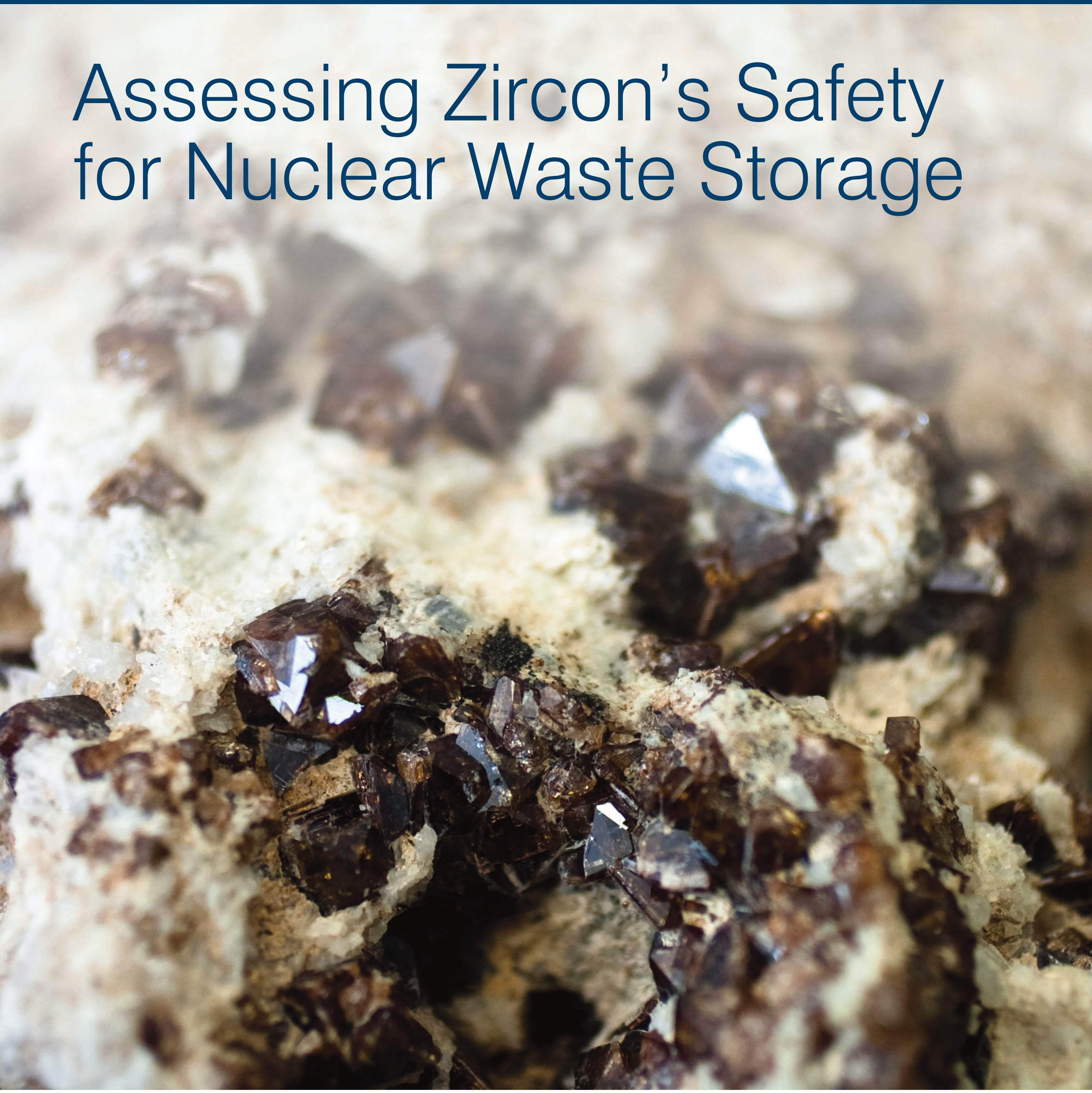
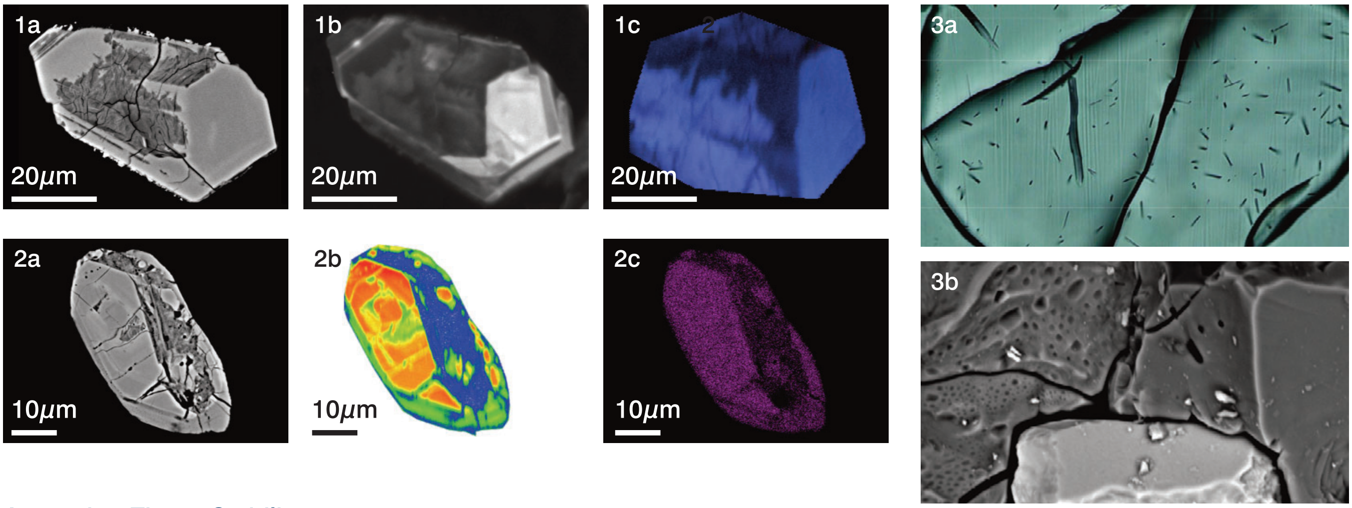
Assessing Zircon's Safety for Nuclear Waste Storage



Zircon nugget

Zircon – A Potential Host for Storage of Radioactive Waste?

The mineral zircon (zirconium silicate) is known to naturally contain significant quantities of two radioactive actinide elements (i.e., metallic chemical elements with atomic numbers from 89 to 103) – uranium and thorium. As such, due to its perceived mechanical and chemical durability, zircon has been suggested as a potential host mineral for the long-term, safe encapsulation of nuclear waste. This notion of durability has emerged from the discovery of preserved zircon grains with ages close to the age of the Earth itself.



Assessing Zircon Stability – A Multi-Disciplinary Approach

Historically, mineral stability has been assessed using equilibrium thermodynamic determinations based on data from experimental petrology. Broadly, results from such methods fit well with observations of naturally occurring minerals. This approach is flawed, however, when dealing with minerals prone to radiation damