobility of actinides and neutron absorbers in radioactive waste disposal

Cooper, J.[1], Neill T.S.[1], Natrajan L.[2], Stagg O.[3], Coker V. S.[1]

[1]RADER National Nuclear User Facility and Williamson Research Centre, Department of Earth and Environmental Sciences, The University of Manchester, james.cooper-8@postgrad.manchester.ac.uk
[2]Department of Chemistry, The University of Manchester
[3]Nuclear Waste Services, Pelham House, Calder Bridge, Seascale, CA20 1DB

The UK has a wide, varied and complex radioactive waste inventory[1] produced during the 70+ years of civilian nuclear history with the current internationally accepted method for disposal of intermediate and high-level radioactive waste is by emplacement within a Geological Disposal Facility (GDF). High-level waste will include plutonium (Pu) wasteforms which will include neutron absorbing elements to help ensure criticality safety[2]. Gadolinium (Gd) is known to have the highest thermal neutron absorption cross section of any non-radioactive element[3] making it an ideal candidate for use as an additive for Pu wasteforms. In the far future it is expected that the radioactive waste within the GDF will be exposed to groundwaters, potentially mobilising the waste components including actinides (uranium (U), Pu) and neutron absorbers. Understanding the fate of radionuclides within the environment is a key area of study for the safety case but there are gaps in understanding of the effect additives, such as neutron absorbers, may have on radionuclide and neutron absorber co-mobility.

In this poster presentation the solubility of gadolinium and co-precipitation behaviour of U and Gd is investigated within simple aqueous solutions to understand fundamental interactions of these elements. Precipitation experiments were performed on Gd and combined $U(IV)O_2$/Gd under GDF relevant conditions (anoxic, pH 7 & 10, High/low salinity and in the presence of carbonate) for a month and monitored using ICP-MS/AES (liquid phase characterisation) and XRD (solid phase characterisation). Initial results indicate that salinity does not affect overall solubility of Gd, with pH being a having a greater influence on Gd solution concentration. Finally, the presence of carbonate & U both decrease the solution concentration of Gd.

This postgraduate research project is jointly funded by the SATURN centre for Doctoral training and Nuclear Waste Services (NWS).

[1] NDA in *2022 UK Radioactive Waste Inventory*, *Vol.* (Ed. E. I. S. Deparatment for Business), **2023**.
[2] M. R. Cole, L. R. Blackburn, L. T. Haigh, D. J. Bailey, L. T. Townsend, K. O. Kvashnina, N. C. Hyatt and C. L. Corkhill, *Materials Advances* **2024**, *5*, 6416-6425.
[3] H. Jing, L. Geng, S. Qiu, H. Zou, M. Liang and D. Deng, *Journal of Rare Earths* **2023**, *41*, 32-41.

Influence of tufa Deposition on the Transport and Mobility of Lead and Zinc in Downstream Environments on the River Lathkill

Ives, M. and Cumberland, S.A.

School of Geography, Earth and Environmental Science, University of Leicester

Toxic metals such as lead (Pb) and zinc (Zn) can enter river systems through both natural processes, including weathering of limestone and dolomite, and anthropogenic sources such as mining (e.g., acid mine drainage), industrial activity, and sewage discharge, with anthropogenic inputs often being dominant (1). Elevated concentrations of these metals pose risks to ecosystems and human health (2, 3). In carbonate-rich streams, CO_2 degassing and photosynthetic activity by aquatic plants and algae promote $CaCO_3$ precipitation, forming tufa deposits (4). Tufa has been shown to entrap metals such as Pb and Zn (4, 5), yet the mechanisms controlling metal transport and incorporation remain poorly understood (6). It is unclear whether metals are transported primarily in dissolved form or bound to sediments, how they are captured within tufa (e.g., laminae or pore spaces), and in what chemical forms they occur (6). This study focuses on the River Lathkill, a Site of Special Scientific Interest (SSSI) in Derbyshire, UK, where historic mining is recorded. An active tufa formation, the Tufa Dam (53°11'19.8"N 1°43'55.7"W), provides an opportunity to investigate these processes. Water and sediment samples were collected on 06/11/2025 during high-flow conditions at five upstream locations and one downstream location. Water was vacuum-filtered (<0.45 µm) and analysed via ICP-MS. Sediments, collected at 5 and 10 cm depths, were sieved into fine (<63 µm) and coarse (2 mm–63 µm) fractions, dried, homogenised, and analysed using portable X-ray fluorescence (Olympus Vanta pXRF) and ICP-MS. Unprocessed tufa pieces were screened with pXRF, and polished sections examined by imaging-XRF (Bruker).

Whole tufa samples contained Pb from 124.2 to 302.2 ppm (± 0.0086) and Zn from 1135.3 to 1943.5 ppm (± 0.0018), showing substantial incorporation within the carbonate matrix. Dissolved Zn (<0.45 µm) decreased downstream from 35.65 to 23.19 ppb (± 0.296), with no significant reduction after the tufa dam. Dissolved Pb slightly increased from 0.23 to 0.30 ppb (± 0.015). Sediment analyses showed higher Zn (822–2660.4 ppm, ± 0.0018) and Pb (266.9–1492.3 ppm, ± 0.0086) in fine fractions than in coarse fractions (Zn: 340.7–2465.8 ppm; Pb: 120.9–1591.1 ppm). Both fractions became increasingly enriched downstream, particularly the fine fraction, indicating that fine sediments are the primary transport medium. Investigating metal incorporation into tufa provides insight into how tufa acts as a natural trap and sink, with implications for remediation strategies.

References:
[1] Turekian KK, Wedepohl KH (1961) Geol Soc Am Bull 72:175–192
[2] Gidlow D (2015) Occup Med 65:770–770
[3] [3] Ahmad, K, et al., (2025), *Environ Monit Assess,* **197**(11), p.1209.
[4] Roza-Llera A, Di Lorenzo F, Churakov SV, Jiménez A, Fernández-Díaz L (2024) Cryst Growth Des 24:79–92
[5] Liang X, Zhang Y, Liu J and Chen Z (2025) Sci Total Environ 959:178334
[6] Cumberland S, Tierney K, Renshaw J, Geraki K, MacDonald J (2022) EGU Gen Assem EGU22-4044

Radionuclide Fate in On-Site Disposal of Activation Product Contaminated Wastes

Jones, W.[1], Graham, J.[2], Morris K.[1], Shaw, S.[1] and Coker, V.[1]

[1] Radioactive Waste Disposal and Environmental Remediation National Nuclear User Facility and Williamson Research Facility, Department of Earth and Environmental Sciences, The University of Manchester, Manchester, M13 9PL, UK.
William.jones@manchester.ac.uk
[2] United Kingdom National Nuclear Laboratory, Sellafield, Cumbria, CA20 1PG, UK.

Decommissioning of nuclear reactors is progressing across the Nuclear Decommissioning Authority (NDA) estate. This will produce large quantities of radioactive materials, including neutron activated infrastructure around the reactor core. Management of these materials is challenging, and on-site disposal is being considered and may be optimal for lightly contaminated/activated concrete and radioactively contaminated land (RCL). To underpin the safety case for on-site disposal, the behaviour of radioactivity needs to be understood in the disposal and surrounding natural environment over appropriate timeframes.

This project will focus on the environmental behaviour of a number of commonly found activation products of concrete, including Ni-63, Co-60, and Eu-152. The solubility of Co, Ni, and Eu was probed at pH 12 and pH 8 in groundwater representative of fresh and aged concrete respectively, showing sub-ppb solubility of Co and Ni at pH 12, with the Eu solubility limit being 1 ppt. At pH 8, solubility was significantly greater: Co solubility was shown to be greater than 70 ppm, and Ni greater than 2 ppm; Eu was still only 25 ppt due to being a trivalent cation compared to the divalent cobalt and nickel ions. Sellafield representative concrete was artificially aged using a dry carbonation chamber at 10% CO_2 concentration showcasing a decrease in pH from 11.7 to 10.9 after 42 days. Wet carbonation was also trialled and showed a drastic decrease in pH, from 11.7 to less than 7 after just 1 hour, with further work to be carried out to refine this method. The project will undertake sorption experiments coupled with fabrication and leaching of doped concrete to understand the immediate and long-term fate of these radionuclides in representative aged and fresh cementitious material in the shallow subsurface under various environmental conditions including groundwater and seawater intrusion. This will be carried out with non-radioactive isotopes and selected experiments using radionuclides. Contaminant fate will be studied with and without iron oxide from rebar. A multi-technique approach will deliver a thorough insight into contaminant behaviour using advanced aqueous, colloidal, and solid techniques coupled to thermodynamic modelling to improve understanding of key neutron activation products in the sub-surface of reactor sites. This work is co-funded by EPSRC SATURN and the Nuclear Decommissioning Authority (NDA) through the NDA PhD bursary scheme and will be supported by the United Kingdom National Nuclear Laboratory (UKNNL).

Nitrate-dependent iron oxidation for remediation of selenium and nickel in mining wastewaters

Koepnick, H.R.[1,2], Peyton, B.M.[2,3] and Lauchnor, E.L.[2,4]

[1]School of Earth Sciences, University of Bristol, Bristol, United Kingdom; hannah.koepnick@montana.edu
[2]Center for Biofilm Engineering, Montana State University, Bozeman, United States
[3]Chemical & Biological Engineering, Montana State University, Bozeman, United States
[4]Civil Engineering, Montana State University, Bozeman, United States

---

Nitrate-dependent iron oxidation (NDFO) is a novel mechanism for bioremediation of metal and metalloid contaminants due to their propensity for sorption to iron minerals produced during NDFO, and, for some contaminants, the possibility of concurrent bioreduction. During NDFO, microbes catalyse a redox reaction wherein nitrate is reduced to nitrite and nitrogen gas while Fe(II) is oxidised to form solid Fe(III) (oxy)hydroxide minerals. The iron (oxy)hydroxides produced by NDFO could aid selenium removal by sorbing selenite, and to a lesser extent selenate; coprecipitating with selenium; and catalysing reduction of selenite to Se(0). Furthermore, many nitrate reducers can also reduce selenium to solid phase Se(0). To the best of the authors' knowledge, this is the first work to investigate NDFO for selenium removal.

Waste rock and influent water from a subsurface bioreactor treating mining wastewater were used to construct batch bioreactors, which were amended with either Fe(II) or methanol to test contaminant removal under NDFO or heterotrophic conditions. This research characterised the effects of NDFO on selenium and nickel remediation, examining rates and extents of contaminant removal and changes in the microbial community. On average, NDFO removed more selenium than heterotrophic bioreduction. Microbial communities in NDFO reactors showed an increase in taxa known to be key players in environmental NDFO enrichments. Addition of Fe(II) after methanol depletion also resulted in near-complete removal of selenium. Fe(II) addition could potentially be used to "cap" in situ reactors, creating iron mineral barriers during decommissioning in order to remove remaining aqueous selenium, cover precipitated selenium with Fe(III) (oxy)hydroxides, and capture remobilised selenium.

The speciation and fate of selenium, along with the stability of iron minerals produced during NDFO, can impact long-term contaminant stability. Ongoing work aims to provide insight into contaminant stability by determining the speciation of selenium in the solid phase, investigating its association with NDFO-formed iron minerals, and identifying the iron minerals produced. A combination of X-ray absorption spectroscopy, scanning electron microscopy, laser ablation inductively coupled plasma-mass spectrometry, and cathodoluminescence is being employed to characterise the post-treatment waste rock.

Geochemical Controls on Radionuclide Adsorption and Fate in Lower Strength Sedimentary Rock

Kraavi, K.E.[1], Morris, K.[1], Robinson, C.[1], Abrahamsen-Mills, L.[2], Boylan, A. [2], and Shaw, S.[1]

[1] RAdioactive waste Disposal and Environmental Remediation (RADER) National Nuclear User Facility and Williamson Research Facility for Molecular Environmental Science, Department of Earth and Environmental Sciences, The University of Manchester, Manchester M13 9PL, karl.kraavi@manchester.ac.uk
[2] United Kingdom National Nuclear Laboratory, WA3 6AE Cheshire, U.K.

Lower strength sedimentary rocks are potential host rocks for geological disposal facilities for higher activity radioactive wastes. Typically, geological disposal facilities are expected to be emplaced in the deep (approximately 200 - 1000m) sub-surface and constructed using a multi-barrier system where waste forms, canisters and engineered barriers act in consort to limit the migration of radionuclides from the waste. A key part of the multi barrier system is the host rock in which the GDF is located. When assessing a potential GDF host rock consideration must be given to radionuclide behaviour within the groundwater present, and radionuclide interactions with the host rock and its associated minerals. Overall, the occurrence, mechanisms, and magnitude of radionuclide sorption processes (e.g. surface adsorption or precipitation) are key controls on the ability of these radionuclides to migrate through the host rock. In this study we aimed to determine the bulk partitioning and sorption mechanisms of key radionuclides to representative lower strength sedimentary rocks, the Oxford Clay and Mercia mudstone, as a function of geochemical conditions.

Rock samples from the Oxford Clay Formation have been characterised, and their interactions with nickel have been assessed. Geological and mineralogical characterisation included scanning electron microscopy, X-ray Diffraction, zeta potential, and Brunauer-Emmett-Teller specific surface area analysis. Batch adsorption experiments have been carried out at three different rock and groundwater solid-to-solution ratios (1:5, 1:25, and 1:250) and at initial radionuclide concentrations between 2 and 100 ppm. The concentrations of radionuclides remaining in solution at equilibrium were determined via inductively coupled plasma mass spectrometry, from which adsorption isotherms have been derived. Mechanistic models of these experiments have been produced using the pH-Redox-Equilibrium (PHREEQC) software and compared to the experimental results. Lastly, speciation and adsorption mechanisms of Ni interactions with the host rock have been determined using X-ray absorption spectroscopy.

The RADioactive waste and Environmental Remediation National Nuclear User Facility: A Unique Capability for Nuclear Minerals, Contaminant Dynamics and Remediation Research.

Morris, K.[1], Coker, V.[1], Foster, L.[1], Lloyd, J.R. [1], Neill, T. [1], Shaw, S[1], Stetten, L.[1], and Stockdale, A.[1]

[1]RAdioactive waste and Environmental Remediation (RADER) National Nuclear User Facility and Williamson Research Facility, Department of Earth & Environmental Sciences, The University of Manchester, M13 9PL.

The RADioactive Waste and Environmental Remediation (RADER) National Nuclear User Facility houses a series of environmental chemistry laboratories and analytical equipment laboratoroes to enable research into characterising and understanding the behaviour of radioactive species in natural and engineered environments. This research base is crucial for underpinning large parts of the UK's >100 year, >£130 billion nuclear decommissioning, clean-up and radioactive waste management programmes and the RADER labs house significant research programmes supported through UKRI and Industry funding including BBSRC, NERC and EPSRC and AWE, the Nuclear Decommissioning Authority, Nuclear Waste Services and the Sellafield Effluent and Decontamination Centre of Expertise.

The laboratories support a capability to work with model experimental systems, field based experiments, and authentic low level samples and include radiological counting facilities, specialist experimental equipment, aqueous and colloid analysis instruments and instruments for solids and biological characterization including specialist laboratory and analytical suites for:

- Batch and Column experiments including mineralogical and biogeochemical characterisation
- Environmental Characterisation of Solids and Liquids with low levels of radionuclides
- Mineralogical, radiometric, solution and microbial characterisation
- Controlled atmosphere handling
- Sample preparation, including cutting and polishing

RADER NNUF operates alongside the Williamson Research Facility for Molecular Environmental Science to allow world leading environmental mineralogy allied research, and in our poster we highlight examples of experimental capability and summarise some recent outputs from the RADER user community.

Applications are currently open for the NNUF funded user access scheme for RADER and we welcome external academic and industry users. Visit https://www.nnuf.ac.uk/rader for more information.

Figure 2 RADER Lab Users

Ni retention during devitrification of high-level radioactive waste glasses

Painter, P.R.W.[1], Litherland, S.P.[2], Byrne, J.M.[2], Corkhill, C.L.[2]

[1]University of Bristol, Wills Memorial Bldg., Queen's Road, Bristol, BS8 1RJ. Email: patrick.painter@bristol.ac.uk
[2]University of Bristol, Wills Memorial Bldg., Queen's Road, Bristol, BS8 1RJ.

The most common medium worldwide for the immobilisation of high-level radioactive waste (HLW) is borosilicate glass [1]. Disposal of this waste in a manner that is safe over geological timescales is necessary owing to the long half-lives of certain highly radiotoxic isotopes, such as ^{59}Ni. Over such timescales, groundwater ingress into a future Geological Disposal Facility (GDF) becomes likely, and the resultant aqueous corrosion of these vitrified wastes may release radionuclides to the environment. [2]

Current safety case modelling prior to the construction of a GDF assumes congruent dissolution of the immobilised radionuclides during glass devitrification, despite complex interactions between the radionuclides and the alteration minerals formed during glass devitrification. This work finds that Ni has the potential to be retained extensively in the surface alteration layer of nuclear glasses in the form of insoluble precipitates, corroborating previous findings on the insolubility of Ni in cementitious intermediate level waste (ILW) [3]. To study Ni during devitrification systematically, this work focuses on a simplified Ni-Si system. Nickel solutions at corrosion-relevant pH's were allowed to form precipitates in both the presence and absence of hydrated silica ($SiO_2{\cdot}nH_2O$), an analogue for the silica gel layer found ubiquitously across corroded borosilicate glasses.

Ni retention was greater in silica bearing samples, with siliceous samples retaining 40 ± 25 mg_{Ni}/L more Ni than the silica absent samples at the highest Ni starting concentration. This retention was, however, significantly lower than geochemical modelling suggests. Modelling using PHREEQC [4] and the Thermochimie thermodynamic database (v13a) [5] suggests precipitation of Ni(SiO_3) should retain significantly more Ni than is observed. Energy Dispersive Spectroscopy (EDS) reveals that the precipitate involved is likely willemseite ($Ni_3Si_4O_{10}(OH)_2$), the nickel-bearing end member of the pyrophyllite-talc group. The Thermochimie database lacks both thermodynamic data for hydrous Ni silicates and formation constants for Ni – SiO_4 aqueous complexes. The lower Ni:Si ratio of willemseite compared to Ni(SiO_3) and a lower Ni activity due to the formation of Ni – SiO_4 complexes are proposed as potential mechanisms for the lower retention of Ni. Samples absent in silica retained less Ni than silica bearing samples but still retained substantially more Ni than expected from geochemical modelling (203 ± 24 mg_{Ni}/L at 500 mg_{Ni}/L starting concentration).

This work highlights the need for more refined thermodynamic data for phases in the Ni – Si system and stresses the need for consideration of hydrous phases in the formulation of thermodynamic datasets, an issue which has been previously noted for the Zn – Si system [6]. This work begins a wider work package on the retention styles of poorly soluble radionuclides in the alteration layer of nuclear glasses.

References:
[1] Thorpe C et al. (2021) npj Mater Degrad 5:61
[2] Grambow B (2006) Elements 2:6 357-364
[3] Felipe-Sotelo M et al. (2016) J Hazard Mater 314:211-219
[4] Parkhurst and Appelo (2013) USGS Report No. 6-A43
[5] Madé B et al. (2025) Appl Geochem 180 106273
[6] Fisher A et al. (2021) MRS Adv 6:4-5 95-102

Geological fate and impact of isosaccharinic acid

Snow, R.[1], Shaw, S.[1], Morris, K.[1], Bassil, J.[2], Bower, W.[2] and Lloyd, J.R.[1]

[1] Department of Earth & Environmental Sciences, NNUF RADER Facility and Williamson Research Laboratories, the University of Manchester, United Kingdom
[2] Nuclear Waste Services

During the disposal of low-heat generating wastes in a cementitious geological disposal facility (GDF), cellulose can degrade via alkaline hydrolysis to form isosaccharinic acid (ISA). This is of interest due to the ability of ISA to complex key radionuclides, and potentially enhance their mobility. This project investigates ISA biodegradation and associated microbial processes GDF-relevant conditions using flow-through column systems. Batch experiments have shown that microbial communities in high-pH anaerobic sediments are able to degrade ISA, particularly using suitable electron acceptors such as nitrate ([1]); however, there is limited research on these interactions under dynamic conditions. Here we develop and apply methods to quantify ISA degradation and evaluate biogeochemical processes in column systems.

Column experiments were carried out using Pearson synthetic groundwater ([3]) as the influent solution. Columns were packed with sediment from Harpur Hill, a legacy lime-working site in Buxton, U.K ([2]), characterised by calcite- and silicate-rich material and average pH of 11–12. A range of ISA treatments were introduced to the influent and monitored over ~200 days to assess ISA removal and changes in redox conditions. Significant ISA removal was observed when nitrate was present as an electron acceptor, indicating active microbial degradation under alkaline, nitrate-reducing conditions.

Follow-on experiments have focused on the impact of ISA-degrading bacteria on the mobility of priority radionuclides. Se^{79} is a long-lived radioactive isotope that is of interest due to its mobility in groundwaters as Se(VI), and column experiments have confirmed Se(VI) reduction and continued ISA removal over ~100 days, accompanied by formation of a red precipitate and Se^{o} nanoparticles (confirmed by SEM-EDS). Further work will assess the bioreduction of U(VI) as an electron acceptor, coupled to ISA oxidation and extend to include genetic, geochemical and mineralogical analyses.

References:
[1] Bassil, N.M. et al (2015) The ISME Journal, 9, pp. 310–320.
[2] Kuippers, G. et al. (2015) Mineralogical Magazine, 79(6), pp. 1443–1454.
[3] Pearson, F.J. et al. (2003): Mont Terri Project – FOWG, Geology Series No. 5.

Underpinning Laboratory-Based High-Level Waste Glass Dissolution Tests

Varga, S.[1], Litherland, S.[1], Byrne, J.[1] and Corkhill, C.[1]

[1]School of Earth Sciences, University of Bristol, UK. CONTACT: Samuel Varga sam.varga@bristol.ac.uk

---

In the UK, high-level nuclear waste (HLW) generated from nuclear fuel reprocessing is immobilised in alkali-borosilicate glass. This waste primarily comprises actinides and fission and activation products [1]. The intention is for vitrified HLW to be isolated from future populations in a deep Geological Disposal Facility (GDF), between 200 – 1000 m underground [2]. The radioactivity of the waste will be considered safe after at least 100,000 years [2]. During these timescales, it is inevitable that groundwater will penetrate the engineered barriers of the GDF and reach the vitrified HLW, which will slowly dissolve releasing radionuclides.

Multiple factors affect the durability of vitrified HLW, including the composition of the groundwater and glass, pH, and temperature. Numerous experiments have been performed on a range of simulant HLW glass compositions, altering different conditions. Most of these experiments are performed under oxic conditions, in equilibrium with air. Comparatively, the GDF environment is expected to become anoxic and reducing over time due to the corrosion of metallic containers, which produce $H_{2(g)}$. It is not well understood how the presence of O_2 and CO_2 in the air can alter the dissolution mechanism of simulant HLW glass.

This study investigated the dissolution of four simulant HLW glass compositions under oxic and anoxic conditions. Two versions of the 6-component international standard glass, the International Simple Glass (ISG), were studied, alongside simulant UK HLW glass produced on two full-scale vitrification campaigns at the National Nuclear Laboratory's Vitrification Test Rig. One comprised a 75:25 ratio of ThORP and Magnox simulant waste, and the other contained only Magnox waste, at 25 and 28 wt.%, respectively. Powders of glasses were subjected to a 35-day dissolution experiment at 40 °C in simulant groundwater, following the ASTM Product Consistency Test standard protocol [3]. The normalised mass loss of elements from the glasses, measured by ICP-OES, was compared for experiments performed in air and in bespoke inert gas reaction vessels. These findings demonstrate how oxic conditions affect corrosion rates, both validating the results of past experiments and providing a baseline for future GDF-relevant experiments.

References:
[1] Radioactive Waste Management (2018) NDA 978-1-84029-585-6.
[2] Corkhill C and Hyatt N (2018) IOP Publishing 10.1088/978-0-7503-1638-5.
[3] ASTM (2021) Book of Standards 10.1520/C1285-21.

Smectite Illitization in mud volcano systems: Implications for geological CO_2 storage – a natural analogue study from Azerbaijan

Aliyeva, A.[1,2], Abdullayev E.[1] and Lemarchand D.[3]

[1] Azerbaijan Oil and Industry University, Baku, Azerbaijan/arzu.aliyeva@ufaz.az
[2] French-Azerbaijan University, Azerbaijan Oil and Industry University, Baku, Azerbaijan
[3] University of Strasbourg, Strasbourg, France

The smectite-to-illite (S-I) transformation represents a fundamental diagenetic process in sedimentary basins, serving as a reliable geothermometer and depth indicator due to its progressive and temperature-dependent nature. [1-3]. Illitization degree increases systematically with burial depth and typically occurs within a temperature window of approximately 90–150°C [1, 2]. Consequently, the presence of illite in ejected mud breccia provides critical constraints on thermal maturity, maximum burial depth, and source regions of mobilized fluids and sediments, offering new insights into mud volcano system dynamics. Beyond its temperature-dependent characteristics, the smectite illitization process holds particular significance for geological CO_2 storage (GCS) research. When CO_2 dissolves in formation waters, which can be sourced from deep sources or biogenic activity, it generates weak carbonic acid, which promotes smectite dissolution and subsequent illitization [3]. This reaction mechanism can be confirmed through changes in exchangeable cation concentrations. Furthermore, elements released during mineral dissolution may combine with CO_2 to precipitate carbonate minerals such as calcite and dolomite, thereby chemically trapping CO_2 in solid form-a permanent storage mechanism [3]. Given that direct subsurface sampling of active CO_2 reservoirs is rarely feasible, mud volcanoes represent valuable natural laboratories, as their ejected materials preserve a readily accessible record of deep fluid-rock interactions.

The aim of this study is to investigate the coupled processes of fluid-rock interactions in the context of geological CO_2 storage, using ejecta from mud volcanoes in Azerbaijan as natural analogues for long-term CO_2-water-rock interactions. To achieve this, we conducted geochemical and mineralogical analysis, employing X-ray diffraction (XRD) for bulk and clay mineralogy, X-ray fluorescence (XRF) for major oxide composition, and ICP-AES and ICP-MS for trace element geochemistry. Our initial results confirm the occurrence of smectite illitization, a process characterized by the release of interlayer water and a relative enrichment in silica. This is evidenced by the consistent dominance of illite over smectite and the high bulk SiO_2 concentrations. The TiO_2-SiO_2 relationship also suggests that SiO_2 is unlikely to be detrital and may instead represent a product of illitization. The dissolution of this CO_2 into formation waters would generate a slightly acidic fluid, a key geochemical condition that promotes the smectite illitization observed in our samples. Given the well-established association of these mud volcanoes with hydrocarbon reservoirs [5], we infer that the CO_2 driving these reactions is sourced from deep thermogenic processes, potentially supplemented by biogenic activity. This interpretation is further supported by the observed precipitation of carbonate minerals, including calcite and dolomite, within the ejecta.

References:
1 Li Niu et al. (1997) Applied Geochemistry
2 Cuadros J. (2006) Geochimica et Cosmochimica Acta
3 D. Martin et al (2022) Applied Sciences
4 Peltonen C., et al (2009) Marine and Petroleum Geology
5 Michael A. Abrams (2005) Marine and Petroleum Geology

Phyllosilicate Interlayer Engineering (PIE) for sustainable potassium supply from clay mine waste in Brazilian sandy soils

Correia, L. T.[1]; Azevedo, A. C.[1]; Secco, A. V.[1]; Dickinson, H.[2,3] and MacDonald, J.M.[2]
[1]Luiz de Queiroz College of Agriculture, University of Sao Paulo, Piracicaba, 13418-900, Brazil,
[2]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G128QQ, UK.
[3]School of Social and Environmental Sustainability, University of Glasgow, Dumfries, DG1 4ZL, UK.
heloisa.dickinson@glasgow.ac.uk

Brazil is the world's second-largest consumer of potash, importing approximately 95% of its requirements, a strategic vulnerability for the planet's fourth-largest food producer. This dependence is intensified by the geographic concentration of global potassium (K) reserves, with nearly 80% of K salts located in only three countries. Developing domestic mineral sources of potassium is critical for strengthening agricultural resilience and reducing supply-chain risks.

Phyllosilicates represent the second most abundant geological reservoir of potassium, offering a promising source of low-cost mineral amendments. When added to sandy soils, 2:1 phyllosilicates can enhance cation exchange capacity (CEC), water retention capacity (WRC), and soil carbon stabilisation. However, potassium release is often limited by interlayer fixation. To address this limitation, we explore phyllosilicate interlayer engineering (PIE) through Al_{13} polyoxocation pillaring of clay interlayers. These clusters stabilise expanded interlayers and prevent potassium re-fixation. Inspired by naturally occurring hydroxy-interlayered clays, this strategy aims to generate slow-release potassium resources for climate-stressed soils. PIE integrates mineral resource valorisation with circular-economy principles, converting mining overburden into a sustainable slow-release potassium source for climate-vulnerable soils.

Clay-bearing siltstones in the Paraná Basin provide a potential feedstock for this strategy. These deposits overlie the basaltic Serra Geral and ag-liming Irati formations, which are widely mined for construction and agriculture. Quarrying removes up to 17 m of siltstone overburden to access a 4 m limestone layer, leaving stockpiled waste that could be repurposed as low-cost soil amendments for sandy soils derived from the Bauru Group sandstones, which cover 9.76 million hectares in São Paulo State and generated £13.7 billion (52%) of the state's agricultural GDP in 2025. Mineralogical characterisation of four siltstones from the Corumbataí and Irati formations identifies the grey siltstone as the most suitable for agronomic use, combining substantial K content (~2.95% K_2O) with higher clay content and greater potassium bioavailability.

Mineralogical Changes in Anthropogenic Sediments: Implications for a Sustainable Environment

MacDonald, J.M.[1], Owen, A.[1], Brown, D.J.[1] and Gribble, L.[1]

[1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G128QQ, UK;
john.macdonald.3@glasgow.ac.uk

Humans are now the primary geomorphic agents on our planet [1]. Tens to hundreds of gigatonnes of sediment is anthropogenically deposited on the Earth's surface each year [e.g. 2, 3]. This loose sediment can be natural in composition (e.g. excavated sand, mining overburden), or anthropogenic material that is manufactured (e.g., slag, concrete, brick). The un-natural mineralogy of these anthropogenic geomaterials can lead to rapid mineralogical changes, relative to equivalent natural clastic sediments.

Weathering of minerals unstable at Earth surface conditions, such as free lime, magnesiowüstite and larnite minerals in ferrous slags, leads to formation of new minerals and associated textures in anthropogenic sediment deposits. In ferrous slag (the by-product of iron and steel making) deposits, weathering of slag minerals leads to formation of new minerals in the pore spaces between slag clasts, binding the sediment together into a larger rock-like mass [4-6]. In this contribution we show examples of this process, using techniques such as Scanning Electron Microscopy and X-Ray Diffraction to document the range of minerals forming as cements in these anthropogenic sediment deposits.

These mineralogical changes in anthropogenic sediment deposits have a range of implications in the context of a sustainable environment. Mineral cements are frequently calcite, with isotopic analysis indicating atmospheric CO_2 being drawn down to form the calcite [4]. The change from a loose sediment to a cemented rock changes the geotechnical properties of the deposit, while the conversion to impermeable strata has implications for surface runoff and flooding, as well as the biota which can colonise these evolving deposits. These implications are all down to the mineralogy of the deposits.

References:
[1] Syvitski J et al. (2022) Nat Revs Earth & Env 3: 179-196
[2] Cooper A et al. (2018) Anth Rev 5: 222-229
[3] Bullock L et al. (2021) Front Clim 3
[4] MacDonald J et al. (2023) Dep Rec 9: 810-819
[5] Hilderman R et al. (2024) Sedimentologika 2
[6] Owen A et al. (2025) Geology 53: 581-586

CO_2 mineralisation in hydrated Mg-silicate microbialites

Oskierski H.C.[1], McCutcheon J.[2], Deditius A.[1], Suvorova A.[3], D'Olivio J.P.[4], Southam G.[5]

[1]Sustainable Geochemistry and Mineral Sciences (GeMS), School of Mathematics, Statistics, Chemistry and Physics, Murdoch University
[2]Department of Earth and Environmental Sciences, University of Waterloo
[3]Centre for Microscopy Characterisation and Analysis, The University of Western Australia
[4]Instituo de Ciencias del Mar y Limnologia, Universidad Nacional Autonoma de Mexico Puerto Morelos
[5]School of the Environment, The University of Queensland

Microbialites are organo-sedimentary structures resulting from mineralisation of benthic microbial mats and/or trapping and binding of sedimentary particles or detritus [1]. They are also considered as one of the oldest traces of life on Earth, dating up to 3.5 billion years back [2]. In addition, microbialites commonly consist of carbonate minerals and thus provide an opportunity to observe microbially mediated CO_2 mineralisation. Despite offering a promising option for carbon sequestration their ability to efficiently store carbon in carbonate minerals remains largely unexplored.

The microbialites studied here were discovered at the Attunga magnesite deposit during a comprehensive study on natural analogues to carbonation of ultramafic rocks in the Great Serpentinite Belt in northern New South Wales, Australia, that also included mine tailings and weathering-derived and hydrothermal magnesite [3]. The water in the mine pond hosting the microbialite is eutrophic, alkaline (pH = 9.1), and of Mg-bicarbonate type with a Mg/Ca ratio of 58, consistent with interaction with the ultramafic and partially carbonated and silicified bedrock. The flat, continuous microbialites are exposed if the pond water level is low. They are poorly laminated, consisting of irregular clots composed of a hydrated Mg-silicate phase and detritus. Abundant pore spaces contain hydromagnesite, detritus and some Ca-carbonates.

Their formation follows established pathways [4], including (i) bacterial growth that increases pH of pond water and leads to saturation of the Mg-silicate phase. This stage is illustrated by the common entombment of filamentous bacteria by Mg-silicate and includes nucleation of Mg-silicate on microbial sheaths. (ii) Biomass decomposition that increases dissolved inorganic carbon concentrations and induces saturation with Mg and Ca carbonates. This stage is consistent with the observed replacement of the Mg-silicate phase by hydromagnesite and of hydromagnesite by Ca-carbonate.

Carbon accounting in the microbialite is based on assumptions of pond shape, microbialite thickness, porosity, density and coverage, as well as quantification of carbonate minerals, total carbon and radiocarbon content. About 2 tonnes of atmospheric carbon are stored in carbonate minerals in the microbialite, resulting in carbon mineralisation rates that are about 10 times higher than background rates of carbon uptake associated with weathering [5]. Twice as much carbon (4 tonnes) is stored in the microbialite as less stable organic material. Magnesium accounting, based on quantitative mineralogy, chemical composition and mineral chemical composition, demonstrates that only 19 % of Mg is present as hydromagnesite. Consequently, 81 % of the mineralised Mg does not participate in carbon fixation. This data emphasises the need to consider the fate of silicon and the competition for cations in both microbially mediated and abiotic carbon mineralisation systems.

[1] Burne and Moore (1987) Palaios 2(3), 241-254.
[2] Wacey et al. (2012) Precambrian Research 220, 234-250.
[3] Oskierski (2013) University of Newcastle, NSW, Australia.
[4] Chagas et al (2016) Earth Science Reviews 162, 338-363.
[5] Hagedorn and Cartwright (2009) Chemical Geology 260(3-4), 234-253.

Mineralogical and microstructural controls on the mechanical behaviour of reservoir sandstones reacted with CO_2-enriched fluids

Skelton, H.[1], Rees, M.[1], Josue, J.[1], Farrell, N.[1], Bigaroni, N.[1], Mecklenburgh, J.[1], Paul, L.[1]

[1]Department of Earth and Environmental Sciences, Williamson Building, University of Manchester, Manchester, United Kingdom (natalie.farrell@manchester.ac.uk)

Injection of carbon dioxide (CO_2) into reservoir sandstones for carbon capture and storage (CCS) alters pore fluid chemistry, producing carbon-rich brines that may react with framework minerals and cements. While geochemical effects on porosity evolution and permeability are widely discussed [1; 2; 3], the impact of CO_2-fluid-rock reactions on mechanical strength of reservoir sandstones remains largely unconstrained. Changes in rock strength through mineral dissolution and precipitation processes may influence reservoir performance and safety by inducing leakage risk and seismic activity.

This study examines the effect of carbonated fluids (water and brine) on the strength of Triassic, Permian and Cretaceous sandstones. Sandstone mineralogy varied from 69-83% quartz, 5-17% feldspar and 1-5% clay content within the sample suite. Sandstone core plugs were saturated with carbonated and uncarbonated distilled water and brine for two weeks under controlled laboratory conditions. Mechanical properties were determined using uniaxial compressive strength apparatus with axial and radial strain gauges and a linear variable differential transformer (LVDT) to quantify variations in strength and elastic properties.

Strength data were integrated with pre-experiment petrophysical (porosity and permeability) and microstructural properties (pore area and mineral textures), using helium porosimetry, permeability, optical and scanning electron microscopy, image analysis, and geochemical characterisation (X-ray diffraction, XRD) to investigate the role of varying sandstone mineralogy and microstructure on sandstone reactivity with carbonated fluids. Preliminary results indicate that water-saturated cores exhibit lower uniaxial compressive strength than dry cores, consistent with previously reported water-weakening behaviour [4]. Contrary to the initial hypothesis that more chemically aggressive CO_2-enriched fluids would enhance microstructural alteration and further reduce strength, early results suggest that cores saturated with carbonated distilled water exhibit higher maximum uniaxial compressive strength than those saturated with uncarbonated distilled water. By investigating the mechanical and microstructural consequences of CO_2–fluid interactions with sandstone, this project aims to quantify how fluid-driven mineral reactions may alter strength and microstructural properties during CO_2 storage operations.

References:
[1] Bertier et al. (2006) JGE 89:10-14.
[2] Hall et al. (2015) Geofluids 16:249-263
[3] Farrell et al. (2026) EGUSE 17:407-427
[4] Baud et al. (2000) JGESE 105:16371-16389

Biotechnological synthesis of nanocatalysts from industrial wastewaters

Harvey, P.[1‡], Egan Morriss, C.[1], Hu, M.[2], Cavet, J.[2], Coker, V.[1], Gallego Schmid, V.[2], Haigh, S.[2], Hardacre, C.[2] and Lloyd, J.R.[1].

‡ Patrick.harvey-3@postgrad.manchester.ac.uk
[1]Lloyd lab, Department of Earth and Environmental Sciences, School of Natural Sciences, Faculty of Science and Engineering, University of Manchester, Manchester, M13 9PL, UK
[2]School of Natural Sciences, Faculty of Science and Engineering, University of Manchester, Manchester, M13 9PL, UK

The Platinum Group Metals (PGMs) are critical to a wide range of industrial applications, often due to their excellent catalytic properties. Recycling of PGMs after their product lifespans represents both an engineering challenge and an environmental boon, with economically successful PGM secondary sources demonstrating up to a 97% decrease in global warming potential per kg of PGM produced compared to newly mined metals [1]. However, the recycling process remains both energy and chemically intensive. PGM bioreduction performed by dissimilatory metal-reducing bacteria such as *Shewanella oneidensis* or *Geobacter sulfurreducens* shows great promise in recovering metallic state PGMs from effluent environments. Biological reduction involves selective electron transfer from organic electron donors to target ions in solution, for the PGMs leading to target precipitation and recovery. Biorecovered PGMs form cell associated nanoparticles which exhibit comparable catalytic performance to industrial standards, potentially introducing a direct route from industrial effluent to revalorised product [2]. In synthetic effluent bioreduction systems, close control over cell phenotype and solution chemistry leads to tailorable nanoparticle properties, influencing both metal recovery and catalytic activity. Addition of secondary- or multi- PGM containing solutions further leads to bi- or multi- metallic nanoparticle formation, potentially allowing for additional nanoparticle tailoring considerations. Here we demonstrate biogenic Pd based nanocatalyst activities against reduction and selective hydrogenation reactions, highlighting both the biological and chemical control aspects of bio-Pd based catalysis. Through a deeper understanding of the bioreduction systems in dissimilatory metal reducing organisms, higher rates of PGM recovery, tailorable, catalytically relevant nanoparticles, and an industrial scale PGM reclamation system all represent achievable goals in the sphere of PGM biorecovery. Should this technology be validated, implementation of PGM biorecovery to compatible effluent waste streams will represent a novel, scalable waste revalorisation strategy.

References:
[1] Johnson Matthey PLC (2025) Circularity Whitepaper
[2] Morriss C. E et al. (2022) Nanoscale Advances 4:654-79

A high-throughput, data-driven workflow to tune carbonate (bio)mineral formation in abiotic and biotic systems

Rehmanji, M.[1] Stigliano, L[1] and Cosmidis, J.[1]

[1] Department of Earth Sciences, University of Oxford, Oxford UK
Email: mohammed.rehmanji@earth.ox.ac.uk

Carbonate minerals formed at mineral–organic–microbe interfaces influence preservation and carbon cycling by modulating carbon turnover and mineral stabilization. More broadly, deliberately designed mineral-based solids are increasingly central to modern materials development, where tailored mineral properties underpin performance in areas ranging from energy and optoelectronics to functional coatings, construction materials, sensing, and long-term waste containment. In this context, both fully synthetic routes and bio-enabled pathways, along with hybrid and surface-modified mineral architectures are being explored to deliver mineral products with controllable structure and function. However, deliberate mineral product design remains difficult because precipitation outcomes depend non-linearly on solution composition, temperature, and biological activity. Consequently, carbonate polymorph, particle size, and crystal habit properties that govern performance-relevant behaviour including CO_2 uptake capacity are still often adjusted by trial-and-error rather than predictive control.

Here we explore Microbially induced carbonate precipitation (MICP) by *Sporosarcina pasteurii* as a route to produce functional carbonate materials. We present a scalable screening and analysis workflow that couples high-throughput experiments with microscopy-driven feature extraction, machine-learning (ML) classification, and response surface methodology (RSM) to identify controllable abiotic and genetic regulators of carbonate formation. Results demonstrated that abiotic precipitates exhibit a non-linear dependence on calcium concentration, with particle area increasing to an optimum and then decreasing. In contrast, biotic systems displayed a strong positive response of total particle area to increasing calcium concentration, indicating Ca^{2+} availability as the dominant control on biomineralization. Calcium source and temperature showed no statistically significant effects, and the tested variables behaved independently. A random-forest classifier trained on seven morphology classes captured systematic shifts in particle types. Abiotic experiments In abiotic systems, at 25-50 mM CaCl2 concentrations new particle types were observed whereas at lower (5-10 mM) and higher (500 mM) concentrations single type was dominant, whereas biotic experiments retained higher morphological richness even at low calcium levels. Evenness metrics further indicated that biological mediation suppresses dominance by a single crystal habit.

Further, to identify genetic controls of biomineralization, we initiated a forward screen of *S. pasteurii* mutants generated by EMS mutagenesis; 71 mutant colonies are currently being phenotyped to identify strains with altered mineralization behaviour. In future work, the RSM framework can be extended beyond total particle area by selecting alternative responses such as particle perimeter, equivalent diameter, particle count, or other single-metric outputs allowing individual aspects of precipitation behaviour to be modelled explicitly. In parallel, ML feature approaches can be used to determine which morphometric attributes (e.g., size, shape, circularity, texture) are most sensitive to biotic versus abiotic controls, enabling targeted tuning of conditions to steer formation toward a desired biomineral type. Together, these results provide a quantitative route to engineer carbonate mineral outcomes by linking process variables and genetic perturbations to reproducible morphology classes relevant to mineral-based technologies.

Biorecovery of gold nanoparticles from industrial wastewaters by *Shewanella oneidensis*

Xie, J.[1], Byrd, N.[1], Bueno, A.[2,3], Coker, V.S.[1], Sankar, M.[2], Cai, R.[4], Haigh, S.J.[4], Lloyd, J.R.[1]

[1] Department of Earth and Environmental Sciences & Williamson Research Centre for Molecular Environmental Science, University of Manchester, Manchester M13 9PL, United Kingdom
[2] Cardiff Catalysis Institute, School of Chemistry, Translational Research Hub, Cardiff University, Cardiff CF24 4HQ, United Kingdom.
[3] Department of Chemical and Environmental Engineering. Bilbao School of Engineering, University of the Basque Country (UPV/EHU), Plaza Ingeniero Torres Quevedo 1, 48013 Bilbao, Spain
[4] Department of Materials, The University of Manchester, Manchester, United Kingdom

---

The increasing demand for precious metals, particularly gold, alongside environmental concerns over conventional recovery methods that rely on hazardous chemicals and high energy inputs, is driving the development of more sustainable processing alternatives. Here, we evaluate the metal-reducing bacterium *Shewanella oneidensis* for gold biorecovery from both synthetic and real waste solutions via the bioreduction of Au(III) to form Au(0) nanoparticles (AuNPs).

Biorecovery was assessed across Au(III) concentrations from 0.05 to 1 mM using lactate or H_2 as electron donors. H_2 consistently outperformed lactate, achieving 60 to 100% Au removal across the concentration range, while maintaining approximately 60% recovery at 1 mM Au(III) with rapid kinetics. XRD and TEM analyses confirmed predominantly nanoscale Au(0) particles (<20 nm). Higher initial Au(III) concentrations produced larger AuNPs, which were primarily localised at the periplasm under H_2-driven conditions. Hydrogenase mutant experiments further indicated a key role for *hyaB* in H_2-dependent Au(III) bioreduction.

In authentic industrial gold leachates at pH ~4.5, *S. oneidensis* removed ~90% of soluble Au. Under more acidic conditions (pH ~1.8), the process yielded triangular and hexagonal AuNPs with high catalytic activity. The biosynthesised AuNPs catalysed the oxidation of 5-hydroxymethylfurfural to furandicarboxylic acid, highlighting their potential value in green catalytic applications. Overall, these results support *S. oneidensis* as a platform for eco-friendly gold recovery coupled with the production of catalytically active AuNPs.

Protein-Templated Polymorph Selection: Engineering Mineral Crystallisation with de novo Designed Proteins

Sriwastava, P.[1], Seaman, A.[2], Bola, J.[3], Khare, S.[2,4], Cosmidis, J.[5], Tosca, N.[6], and Anderson, R.[1]

[1]Museum of Natural History, University of Oxford, UK
[2]Department of Chemistry and Chemical Biology, Rutgers, The State University of New Jersey, Piscataway, NJ, USA
[3]Department of Biochemistry, University of Oxford, UK
[4]Institute of Quantitative Biomedicine, Rutgers, The State University of New Jersey, Piscataway, NJ, USA
[5]Department of Earth Sciences, University of Oxford, UK
[6]Department of Earth Sciences, University of Cambridge, UK

Biomolecular control of mineral crystallisation offers a powerful route to engineering minerals with precise crystallographic properties. Recent advances in AI-based de novo protein design — particularly RFdiffusion and AlphaFold — have made it possible to computationally design proteins with surface chemistries tailored to specific mineral faces, opening new avenues in crystal engineering.

Following the Baker lab pipeline [1,2], we designed protein FD-15 with surface chemistry complementary to the calcite (104) face, expressed it in *E. coli*, and introduced the purified protein into controlled mineralisation environments. At 15 mM $CaCl_2$ and $NaHCO_3$, conditions that otherwise yield metastable vaterite and aragonite, FD-15 directed the formation of rhombic calcite crystals, demonstrating selective polymorph control through protein templating.

We are extending this approach to aluminosilicate mineralisation, designing kaolinite-binding proteins to investigate molecular controls on clay mineral formation and their potential role in Konservat-Lagerstätten preservation. Our broader aim is to establish sequence-to-crystal relationships between amino acid chemistry and biomineral crystallographic parameters, providing a programmable framework for engineering minerals with targeted structural and functional properties for technological applications.

References:
[1] Fathima D H (2023) Nature Communication
[2] Saragovi A (2024) bioRxiv

Critical raw material and weathering potential of mine waste in the Leadhills-Wanlockhead Orefield

Bryce, A.[1, 2] , Burnside, N.[2], Dobson, K.[1], and Currie, D.[2]

[1]University of Strathclyde, Glasgow. andie.bryce.2023@uni.strath.ac.uk
[2]British Geological Survey, Keyworth.

The global energy transition is reliant on critical raw materials (CRMs). The Critical Minerals Intelligence Centre identifies 34 materials as CRMs, defined by high economic importance and vulnerability to supply risks [1]. Many CRMs are imported into the UK, due to factors including the low concentrations in which they are present in ores (typically <0.1%), the limited mining, processing and recycling technologies, and the geographic concentration of production. The global CRM market is vulnerable to supply risks and shocks, due to factors including climate change related events, conflicts, and export controls. It is essential that the UK increases domestic supply and production of CRMs to achieve successful energy transition while ensuring national security.

Waste from abandoned metal mines across the UK may provide potential resources of CRMs. Reprocessing mine tailings for CRM extraction yields many benefits including contribution to a circular economy, decreasing dependence on primary extraction, reducing metal contamination, and job creation in communities which were once reliant on mining [2].

This research will aim to determine the opportunity for economic extraction of CRMs from historical mining waste from the Leadhills-Wanlockhead Orefield (LWO), which has been identified as prospective for hosting gallium, germanium and indium [3]. The area contains numerous abandoned Pb-Zn mines and associated wastes with exceptional mineral diversity. Over 70 veins were mined extensively for galena and sphalerite, which produced over 90% of Scotland's, and 10% of the UK's total Pb output during industrial peak. CRM presence in the tailings has been confirmed in historical studies [4], as well as a recent study which identified up to 860ppm germanium and 141ppm gallium in sphalerite, up to 148ppm indium in chalcopyrite, as well as 1264ppm and 956ppm of Sb in galena and sphalerite, respectively [5].

Analysis will focus on the primary minerals, galena, sphalerite, chalcopyrite, and pyrite, collected from mine tailings in the LWO. The EPSRC funded IMA3GES facility will be used to characterise samples, preliminary results of which are presented here. This results of this initial analysis will inform the future experimental programme which will involve accelerated weathering, determination of optimal conditions for CRM extraction, in situ imaging of the internal material structure, and 3D mineral mapping through time. XCT analysis coupled to an environmental cell will enable enhanced mineral identification, crystallographic orientation mapping, and map physicochemical evolution under variable temperature, saturation, and load conditions. This will provide an accurate simulation of ore processing and accelerated weathering processes. Analysis of evolving fluid chemistry of produced leachates will provide advanced predictions of future environmental contaminants and CRM presence.

References:
[1] Mudd G et al. (2024) CMIC, BGS.
[2] Sarker S K et al. (2022) Env Chem Eng 10(3).
[3] Deady E et al. (2023) CMIC, BGS.
[4] Temple A. (1954) Uni of Leeds.
[5] Currie D et al. (2026) SJG.

Mineralogical and microstructural controls on pore networks in lithium-bearing granites

Eygi, A.[1], Skellern, A.[1], Farrell, N.[1], Pawley, A.[1], Bigaroni, N.[1], Mecklenburgh, J.[1], Paul, L.[1], Waters, J.[1]

[1] Department of Earth and Environmental Sciences, Williamson Building, University of Manchester, Manchester, United Kingdom (natalie.farrell@manchester.ac.uk)

Understanding the distribution and connectivity of pore networks in lithium-bearing granites is important for constraining fluid-flow processes responsible for the mobilisation and concentration of critical metals. Within the Cornubian Batholith (Cornwall, UK) many granites host significant lithium and other critical metal mineralisation [1]. However, the links between mineral alteration, microstructure and key petrophysical properties such as porosity, permeability and seismic velocity remain poorly constrained. This limits our ability to interpret subsurface datasets, such as wireline logs, and to assess the distribution and quality of critical metal resources in the subsurface.

This study investigates how mineralogical alteration and resulting microstructural variability influence porosity, fluid-flow pathways and mechanical properties in lithium-bearing granites. In addition, we assess whether Raman spectroscopy can provide a rapid method for identifying lithium-bearing mica phases within granitic rocks. Previous work has shown that Raman spectra can reliably distinguish mica species, including muscovite, biotite, lepidolite and zinnwaldite, based on diagnostic spectral peaks, allowing lithium-bearing micas to be differentiated from more common varieties [2]. A suite of variably altered granites (including kaolinitised samples from the Trelavour lithium project in St Austell, Cornwall), were analysed to characterise mineralogy, pore networks and petrophysical properties. Helium porosimetry indicates porosity values of ~1–15%, corresponding to P-wave velocities of ~2000 – 5000 m s^{-1}. High-resolution optical and back-scattered electron imaging on corresponding thin sections document lithium-mica textures and pore geometries, with image analysis used to quantify pore size, shape and distribution relative to alteration textures. Preliminary observations identify multiple pore types associated with mineral alteration, grain boundary modification and microfracturing. To place these observations in a broader subsurface context, fracture porosity networks were also investigated in lithium granites subjected to laboratory thermal treating and uniaxial deformation. Quantifying fracture distributions generated by these processes provides insight into the crack porosity that may exist at depth, enabling comparison between pore networks observed in surface samples and those expected in subsurface reservoirs.

Complementary mineralogical analyses using X-ray diffraction (XRD) and Raman spectroscopy were undertaken to characterise lithium-bearing micas within the granites. Preliminary analysis of Raman spectra indicate clear distinctions between muscovite and lepidolite, suggesting that Raman spectroscopy may provide an effective method for identifying lithium-bearing mica phases where bulk mineralogical techniques such as XRD are inconclusive. Together, these datasets aim to link mineralogy, microstructure and petrophysical properties in lithium granites, improving understanding of pore network development and its implications for fluid flow, lithium mobilisation and resource exploitation in granitic systems.

References

[1]Simons et al, 2017, Lithos, 278: 491-512
[2]McHugh et al, 2025, *J.Raman Spec*, *56*:1378-1385

A quest for the "holy grail" of rare earth discovery: potential original material of gadolinite-(Y) from Ytterby

Holtstam, D.[1], Taddei, A.[2, 3], Förster, H.-J.[4] and Appelt, O.[4]

[1]Department of Geosciences, Swedish Museum of Natural History, Box 50007, SE-10405 Stockholm, Sweden
[2]Museo di Scienze Planetarie-Fondazione Parsec, Via Galcianese 20H, I-59100 Prato, Italy
[3]Dipartimento di Scienze della Terra, Università degli Studi di Firenze, via La Pira 4, I-50121 Firenze, Italy
[4]GFZ Helmholtz Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Germany

---

The granitic pegmatite at Ytterby, Resarö, Sweden, is globally renowned as the cradle of rare earth element (REE) chemistry. Within this NYF-family (Nb–Y–F) type pegmatite, enriched in HREE–Y–Be–Ta–Nb, the mineral later named gadolinite-(Y), ideally $Y_2Fe^{2+}Be_2Si_2O_{10}$, was first recognized in 1787 by Carl Axel Arrhenius. Samples from Ytterby formed the basis for the seminal chemical investigations of Johan Gadolin (1794), who identified a previously unknown "earth", marking the beginning of systematic rare earth research. Subsequent decisive work was carried out by Anders Gustaf Ekeberg, who introduced the term "yttria" (= yttrium oxide) and determined beryllium as an essential component, and by Martin Heinrich Klaproth who established the mineral root name, while Carl Gustaf Mosander and others later used the Ytterby mineral for separations of new rare earth metals. Despite this central historical significance, no officially recognized type material for the species has hitherto been identified.

We report on a historically documented specimen preserved at the Swedish Museum of Natural History, consisting of two pieces labelled as the first gadolinite samples discovered by Arrhenius at Ytterby. The original handwritten label–closely resembling Mosander's handwriting–explicitly states that the samples were collected by Arrhenius himself and purchased for 50 riksdaler banco, a substantial sum at the time. The recorded weights (101.1 g for the "pure" piece and 6 $^5/_8$ "lod" ≈ 88 g for the second piece, associated with muscovite and orthoclase) agree with present measurements, supporting the integrity and continuity of the material. While absolute proof that fragments of this specimen were used in the earliest analytical studies cannot be provided, the documented provenance, early acquisition, and institutional continuity make it the closest available approximation to original material from the 1787 discovery.

The larger piece is a black, vitreous mass up to 5 cm across, associated with minor anorthite as crack fillings. In thin section the mineral is green, and optically isotropic due to metamictization. Upon annealing (1000°C, 1 h), crystallinity is restored, and powder X-ray diffraction data are consistent with monoclinic gadolinite-(Y) (space group $P2_1/c$). Refined unit-cell parameters [a = 4.729(2) Å, b = 7.487(2) Å, c = 9.937(3) Å, β = 90.37(3)°, V = 351.8(2) Å³, Z = 2] agree well with published data for crystalline material. Based on electron-microprobe analyses, the following empirical formula is obtained:
$(Y_{1.49}Dy_{0.09}Yb_{0.08}Nd_{0.06}Er_{0.06}Sm_{0.05}Gd_{0.03}Ce_{0.03}Ho_{0.02}Pr_{0.01}Tm_{0.01}Lu_{0.01}Tb_{0.01}Ca_{0.01}Mn_{0.01}Th_{0.005})_{\Sigma 1.97}$-$Fe^{2+}_{0.94}Fe^{3+}_{0.06}Be_{2.00}Si_{2.00}O_{10}$. The chemical composition aligns well with late 19th-century wet-chemical analyses of Ytterby gadolinite-(Y), supporting the representative nature of the studied material. Mössbauer spectroscopy indicates Fe^{2+} as the dominant valence state, with ~6% Fe^{3+}, in agreement with the historic analyses. Raman and infrared spectra of metamict and annealed material closely match previously published data for gadolinite-(Y).

The separation experiments by Mosander of new elements, named erbium and terbium, relied on fractional precipitation and physical observations of precipitates that were not pure compounds. Subsequent interpretations by Nils Johan Berlin and Marc Delafontaine reassigned names, effectively transposing Mosander's original terminology. Only with spectroscopic advances in the 1860s to 1880s–used by chemists including Paul-Émile Lecoq de Boisbaudran and Jean Charles Galissard de Marignac–were elements like dysprosium and ytterbium reliably isolated, explaining why those metals eluded discovery by Mosander despite the high concentrations in gadolinite-(Y).

Optimised physical upgrading of lateritic mine waste to enhance bioprocessing for cobalt recovery

Dybowska, A.[1], Hubau, A.[2], Schofield, P.F.[1], Gianolo, D.[3], Santos, A.[1], Pino-Herrera, D.[2], Hafida, T.[2], Erard, M.[2], Herrington, R.J.[1], Joulian, C.[2], Guezennec, A.-G. [2]

[1]Resourcing the Green Economy, Natural History Museum, London, SW7 5BD, UK p.schofield@nhm.ac.uk
[2]BRGM, F-45060, Orléans, France
[3]Diamond Light Source Ltd, Harwell Science Campus, Chilton, OX11 0QX, UK

The Fe-oxide rich limonitic component of laterite deposits is usually discarded as mine waste to provide access to the high-grade silicate rich units below. Although limonites contain only low concentrations of Co and Ni they are volumetrically enormous leading to hundreds of thousands up to millions of tonnes of Co, Ni, and other critical metals being stockpiled as waste. Low-impact, low-cost processing technologies such as atmospheric heap leaching [1] and bioprocessing [e.g. 2] have been shown to successfully process these materials and recover this lost resource.

Within the H2020 CROCODILE project [3] we have been testing the relative benefits of pre-processing two mineralogically distinct limonites from New Caledonia. Using gravimetric sieving we have separated a limonite from Penamax into 7 different size fractions and a limonite from Tiébaghi into 6 distinct size fractions. The size fractionation ranges from < 50 µm up to >2 mm. To further concentrate the Co, density separation using a Mozley table was performed on the Penamax 100 – 400 µm size fraction.

These size fractioned and enriched samples have been analysed for bulk properties, including chemistry and mineralogy, and mineralogical properties including mineral chemistry, modal mineralogy and grain-scale texture. For both limonites the concentration of cobalt increases as the particle size increases with >50 and >8 times more cobalt in the largest size fraction compared to the smallest size fraction in the Penamax and Tiébaghi limonites respectively. Along with these increases in cobalt are substantial decreases in Fe_2O_3. Mineralogically, the primary host phase for cobalt increases from 0.04% in the smallest size fraction to 23% in the largest for the Penamax limonite and from 0.85% to 53% for the Tiébaghi limonite. Use of the Mozley table concentrated the Co in the light fraction and enabled the production of a Co-enriched material. The volume/mass of the samples was drastically decreased, with the mass of the final Penamax sample being only 3.3 % of the initial one. Additionally, the Co content increased from 0.16 wt% in the Penamax limonite to 2.3 wt% in the final Co-rich concentrate, representing an enrichment factor of 13.8 and recovery yield of 60 %.

Biotoxic quantities of the hexavalent Cr oxyanion has been reported in limonites form New Caledonia, including that from Penamax [5]. Using X-ray Absorption Near Edge Structure (XANES) spectroscopy we found the Cr^{6+} to be associated with the goethite which is concentrated into the smallest size fraction and removed larger size fractions. Subsequently the final Co-rich Penamax sample is suitable for bioprocessing without further pre-processing or the addition of ferrous iron.

The full range of mineralogical and chemical changes associated with the pre-processing will be described along with the fate and distribution of Co, Ni, Mn and other critical metals such as Li, Sc and Cu.

References:
[1] Oxley A et al (2016) Mineral Eng 88:53-60
[2] Santos et al (2020) Hydromet 195: 105396
[3] Crocodile, the first of a kind commercial compact system for the efficient recovery of cobalt designed with novel integrated leading technologies. https://h2020-crocodile.eu/
[4] Hubau A et al. (2025) Appl Geochem 193: 106569
[5] Santos A et al. (2022) Front Microbio 12: 802991

The Geological Controls and Mineral Parageneses of the Gunheath Lithium Deposit, St Austell, Cornwall

Sutton, B.T.C.[1,*], Shail, R.K.[1], Gleeson, P.[2], Broom-Fendley, S.[1], Andersen, J.C.Ø.[1], Roberts, N.M.W.[3] and Tapster, S.[3]

[1]Camborne School of Mines, University of Exeter, Cornwall TR10 9FE, United Kingdom (*bs712@exeter.ac.uk)
[2]Imerys, Par Moor Centre, Moor Road, Cornwall PL24 2SQ, United Kingdom
[3]Geochronology and Tracers Facility, British Geological Survey, Nottingham NG12 5GG, United Kingdom

---

The peraluminous granites of the early Permian Cornubian Batholith have been divided into five categories based on mineral assemblage, geochemistry and texture, with the rare-metal topaz granites (known as G5) hosting significant lithium concentrations principally within micas [1]. The Gunheath Project represents one of the four significant locations in SW England where the G5 granites occur near the surface of the Cornubian Batholith [2,3]. However, mica composition and paragenesis are influenced by regional-scale complexity [4].

By integrating whole-rock geochemical data, trace-element mapping and 3D deposit modelling, this research aims to quantitatively characterise variation in lithium and tin grades within the Gunheath deposit as a product of repeated cycles of magmatic fractionation (typically leading to Li enrichment) and magmatic-hydrothermal alteration (typically leading to Li depletion) associated with incremental assembly from multiple magma batches. Substantial volumes of magmatic-hydrothermal fluids, exsolved from each G5 batch and adjacent G4 tourmaline granite, may have scavenged Li from the primary magmatic micas and subsequently precipitated Li-rich overgrowths or new mica at higher levels in the system [4]. Timescales of deposit assembly will be established using high-precision U-Pb and Rb-Sr geochronology.

Understanding the relative contributions of magmatic and magmatic-hydrothermal processes on mica-hosted lithium grade at deposit scale, and the associated variability in Li-mica species, will inform how minerals are processed, which will affect commercial viability. An accurate paragenetic model could establish transferable criteria for other mica-hosted lithium projects.

References:
[1] Simons et al. (2017) Lith 278-281:491-512
[2] Manning et al. (1996) J. Geol. Soc. 153:827–838
[3] Simons et al. (2016) Lith 260:76-94
[4] Putzolu et al. (2024) Mineralium Deposita 59:1067–1088

Silica Precipitation Occurs Under Low-temperature Alkaline Conditions

Zhang Y.H.[1], Rajagoaplan A[2], Shaw S.[3] and Shang J.L.[1]

[1] DCivil Engineering and Management. Corresponding author: Shang J. Junlong.Shang@manchester.ac.u
[2] Chemical Engineering. Corresponding author: Rajagoaplan A. a.rajagopalan@manchester.ac.uk
[3] Earth Science. Corresponding author: Shaw S. sam.shaw@manchester.ac.uk

---

Granite and other crystalline rocks are widely considered potential host rocks for deep geological disposal facilities (GDFs) due to their high mechanical strength, relatively low permeability, and long-term geological stability. However, natural fractures in granite can significantly increase permeability and create potential pathways for fluid flow, compromising the containment functionality of GDFs. In the context of geological disposal of radioactive waste, radionuclides may transport through fractures and thus pose a major risk to people and the environment [1]. Therefore, reducing fracture permeability and promoting fracture healing are critical for maintaining the integrity of the host rocks of GDFs. Mineral precipitation within fractures is widely regarded as a potential healing mechanism because it can progressively clog flow pathways and reduce permeability and may also contribute to the longer-term recovery of fracture integrity and strength. Such precipitation may represent an initial stage of fracture healing and may help support the long-term mechanical stability of the host rock barrier system over geological timescales [2] [3].

Among different mineral systems, silica precipitation is particularly attractive because silica minerals such as quartz exhibit high chemical durability and low solubility in many geological environments [4]. In natural systems, silica precipitation commonly occurs through dissolution–precipitation reactions and may contribute to longer-term fracture healing [2] [5]. However, the mechanisms controlling silica precipitation under low-temperature alkaline conditions and their impactions for fracture healing, remain poorly constrained. Alkaline environments can significantly influence quartz dissolution and silica precipitation behaviour [6], highlighting the need to better understand these processes in subsurface systems.

To investigate silica precipitation under alkaline conditions, laboratory experiments were conducted using amorphous silica in NaOH solutions at 95 °C. Experiments were performed both in the absence and presence of granite samples to distinguish intrinsic silica dissolution–precipitation behaviour from potential rock–fluid interactions. The resulting reaction products were analysed using X-ray diffraction (XRD) to determine mineral phases, while scanning electron microscopy (SEM) was used to examine surface alteration and precipitation features.

SEM observations showed clear alteration of the granite surfaces under alkaline conditions, including dissolution features and the appearance of irregular silica-rich particles. XRD patterns exhibited a broad halo around 20–23° (2θ), consistent with the presence of amorphous silica rather than crystalline quartz. Together, these findings suggest that silica precipitation can occur under low-temperature alkaline conditions, but crystalline quartz did not form under the conditions tested and may require higher temperature or pressure. Future work will focus on hydrothermal experiments using autoclave systems, as well as flow-through experiments, to explore silica precipitation under conditions that are closer to those in the subsurface.

References:

[1] Zhang X, Ma F, Dai Z, Wang J, Chen L, Ling H and Soltanian MR (2022) J Hazard Mater 424:127550
[2] Okamoto A and Vinis E (2025) Nat Commun 16(1)
[3] Williams RT and Fagereng Å (2022) Rev Geophys 60(1)
[4] Dove PM (1999) Geochim Cosmochim Acta 63(22):3715–3727
[5] Saishu H, Okamoto A and Otsubo M (2017) Sci Rep 7(1)
[6] Knauss KG and Wolery TJ (1988) Geochim Cosmochim Acta 52(1):43–53

A reclassification of the Kit Hill granite and the mineralisation impact on the Redmoor deposit, Cornwall

Cundell, M. [1], Andersen, J. C. Ø. [1], Broom-Fendley, S. [1], Thorne, R.[2] and Lambert-Smith, J.[3]

[1] Camborne School of Mines, University of Exeter, Penryn TR10 9FE, mac254@exeter.ac.uk
[2] Cornwall Resources Limited, 15a Beeching Park, Kelly Bray, Callington PL17 8QS
[3] University of Cardiff, Main Building, Park Place, Cardiff, CF10 3AT

Underneath the historical Redmoor mine workings between Kelly Bray and Callington, Cornwall, lies the Redmoor deposit. It is a steeply dipping polymetallic sheeted vein system (SVS), rich in tin, tungsten, and copper [2]. Mineralisation is exogranitic, situated in veins in folded metapelites and metapsammites in the forms of cassiterite, wolframite, and chalcopyrite, with arsenopyrite, löllingite, stannite, sphalerite, and pyrite also identified [1]. Early research by Van der Stricht [7] identified native bismuth, bismuthianite, proustite, pyrrhotite, and marcasite also as primary ore minerals. Associated gangue minerals are muscovite, k-feldspar, quartz, tourmaline, kaolin, chlorite, sericite, and siderite [1, 7]. Adjacent to the developed SVS, lies the Kit Hill granite, which forms one of the small stocks of the Cornubian Batholith. The granite has been described as a G2 muscovite granite: fine- to coarse-grained with variable phenocrysts [3]. The observations, geochemistry, and age range by Simons et al. [6] and Moscati and Neymark [4] were obtained from surficial and ore samples, which contrasts with the underlying granite observed at depth from drill core.

There is a diverse range of mineralisation styles at Redmoor including greisen bordered veins (with and without tourmaline), skarns, polymetallic quartz-chlorite-sulphide lodes, and quartz-tourmaline breccias [1, 5]. Veins show evidence of repeated mineral deposition, suggesting the system has been rejuvenated during deposition and that mineralisation evolved from different granitic sources. Generally, copper and tin are more distal to the granite and appear to be remobilised, further suggesting multiple fluid injections from different sources [2]. With limited research into the genesis of Redmoor, understanding source rock geochemistry is valuable.

References:
[1] Andersen et al. (2016) Ore Geol Rev 78:213-238
[2] Blight et al. (2019) App Earth Sci 128:40-41
[3] Dangerfield and Hawkes (1981) Proc Ussher Soc 5:116-120
[4] Moscati and Neymark (2020) Min Dep 55:1-20
[5] Newall (1994) J Southeast Asian Earth Sci 10:109-130
[6] Simons et al. (2016) Lith 260:76-94
[7] Van der Stricht (1982) MSc Thesis.

Grain-scale simulations of olivine phase transitions under stress: Insights from a phase-field model and implications for mantle discontinuities

Lu, L.[1] and Wheeler, J.[1]

[1]University of Liverpool, Department of Earth, Ocean and Ecological Sciences, UK

Olivine, the dominant mineral in the upper mantle, transforms into its high-pressure polymorphs (wadsleyite and ringwoodite) with increasing depth. These phase transitions are accompanied by volume decreases that produce density contrasts, which manifest as seismic discontinuities in the mantle (e.g., d410 and d660). Based on thermodynamic equilibrium, pressure is the first-order control on these transformations and has therefore been commonly used to interpret the depths of mantel discontinuities. However, seismic observations reveal variations in discontinuity depths. Some of them can be explained by lateral temperature variations, but anomalies remain, such as the unusually deep d410 observed in the east of the subducting Nazca plate [1].

When temperature variations alone cannot account for such anomalies, additional factors including chemical composition, water content, and kinetic effects have been considered. However, stress in the mantle has largely been neglected due to the limitations of conventional hydrostatic thermodynamics.

Mantle slab models infer that nonhydrostatic stress within subducting slabs could reach gigapascal levels [2]. Theoretical and experimental studies suggest that both nonhydrostatic stress and stress variations associated with the transformation-induced volume changes can influence phase transitions [3-5] and therefore affect the interpretations of the depths of mantel discontinuities.

Here we employ a phase-field model [6] to investigate the microstructure evolution of the olivine-wadsleyite phase transition under stress at the grain scale. This model incorporates both the Helmholtz free energy difference between phases and stress-zero conditions and the stored elastic free energy during the transformation.

We first examine the feedback between stress generated by transformation-induced volume change and the olivine-wadsleyite phase transition. Stress heterogeneities between phases arising from volume changes increase the stored elastic energy and therefore inhibit the phase transition. To overcome this energy barrier, an overpressure exceeding 1 GPa is required for the olivine-to-wadsleyite transformation to proceed (or an underpressure > 1 GPa for the reverse reaction). These results highlight the effects of stress variations due to volume changes as well as the microstructural influences on the phase transition, effects that cannot be captured by hydrostatic thermodynamics. If such a large overpressure required for the olivine-to-wadsleyite transition is translated into a discontinuity depth offset, it would correspond to an approximately 30 km depression of the d410, providing a potential explanation for the unusually deep d410.

We also investigate the feedback between nonhydrostatic stress and the olivine-wadsleyite phase transition using the current model. Our preliminary results indicate that nonhydrostatic stress does not significantly influence the reaction threshold at which the phase transition occurs; hydrostatic stress remains the primary controlling factor. However, nonhydrostatic stress affects the reaction kinetics. Specifically, it promotes faster growth rate of wadsleyite along the direction of maximum compressive stress, leading to an elongated shape of wadsleyite grain in that direction. At the same time, it appears to slightly reduce the overall volumetric growth rate of wadsleyite.

References:
[1] Schmerr N and Garnero E (2007) Science 318 (5850), 623–626
[2] McNamara A et al. (2001) EPSL 191(1-2), 85-99
[3] Wheeler J (2014) Geology 42(8), 647-650
[4] Vaughan P et al. (1984) Tectonophysics 108(3-4), 299-322
[6] Kerschhofer L et al., 1998 Mineralogical Magazine 62 (5), 617–638
[7] Steinbach I and Salama H (2023). Lectures on phase field. Springer.

Quantifying Dome Formation at Showa-Shinzan, Mount Usu (Hokkaido, Japan) Using Crystal Size Distribution Analysis

Bradshaw, S.J.[1], Gertisser, R.[1], and Goto, Y.[2]

[1]School of Life Sciences, Keele University, Keele, ST5 5BG, UK (s.j.bradshaw@keele.ac.uk)
[2]Muroran Institute of Technology, Muroran, 050-8585, Japan

Showa-Shinzan, a dome-cryptodome located on the eastern flank of Mount Usu in Hokkaido, Japan, is one of the first domes whose formation was carefully recorded [1]. During 1943–1945, the ground surface rose by ~300 m as a cryptodome (Yaneyama) inflated beneath the pre-existing terrain. This was followed by extrusion of dacite lava, which built the present Showa-Shinzan dome to a final height of ~400 m. This well-documented uplift–extrusion sequence provides a rare opportunity to quantitatively investigate groundmass crystallisation in a dome where the timing of both cryptodome inflation and lava emplacement is tightly constrained, enabling direct correlation between rock texture and uplift-extrusion history.

To investigate these processes, we collected samples from the dome margin and adjacent breccia of the extrusive portion of Showa-Shinzan. The rocks are dacitic in composition and contain a crystal cargo dominated by plagioclase, orthopyroxene, and opaque phases, set within a fine-grained, plagioclase-rich groundmass.

Using these samples, we conduct a quantitative textural analysis of plagioclase microlites in the groundmass, applying crystal size distribution (CSD) methods to determine crystal number density, morphology, size, modal abundance, and size distributions. These data enable us to reconstruct magma ascent, degassing, and crystallisation during cryptodome inflation and lava extrusion between 1943 and 1945, and to compare our textural results with the documented chronology of uplift and extrusion.

Our analysis further assesses the extent to which the growth history of Showa-Shinzan is recorded in the rock texture and evaluates whether plagioclase microlite growth rates can be inferred. Finally, we place our findings in the context of published CSD studies of dome-forming systems [e.g. 2–4], demonstrating how crystallisation at Showa-Shinzan reflects shallow magmatic processes during coupled cryptodome–dome growth within the broader framework of dome-forming eruptions.

References:
[1] Mimatsu M (1995) Showa-Shinzan Diary. Hokkaido Shinbun Press, 216 pp
[2] Hammer JE et al. (2000) J Geophys Res 105:19135–19154
[3] Preece K et al. (2016) J Volcanol Geotherm Res 328:1–15
[4] Cashman KV (2020) Front Earth Sci 8:1–16

Timescales of pre-eruptive processes before the 23rd November 2013 paroxysmal explosive eruption at Etna using olivine diffusion chronometry

Haines, F.M.[1], Andronico D.[2], Hughes E.C.[1], Stanley, M.[1], and Thomson A.R.[1]
[1]Dept of Earth Sciences, University College London. Email: fiona.haines.24@ucl.ac.uk
[2]Osservatorio Etneo, Catania - INGV

Diffusion chronometry is a well-established technique in volcanology that uses the zoned composition of crystals to calculate timescales of diffusive processes that occurred prior to eruption [1]. Olivine is a perfect mineral to examine using this technique, as its major element Mg-Fe diffusion coefficients are well known and move on timescales relevant for volcanology.

Previous work using this technique has typically focused on measuring zonal composition along 1D transects from core to outer crystal. While useful, this has limitations, and it has been demonstrated that multiple 1D transects are needed for each crystal in order to constrain accurate timescales [2]. In an anisotropic material (like olivine) knowledge of the grain orientation is vital as this affects diffusion rate. The new Tescan Clara Field Emission Gun (FEG) Scanning Electron Microscope (SEM) at UCL Earth Sciences is equipped with Oxford Instruments Symmetry Electron Backscatter Diffraction (EBSD) and Ultim Max Energy Dispersive Spectroscopy (EDS) detectors that can collect data simultaneously, allowing rapid analysis of samples' zoning, chemical composition (Fe-Mg content), and crystal orientation in a single measurement.

We isolated olivine crystals in scoria samples obtained from the 23rd November 2013 eruption of Etna, the most explosive paroxysmal event of the 2011– 2013 sequence of eruptions. This eruption behaved differently from the preceding series, with a similar volume of magma erupting during a rapid and more violent explosive phase, with a large lava fountain. It has been suggested that this represents a more primitive magma source with a greater gas content [3]. Olivine crystals showing zoned compositions were identified through backscatter electron (BSE) imaging. Further analysis is currently underway, including greyscale calibration of BSE images using calibrated energy dispersive spectroscopy analysis to quantify composition, and electron backscatter diffraction (EBSD) to determine orientation.

Our aim is to collect two-dimensional maps, allowing identification of grain direction, and analysis of a series of 1D transects at various orientations to look for inter-line variability. As well as enabling us to derive timescales which can be interpreted to constrain magma movement in the time prior to this eruption, this will give a greater understanding of the reliability of single line analyses in diffusion chronography, informing future investigative techniques.

References:
[1] Dohmen R et al. (2017) Rev Mineral Geochem 83: 535–575
[2] Shea T et al. (2015) Am Mineral 100: 2026-2042 [3] Bonaccorso A et al. (2014) Geophys Res Lett 41: 4912–4919

Controls on metal endowment in volcanogenic massive sulphide (VMS) deposits of the Caledonian-Appalachian orogen

Hollis, S.P.[1], Mongeau, P.[1], Roberts, N.[2], Cooper, M.R.[3], Grant, H.[2], McFall, K.[4], Zagorevski, A.,[5] Sparkes, G.W.[6], Tapster, S.,[2] Condon, D.J.,[2] and Piercey, S.J.[7]

[1]University of Edinburgh, Edinburgh, UK; steven.hollis@ed.ac.uk
[2]British Geological Survey, Keyworth, UK
[3]Geological Survey of Northern Ireland, Belfast, UK
[4]University College London, London, UK
[5]Geological Survey of Canada, Ottawa, Ontario, Canada
[6]Mineral Deposits Section, Geological Survey of Newfoundland and Labrador, St John's, Newfoundland, Canada
[7]Memorial University of Newfoundland, St. John's, Newfoundland, Canada

---

Volcanogenic massive sulfide (VMS) deposits, not only host significant quantities of base metals (Zn, Cu, Pb), but can also be enriched in several critical minerals (e.g. Co, Ga, Ge, In, Sb, Sn, Te). VMS deposits form near the seafloor through magmatic-hydrothermal processes in extensional tectonic settings and are preserved within ophiolites and volcanic arcs within orogenic belts. Significant differences occur in the abundance, size and grade of VMS deposits both within, and between accreted arc systems, yet the fundamental processes controlling metal enrichment and distribution are largely unknown.

The Caledonian-Appalachian orogen (CAO) extends from Norway, through Scotland, Ireland and Newfoundland, to maritime Canada and the northeast USA. Along its length it hosts various sub-types of VMS deposits in arc and ophiolite sequences of varying age, host stratigraphy, magmatic affinity, and tectonic setting, including numerous mined deposits. World-class deposits occur on both sides of the Iapetus suture in arc/backarc sequences upon Laurentian and Gondwanan affinity crust. In the Canadian Appalachians, these include both some of the largest VMS deposits globally (e.g. Brunswick No.12, 229 Mt at 10.8% Zn+Pb+Cu), and some of the highest-grade deposits known (e.g. Buchans deposits collectively - 16.2 Mt at 24.4% Zn+Pb+Cu). In stark contrast only a handful are known to occur in the British and Irish Caledonides, including two mined deposits (i.e. Avoca and Parys Mountain).

This two-year UKRI funded project aims to determine the controls on the metal enrichment and distribution of VMS deposits across the CAO through detailed whole rock geochemical, zircon trace element and Hf isotope, fluid inclusion, and sulfide trace element studies. Here we present the results of preliminary whole rock geochemical, isotopic and zircon trace element data collected from felsic volcanic rocks across the Grampian-Taconic sector of the orogen to assess their magmatic affinity and fertility for VMS deposits.

Petrological insights into the magma system of Santorini volcano (Greece) after the caldera-forming Late Bronze Age eruption

Keeley, N.[1], Gertisser, R.[1], Petrone, C. M.[2], Druitt, T.[3], Kutterolf, S.[4], Ronge, T.[5] and the Expedition 398 Scientists

[1]School of Life Sciences, Keele University, Keele, ST5 5BG (n.keeley@keele.ac.uk)
[2]Natural History Museum, Volcano Petrology Group, Cromwell Road, London, SW7 5BD, UK
[3]Laboratoire Magmas et Volcans, Université Clermont Auvergne, F-63000 Clermont-Ferrand, France
[4]GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, D-24148 Kiel, Germany
[5]Texas A&M University, College Station TX 77845, USA

Following the most recent caldera-forming eruption, the ~1627-1600 BCE Late Bronze Age (Minoan) eruption [1], continued volcanic activity of Santorini volcano (Greece) built up the Kameni volcanic edifice within the flooded Minoan caldera. Recent episodes of seismic unrest and ground deformation in 2011-2012 and 2024-2025, attributed to magma recharge, highlight the need to better constrain the structure, depth and behaviour of the active magmatic system beneath Santorini and its neighbour Kolumbo. In this contribution, we refine existing models of the post-Minoan magma plumbing system of Santorini [e.g 2, 3] by characterising magmatic storage conditions, processes and longer-term evolution from the immediate post-caldera transition through to the most recent eruptions (up to ~1950 CE). We analysed samples from deep-drilling Site U1595 in the southern caldera basin, obtained during International Ocean Discovery Programme Expedition 398 to the South Aegean Volcanic Arc [4].

Whole-rock compositions define a narrow low-K dacitic range (66.4-68.4 wt% SiO2), overlapping the post-Minoan onshore record and contrasting with the rhyolitic medium-K Minoan magma. All analysed units show uniformly low Ba/Zr ratios, lacking the high Ba/Zr signature of some Minoan products [5]. Dacitic mineral assemblages comprise plagioclase, orthopyroxene, clinopyroxene, Fe-Ti oxides ± apatite. Orthopyroxene compositions span Mg# 48-72, clinopyroxenes Mg# 48-89 (with 97% >Mg# 65), plagioclase An21-87, magnetite Usp29-60, and homogenous ilmenite (~Ilm86). Ilmenite-magnetite thermometry and oxygen barometry indicate eruption temperatures of ~845-951 °C and oxygen fugacities of NNO -0.3 to +0.4. Thermometry of plagioclase-liquid and orthopyroxene-liquid pairs indicate dacitic magma temperatures of ~902-1275 °C, while barometry from orthopyroxene-liquid and clinopyroxene-only records pressures up to ~570 MPa corresponding to depths of <22 km assuming a crustal density of 2640 kgm^{-3} [6]. Most dacitic and mafic pyroxene crystallisation pressures fall between 0-400 MPa (~0-15 km), forming a broadly continuous range. Wide pressure ranges for dacitic orthopyroxene suggest multiple dacitic reservoirs in the mid- to upper crust, while zoning patterns consistent with similar Mg# melts imply recharge by compositionally similar magmas. The mafic assemblage, including Mg# >86 clinopyroxene, Mg# >69 orthopyroxene and An >50 plagioclase, are equilibrated with andesite to basaltic andesite magma, with few measured andesitic glasses (~60 wt% SiO_2). Slightly deeper crystallisation of mafic phases and disequilibrium textures indicates minor mafic recharge into shallower silicic reservoirs. These temperature-pressure estimates, together with compositionally diverse pyroxene and plagioclase populations exhibiting both reverse and normal zoning, indicate repeated mafic-intermediate and silicic recharge within an open, upper-mid crustal magma system. Collectively, the results suggest the development of a geochemically distinct magma system following the Minoan eruption, producing compositionally uniform dacitic magma with minor mafic recharge into silicic reservoirs after structural reorganisation of magma pathways and storage regions following caldera collapse.

References
[1] Friedrich W et al. (2006) Science 312: 548
[2] Barton M and Huijsmans J (1986) Contrib Mineral Petrol 94: 472-495
[3] Higgins M et al. (2021) Contrib Mineral Petrol 176: 13
[4] Druitt T et al. (2024) Proc International Ocean Discovery Program
[5] Karatson D et al. (2018) Sci Rep 8: 7026
[6] Konstantinou K (2010) J Geodyn 50: 400-409

Developing an H-in-zircon magmatic water proxy using apatite inclusions,

MacRae, C.[1], De Hoog, J.C.M.[1], Talavera, C.[1] and Jollands, M.[2]

[1]School of GeoSciences, University of Edinburgh, Edinburgh, UK. Email: Careen.MacRae@ed.ac.uk
[2]Gemological Institute of America, New York City, USA

Trace element and isotope chemistry of zircon is commonly used to track magmatic processes, including $\delta^{18}O$, εHf, Ti, and rare earth elements (REE). H content in zircon has received little attention in comparison to other Nominally Anhydrous Minerals (NAMs), however recent Secondary Ion Mass Spectrometry (SIMS) studies suggest this is a viable tracer of the H_2O content of melts [1].

Uncertainties remain surrounding the uptake mechanisms of H into zircon which preclude accurate interpretations of volatile evolution of magmas. In particular, the relative significance of charge balance substitutions relating to REE incorporation. REE + H = Zr has shown to be significant for H incorporation, but is in competition with the so-called xenotime substitution, REE + P = Zr + Si, creating an interdependence between REE-P-H [2]. Investigation into H in zircon is further hindered by the limited availability of suitable zircon standards with characterised H concentrations [3].

This research aims to use SIMS trace element analyses of zircon, and apatite inclusions therein, to constrain the relationship between H concentration in zircon and H_2O of the melt. Existing apatite-volatile models will be used with the apatite analyses to identify the H_2O content of the melt [4,5] to be compared to inclusion-adjacent zircon analyses. Current zircon samples under investigation are from the NW Argentinian Andes; Gran Canaria, Canary Islands, and the Fish Canyon Tuff. Initial results suggest the Gran Canaria zircon are most suitable for constraining the H_2O zircon-melt relationship as these show the most consistent apatite volatile composition and H in zircon composition. The Gran Canaria apatite inclusions are fluorapatite and have F concentrations between 3.46-5.08 ppm, Cl concentrations between 0.21-0.41 ppm, and H_2O concentrations between 0.01-0.93 ppm. H_2O concentrations in the Gran Canaria zircon range between 39-135 ppm.

This project also aims to address the lack of available standard reference materials. Trace element SIMS analyses have been conducted on a suite of gem quality zircon samples, as well as a sample of the Mudtank carbonatite zircon standard and SL-1, an in-house zircon standard. Fourier Transform Infra-Red spectroscopy (FTIR) will be also used to map the H contents of these samples. SIMS and FTIR results will be used in conjunction to characterise their H concentration and assess their suitability for use as H in zircon standards.

References:
[1] Xia X-P et al. (2021) Lithos 404-405: 106445
[2] De Hoog JCM et al. (2014) GCA 141:472-486
[3] Cui Z et al. (2022) At Spectrosc 43: 70-76
[4] Li W and Costa F (2020) GCA 269: 203-222
[5] Lormand C et al. (2024) Lithos 480-481: 107623

Variations in the crystal content of basalts from the Eastern Volcanic Zone of Iceland

Pierce-Jones, T.[1], Hartley, M.E.[1], Namur, O.[2], Vander Auwera, J.[3] and Neave D.A.[1]

[1]Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK; thomas.pierce-jones@manchester.ac.uk
[2]Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium
[3]Department of Geology, Université de Liège, Liège, Belgium

---

The crystal content of lavas can be used to interpret their magmatic histories and to infer both the structure of magma reservoirs and the nature of the processes that operate within them. Magma reservoirs are increasingly viewed as complex, crystal-rich systems, often expressed in terms of a crystal mush paradigm, where melt is distributed within vertically extensive crystal frameworks [1]. Crystal mush models were primarily developed at volcanic arc systems, where magma flux and volatile content are high, sustaining trans-crustal mushes. It is uncertain whether such trans-crustal mushes are viable at ocean island volcanic systems, due to their generally lower magma fluxes and volatile contents. In some ocean island systems, such as the Eastern Volcanic Zone (EVZ) of Iceland, spatially and temporally proximal samples have a wide range of crystal contents. In the EVZ, plagioclase-phyric magmas are erupted alongside crystal-poor magmas. It is possible that the variation in crystal content reflects the level of interaction between the magma and a crystal mush structure, as portions of the mush are entrained during magma ascent [2].

In this study, we use the geochemistry and petrology of 32 basalt samples from the EVZ, which were mostly erupted beneath ice, to investigate the nature and cause of variation in crystal abundances and proportions. We combine whole-rock analyses from X-ray fluorescence, thin section textural observations from optical and electron imaging (backscattered electron imaging and scanning electron microscope energy dispersive spectroscopy), and geochemical microanalysis (electron probe microanalysis) to constrain magma storage conditions and examine the processes controlling crystal content. Our goal is to evaluate magma storage models of ocean island systems, using the EVZ as a case study of an ocean island system with relatively high magma flux.

References

[1] Sparks et al. (2019). Phil Trans R Soc A 377: 20180019
[2] Neave et al. (2014). J Pet 55(12): 2311-2346

Mantle Source Heterogeneity and Phlogopite-Rich Lithospheric Mantle Contribution to Early Cretaceous Ultrapotassic Magmatism in the Damodar Valley, Eastern India

Shareef, M.[a*], Sujoy Ghosh[a], Soumendu Sarkar[b], Vivek P. Malviya[c], Makoto Arima[d], Sanjay Kumar Mandal[e]

[a] Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, India. Email: mshareef@iitkgp.ac.in
[b] University of Alberta, Department of Earth and Atmospheric Sciences, Edmonton, AB, Canada
[c] Department of Applied Geology Dr Harisingh Gour Central University, Sagar, Madhya Pradesh, 470002, India
[d] Geological Institute, Yokohama National University, Yokohama, 240-8501, Japan
[e] Department of Earth Sciences, Indian Institute of Science Education and Research Kolkata, Mohanpur, 741246, India

---

The Damodar Valley lamprophyres provide valuable evidence for the compositional heterogeneity and metasomatic evolution of the subcontinental lithospheric mantle. The studied lamprophyres are composed of phlogopite, apatite, alkali feldspar, aegirine, diopside, siderite, magnesite, dolomite, rutile, and quartz. Electron microprobe analyses and BSE imaging reveal distinct zoning in phlogopite, with TiO_2 up to 11.8 wt.% in the cores and 5–8 wt.% in the rims, and BaO ranging from 1.2–2.1 wt.% in the rims to as high as 3.8 wt.% in the cores. Such variations and dominance of phlogopite indicate progressive crystallisation from a hydrous volatile rich mafic magma. Textural and compositional features suggest the presence of phlogopite antecrysts, which are early formed phlogopite crystals that were later incorporated into the host magma before eruption, indicating magma mingling. The elevated Ba concentrations and Fe enrichment (up to 9.61 wt.% FeO_T) displayed by these micas may represent evolution under oxidising conditions with the majority of iron present as Fe^{3+}, further supporting the oxidising nature of the lamprophyric magma inferred from phlogopite compositions. Bulk rock compositions of Damodar Valley lamprophyre (SiO_2 41.74 wt.%; Mg# = 67–76) indicate silica-undersaturated mantle derived primitive ultrapotassic magmas. The presence of abundant rutile and apatite provides additional constraints on the petrogenesis of these ultrapotassic magmas. Rutile indicates a Ti-rich metasomatic component in the mantle source, whereas apatite reflects enrichment of phosphorus during mantle metasomatism. Carbonate minerals occurring in the groundmass further suggest involvement of CO_2-rich metasomatic fluids or melts within the lithospheric mantle. Trace element ratios further reveal mantle heterogeneity, elevated Nb/La, and variable La/Yb suggest contributions from both lithosphere and asthenosphere mantle. The low Nb/Ta and high Zr/Hf ratios, along with abundant carbonates and apatite, suggest carbonate rich metasomatism. Higher Rb/Sr and lower Ba/Rb ratios suggest the presence of phlogopite in the source region. The combined mineralogical and geochemical evidence highlights the role of hydrous carbonated metasomatism, phlogopite antecrysts, and source hybridisation in generating lamprophyric magmas through partial melting of a heterogeneous sub-continental lithospheric mantle in the Damodar Valley during the Cretaceous.

A textural perspective on the eruptive behaviour of Ciomadul volcano, East Carpathians, Romania

Spring, B.[1], Gertisser, R.[1], and Karátson, D.[2]

[1]School of Life Sciences, Keele University, Keele, ST5 5BG, UK (b.o.spring@keele.ac.uk)
[2]Department of Physical Geography, Eötvös University, Budapest, H-1117, Hungary

---

Effusive and explosive activity of compositionally similar magmas is common at intermediate to silicic volcanoes. At these systems, dome-forming eruptions may alternate with explosive phases over time, and transitions between effusive and explosive behaviour can also occur within single eruptive episodes. Where magma compositions and overall reservoir architecture show only limited variability, differences in eruption style are often interpreted to reflect shallow conduit processes, including the interplay between magma ascent, degassing-induced crystallisation, and the subsequent modification of magma rheology.

Ciomadul, a long-dormant volcano in the East Carpathians (Romania) [1], experienced a prolonged phase of effusive activity that produced dacitic lava domes between ~850 and 60 ka [2]. This was followed by a period of silicic explosive eruptions from ≥51 ka to 27.7 ± 1.4 ka, spanning styles from phreatomagmatic to Vulcanian and sub-Plinian/Plinian [3, 4]. As such, Ciomadul provides an excellent natural laboratory for investigating the factors that may have driven the transition to more explosive activity at ~50–60 ka, as well as variations in eruption style more broadly.

We address these questions through a quantitative textural analysis of groundmass feldspar, including crystal number density, morphology, size, abundance, and size distributions. These data provide constraints on magma ascent dynamics during both effusive and explosive eruptions, the timescales over which they operate, and the potential role of shallow conduit processes in modulating eruption style. We further evaluate our results in the context of published crystal size distribution studies of effusive and explosive eruptions at other volcanoes, placing Ciomadul within a broader framework of high- and low-intensity eruptive behaviour and associated groundmass textural characteristics.

Improved understanding of the controls on effusive versus explosive activity at Ciomadul is particularly important, as geophysical studies indicate that the volcano is still underlain by a potentially active magma storage system [5].

References:
[1] Karatson D et al. (2017) Geology Today 33:60-65
[2] Lahitte P et al. (2019) Bulletin of Volcanology 81:27
[3] Karatson D et al. (2019) Bulletin of Volcanology 81:28
[4] Karatson D et al. (2016) Journal of Volcanology and Geothermal Research 319:29-51
[5] Harangi S et al. (2015) Journal of Volcanology and Geothermal Research 290:82-96

Constraining the age, geology, geochemistry, and VMS prospectivity of the Tallering Greenstone Belt, Yilgarn Craton, Western Australia

Turanski, M., Hollis, S., Diers, S., Dana, C., Fitton, G., Tavazzani, L., Chelle-Michou, C.[3], Glorie, S.[4], Morey, B.

[1]University of Edinburgh, Grant Institute, James Hutton Rd, Kings Buildings, Edinburgh EH9 3FE – m.turanski@ed.ac.uk
[2]MGX, 1/2 Kings Park Rd, West Perth, WA 6005, Australia
[3]ETH Zürich, Rämistrasse 101, 8092 Zürich, Switzerland
[4]University of Adelaide, Adelaide SA 6005, Australia

The Tallering Greenstone Belt is located in the Youanmi Terrane of the western Archean Yilgarn Craton [1] [2]. The greenstone belt has experienced greenschist-to-amphibolite facies metamorphism across its length, and has been historically exploited for Fe-ore by MGX Ltd. from banded iron formations (BIFs) [2]. Recent efforts have now shifted towards VMS exploration given the occurrence of thick sequences of massive sulfide mineralization underlying the units of the BIF [2]. This study presents the first detailed account the age, geology, and geochemistry of the Tallering Greenstone Belt. The research objectives guiding this investigation include characterizing the host stratigraphy, determining its tectonic-magmatic evolution, characterizing the type and intensity of hydrothermal alteration, and identifying geochemical and mineral-chemical halos to sulfide mineralization. These were achieved through core logging of diamond drill holes, petrography, Scanning Electron Microscope (SEM) analysis, whole rock geochemical analysis, and trace element analysis of garnet, white mica, and chlorite using Electron Probe Mirco-Analysis (EPMA) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). U-Pb zircon and Lu-Hf garnet geochronology was also completed to determine the age of the host stratigraphy and timing of peak metamorphism, respectively.

This investigation revealed that the Tallering Greenstone Belt is composed of a calc-alkaline, largely volcaniclastic stratigraphy. It is dominated by andesitic rocks with lesser basalt, dacite, and rare ultramafic rocks. Overlying meta-sedimentary rocks to massive sulfide mineralization include thick sequences of BIF and polymict conglomerates. The volcaniclastics were dated to c. 2.74 Ga using U-Pb zircon geochronology. A minor zircon population at c. 2.94 Ga is consistent with existing geochronology, suggesting the presence of a large regional unconformity in the greenstone belt. Most of the sulfide mineralization observed is composed of pyrite and pyrrhotite, though minor sphalerite, galena, and chalcopyrite were observed. Hydrothermal alteration in diamond drillcore is extensive and consistent with the distal portions of a VMS system, and it includes largely sericitic and chloritic assemblages. Mineral assemblages, whole rock geochemistry (e.g. Eu/Eu*), and garnet trace element geochemistry (e.g. Heavy Rare Earth Element (HREE) abundance) distinguish footwall from hanging-wall alteration across the system. Massive sulfide mineralization is associated with increased Mn contents in garnet in the laser ablation and EPMA data. Whole rock geochemical data from RC drilling suggests the NE area is increasingly prospective. Lu-Hf garnet analysis revealed ages of ~2.0 Ga, suggesting that peak metamorphism is likely associated with the Glenburgh Orogeny [3].

References:
[1] Hollis S et al (2017) GSWA Report 165
[2] Diers S (2023 - Unpublished) MGX Annual Report C18/2000
[3] Johnson S et al. (2010) GSWA Record 2010/5

Volatile Behaviour During Serpentinisation at Atlantis Massif: Insights from Halogens and Petrology

Green, H.R.[1*], Carter, E.J.[1], Stimpson, I.G.[1], Tartèse, R.[2], Osborne, W.[3], Savov, I.[3]

[1] School of Geography, Geology and the Environment, Keele University, Newcastle-under-Lyme, UK
[2] Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK
[3] School of Earth and Environment, University of Leeds, Leeds, UK
*h.r.green@keele.ac.uk

Hydrothermal alteration of exhumed lithospheric mantle at the seafloor facilitates a flux of volatiles and fluid-mobile elements via incorporation into secondary minerals, which are transported through the oceanic conveyor belt and subsequently remobilised during fluid fluxing and melting at subduction zones [1,2]. Constraining the mechanisms and extent of volatile incorporation at spreading centres is therefore essential for quantifying elemental inputs into subduction zones and evaluating their contribution to global geochemical cycles.

Atlantis Massif is an oceanic core complex located 30°N, just west of the Mid-Atlantic Ridge which hosts the Lost City hydrothermal field. Serpentinised peridotites and altered gabbros were recently sampled by ocean drilling during IODP Expedition 399 yielding a unique deep drill core extending >1.2 km beneath the seafloor. Because halogens are fluid-mobile and possess ionic radii and charge comparable to OH^-, they are possibly incorporated into the serpentine lattice and make ideal tracers of fluid processes. This study uses halogen (Cl, Br, I) geochemistry to interrogate the conditions and fluids driving serpentinisation beneath Atlantis Massif.

Preliminary halogen data from serpentine analysed *in situ* laser-ablation inductively-coupled-plasma mass-spectrometry show very high concentrations in the top 200 m of the core, decreasing downhole. However, these do not agree with Cl measurements from electron-probe microanalysis (EPMA). The disparity may relate to water-soluble Cl-bearing phases within the samples, concentrated along grain boundaries [3]. Ongoing work to investigate this focuses on the potential presence of water-soluble halides through leaching experiments and powder X-ray diffraction, enabling evaluation of both structurally bound and fluid-mobile (grain boundary) halogen reservoirs.

Quantification of halogen abundance and elucidation of host phases will allow better estimation of halogen fluxes associated with serpentinised lithologies during subduction-related processes [2]. These results will contribute to improved constraints on volatile cycling at slow-spreading ridges and important knock-on effects that may affect melting behaviour and metallogenesis.

References:

[1] Kendrick, M.A., Michael, and Godard, M. (2022). Halogens in serpentinised-troctolites from the Atlantis Massif: implications for alteration and global volatile cycling. Contributions to Mineralogy and Petrology, 177(12). doi: https://doi.org/10.1007/s00410- 022-01974-x.
[2] Scambelluri, M., Othmar Müntener, Ottolini, L., Pettke, T. and Vannucci, R. (2004a). The fate of B, Cl and Li in the subducted oceanic mantle and in the antigorite breakdown fluids. Earth and Planetary Science Letters, 222(1), pp.217-234. doi: https://doi.org/10.1016/j.epsl.2004.02.012
[3] Sharp, Z.D. and Barnes, J.W. (2004). Water-soluble chlorides in massive seafloor serpentinites: a source of chloride in subduction zones. Earth and Planetary Science Letters, 226(1-2), pp.243-254. doi: https://doi.org/10.1016/j.epsl.2004.06.016.

High-Grade Pelitic Granulites from the Diwani Hills: P–T–fO_2 Evolution and Tonian Metamorphism in the Aravalli–Delhi Mobile Belt, India

Kumar, M. and Kumar Yadav, M.

Depart. Of Geology, University of Lucknow, Lucknow, India
manishkumar562@gmail.com (Corresponding Author)

The Diwani Hills, located southeast of Balaram–Abu Road in the Banaskantha district of north Gujarat, expose a diverse assemblage of Precambrian metamorphic and igneous rocks within the Aravalli–Delhi Mobile Belt. These crystalline rocks record a complex metamorphic history predating or coeval with the Aravalli orogeny. The presence of garnet–spinel–orthopyroxene–quartz (grt–sp–opx–qz) assemblages in pelitic granulites indicates formation under anhydrous conditions typical of pyroxene granulite facies. Field relations and microstructural features suggest that these high-grade rocks were subsequently deformed during the Delhi orogenic event and later intruded by the Erinpura Granite, reflecting multiple stages of tectono-thermal reworking within the lithosphere.

An integrated approach combining petrography, mineral chemistry, oxidation state analysis, and P–T–X pseudosection modelling in the NCKFMASHTO system using Perple_X software has been employed to constrain the metamorphic evolution. The pelitic granulites attained peak conditions of approximately 8.6 kbar and 770 °C. Oxygen fugacity calculations at 6.2 kbar yield log fO_2 values around −13.0 at ~765 °C, suggesting relatively reduced metamorphic conditions. Electron microprobe dating of monazite grains provides ages between 855 and 769 Ma, indicating a Tonian (Neoproterozoic) metamorphic event. These results contribute to understanding lower crustal processes and fluid–melt–rock interactions during high-grade metamorphism in western India.

Origin of sanukitoid magmas linked to Archaean intrusion-related Au deposits: Insights from the Yilgarn Craton, Australia

Nash, I.J.[1], Hollis, S.P.[1], Hastie, A.R.[1], Smithies, R.H.[2], Verbeeten, A.[2], Holder, D.[3] and Stock, E.[3]

[1]School of GeoSciences, The University of Edinburgh, Edinburgh, United Kingdom (i.j.nash@sms.ed.ac.uk)
[2]Geological Survey of Western Australia, Department of Mines, Petroleum and Exploration, East Perth, Australia
[3]Barrick Mining Corporation, London, United Kingdom

Archaean lamprophyres and sanukitoids have been spatially and temporally linked to magmatic-hydrothermal gold deposits across the Yilgarn Craton of western Australia. Lamprophyres are considered to be the product of hydrous low-degree partial melting of metasomatic mantle source regions. Sanukitoids are relatively rare late Archaean mantle-derived hornblende-plagioclase porphyritic granitic complexes characterised by high MgO and relatively elevated concentrations of Ba and Sr. Therefore, sanukitoids exhibit mantle-derived (Mg, Ni, Cr) and incompatible element-enriched components (Sr and Ba) indicative of contributions from both mantle and crustal sources. Cognate xenoliths within the sanukitoids are amphibole-rich and/or biotite-rich metabasites. One model proposed for explaining sanukitoid formation is through amphibole-dominated fractional crystallisation of a lamprophyric parental melt[1].

Understanding whether the spatial relationship between gold systems and sanukitoid-lamprophyre magmatic systems is also genetic will be important for updating Archaean magmatic-hydrothermal gold deposit models. High precision trace gold analyses, with detection limits of 0.02 ppb, have been conducted on systematic samples of lamprophyres and sanukitoids to quantify the gold concentration variation during magmatic differentiation.

Here, we present mineral chemistry (amphibole, feldspar, mica) from sanukitoids associated with gold deposits and their cognate xenoliths in conjunction with whole-rock, and trace gold, geochemistry from the Yilgarn Craton. We present our results of fractional crystallisation modelling and our investigation into the behaviour of gold during mantle (primitive lamprophyres) and crust (evolved sanukitoid) transportation. We test whether the Archean lamprophyre-sanukitoid magmatic system is intrinsically elevated in gold or whether lamprophyre-sanukitoid magmas provide fertile fluid conduits for gold deposit formation.

References:
[1] Smithies et al., 2019. Nature Communications, 10(1), p.5559.

The NERC Ion Microprobe Facility: SIMS analyses to support Earth Science and Mineralogy research

De Hoog, J.C.M.[1], Talavera, C.[1], Barosch J.P. [1] and EIMF

[1]Edinburgh Ion Microprobe Facility, School of GeoSciences, University of Edinburgh, ionprobe@ed.ac.uk

---

The NERC Ion Microprobe Facility (IMF) at the University of Edinburgh supports academic and commercial services in Secondary Ion Mass Spectrometry (SIMS) for chemical and isotopic analyses of small volumes of solid material. SIMS can achieve detection limits down to parts per billion for many elements, including those relevant to igneous and metamorphic petrology, climate research, mineral deposits research, planetary science, geomorphology, heritage and archaeology, and material and mineral science.

The Facility hosts two state-of-the-art ion microprobes. The compact Cameca IMS 7f-Geo was commissioned in 2019 and is particularly well suited for the analysis of volatile and light elements in glasses, melt inclusions, hydrous and nominally anhydrous minerals, as well as trace element concentrations in both silicate and non-silicate materials.

The large-geometry Cameca IMS-1300 HR^3 was delivered in November 2025 and is expected to be fully operational by April 2026. It features high secondary ion transmission, high mass resolving power and multicollection capabilities. It is ideally suited to measure high-precision stable isotope ratios (e.g., H, Li, B, C, N, O, S, Si, Mg, Fe), K-Ca and U-Pb geochronology, and to the analysis of elements that require extremely high mass resolution such as heavy halogens (Br, I) and transition metals. Both instruments are supported by comprehensive sample preparation facilities, experienced technical staff, and a wide range of well-characterised standard materials.

The facility also participates in the development, characterisation and distribution of reference materials.

Examples of recently publication highlights using EIMF data are:

Carter et al. [1] presented a study showing that carbonated mantle peridotites represent a hidden sink for subducted CO_2. Meanwhile, Kendall-Langley et al. [2] evaluated the use of apatite and zircon as Cu–Au porphyry fertility indicators, and applied this to arc-related intrusions of the Lachlan Orogen, eastern Australia. A study exploring the role of COHF-Cl fluids in the making of Earth's continental roots was published by Gibson et al. [3]. Finally, Georgieva et al. [4] used sulfur isotopes of lower Palaeozoic hydrothermal vent fossils to gain insights into microbial sulfur cycling.

The IMF is keen to engage with new and prospective SIMS users from the wider Earth Science community. We invite any interested researchers to contact the facility staff to discuss the needs of your project.

References:
[1] Carter et al. (2026) Nature Communications DOI:10.1038/s41467-026-68646-3
[2] Kendall-Langley et al. (2025) Contrib Mineral Petrol 180:Art 35
[3] Gibson et al. (2025) Nature Communications 16 (1) 7842
[4] Georgieva et al. (2022) GeoBiology DOI: 10.1111/gbi.12495

Applying cutting-edge facilities to investigate mineral-fluid interactions

Hao, J.[1], Ma, L.[1] and Taylor, K.G.[2]

[1] Department of Chemical Engineering, University of Manchester, Manchester M13 9PL, UK.
[2] Department of Earth and Environmental Sciences, University of Manchester, Manchester, M13 9PL, UK.

In the 21st century, advances in mineralogical research have increasingly focused on resolving the fundamental physicochemical processes that govern fluid-rock interactions across spatial and temporal scales. The development of multi-scale and multimodal imaging approaches, spanning two-dimensional to three-dimensional (3D) characterisation, has enabled direct observation of mineral reactions under conditions that closely replicate natural subsurface environments. These approaches provide new opportunities to investigate reaction mechanisms, mass transfer, and the evolution of pore structures in heterogeneous geological materials.

In this study, we present selected examples illustrating how advanced imaging techniques can be used to address key scientific challenges in mineralogy and geochemistry. Synchrotron-based imaging enables real-time observation of mineral dissolution and precipitation, revealing interface-coupled processes, reactive surface area evolution, and the coupling between transport and reaction kinetics. Complementary methods, including neutron imaging and X-ray computed tomography, allow quantification of pore-scale heterogeneity, permeability evolution, and multiphase fluid distribution within complex porous media. These observations provide critical constraints on reaction rates, feedback mechanisms between mineral transformation and fluid flow, and the development of preferential pathways during reactive transport. Particular attention is given to processes relevant to carbon capture and storage, geothermal systems, and radioactive waste disposal, where mineral-fluid interactions control sealing integrity, reservoir performance, and long-term system stability. By integrating high-resolution experimental observations with quantitative analysis, this work advances our understanding of how microscale processes govern macroscopic behavior in geological systems. The resulting insights improve reactive transport models and reduce uncertainties in predicting the long-term evolution of subsurface environments.

Advancing Iron Mineral Characterisation in Geoscience with MinSight: A User-Friendly Web App for Mössbauer Spectroscopy

Heinen, B.J.[1] and Byrne J.M.[1]

[1]School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol, BS81RJ, United Kingdom. benedict.heinen@bristol.ac.uk

---

Mössbauer spectroscopy is a powerful technique used across the material, Earth, and environmental sciences to determine the oxidation state, coordination environment, and mineralogy of iron-bearing phases. Processing and interpreting Mössbauer data often relies on domain expertise, complex analytical pipelines, and outdated software tools that require repetitive steps and hinder automation. This creates an entry barrier to new users and limits broader adoption. To address these challenges, we have developed *MinSight (www.minsight.org),* a user-friendly web application to process and interpret Mössbauer spectroscopy data.

MinSight is designed to be an accessible, easy-to-use platform that supports high throughput data pipelines, automated analysis and reporting, and collaborative workflows. As a cloud-based tool, users can access *MinSight* and their saved data from any device with an internet connection.

MinSight supports most file formats for uploading raw data and allows users to organise spectra into projects which can also be shared between users to allow collaboration. Simple inputs allow easy annotation with project and sample-specific metadata. The core analysis module supports fitting with standard physical models for lab-based and synchrotron source Mössbauer spectroscopy, including Lorentzian, squared Lorentzian, Voigt-based fitting (VBF) and extended Voigt-based fitting (xVBF), as well as a full static Hamiltonian (FSH) approach.

Several features are provided to simplify and accelerate data analysis. Initial parameter values for common materials (based on published literature) can be easily selected. Alternatively, user spectra can be auto-compared against a spectral database and the published parameters for matching materials loaded in and used to fit the data. This can provide a starting point for complex spectra such as those from environmental soils and sediments, enable users to quickly access relevant publications which may help in their interpretations, or allow fingerprint identification of unknown samples. *MinSight* also supports batch and sequential fitting of model parameters to multiple spectra in the project. This can dramatically speed up the processing of large datasets, such as multiple spectra collected at different conditions for the same sample or spatially resolved 2D maps.

MinSight also provides tools for interpretation and automated reporting. Fitted models can be compared against a hyperfine parameter database for sample identification. Auto-updating plots display hyperfine parameter correlations, comparisons between spectra, and relative abundance. A configurable multi-panel report can be generated from any combination of plots (including the model fits) and downloaded as raw data or a fully rendered figure.

Ongoing development is focusing on expanding the spectral and hyperfine parameter databases, improving automated fitting and sample identification tools, and implementing easy export of projects for archiving in data repositories. We also invite feedback and suggestions for new features.

Resolving structures in fine-grained mineral samples using 3D electron diffraction

Collings, I.E.[1], Tidey J.P.[2], Rumsey, M.S.[1], Missen O.P.[3], Cortes Calderon A.[1], Najorka J.[1], Palatinus L.[4], Mills S.J.[5]

[1]Natural History Museum, Cromwell Road, London SW7 5BD, United Kingdom; ines.collings@nhm.ac.uk.
[2]Department of Physics, University of Warwick, Gibbet Hill, Coventry CV4 7AL, United Kingdom.
[3]Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Australia.
[4]Institute of Physics of the Czech Academy of Sciences, Prague, Czechia.
[5]Gallery of Natural Art, Richardson, TX 75083, United States of America.

Rare and fine-grained mineral samples can pose a challenge for structure solution. This is particularly true of the tellurium oxysalt secondary minerals xocomecatlite and brumadoite, which have no known crystal structure despite being discovered over 50 and 18 years ago, respectively.[1,2] Both samples are polycrystalline, but their structures could not be solved using traditional powder or single crystal X-ray diffraction techniques. The polished sections, resulting from the chemical analysis of both specimens, are housed at the Natural History Museum. The combination of small crystallite sizes and the low sample availability of these minerals make 3D electron diffraction an ideal technique to shed insight into their structures [Figure 1]. In this contribution, I will present the 3D electron diffraction methodology used to determine the structures of xocomecatlite and brumadoite, and compare them with the known mineral cesbronite of related composition.[3]

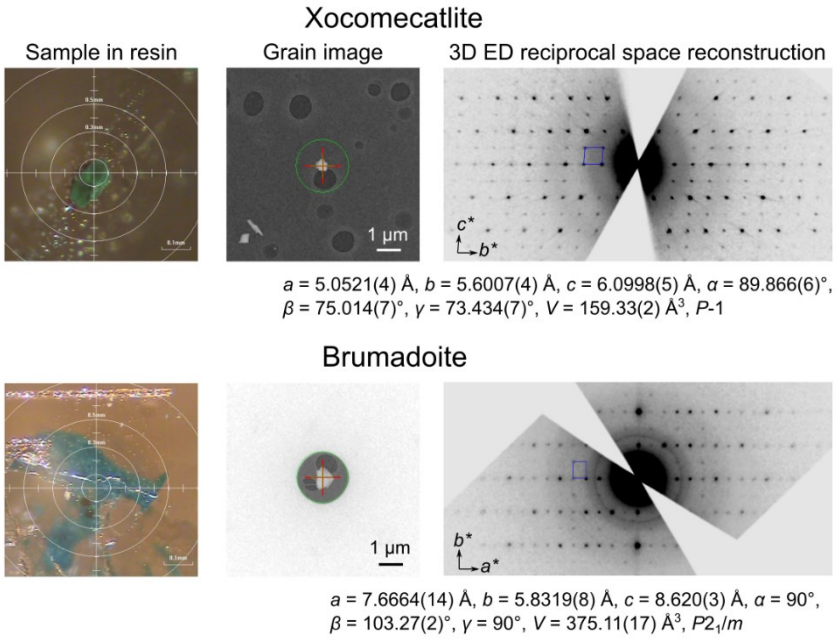


Figure 3. (Left) The samples of xocomecatlite and brumadoite embedded in resin with the scale bar overlaid. (Middle) The imaged grain and (right) its corresponding 3D electron diffraction reciprocal space reconstructions and reciprocal unit cells (shown in blue). The unit cell parameters are given below for each sample.

References:

1. Williams, S. A. Mineralogical Magazine **40**, 221–226 (1975).
2. Atencio, D. et al. Mineralogical Magazine **72**, 1201–1205 (2008).
3. Missen, O. P. et al. Acta Crystallographica Section B **74**, 24–31 (2018).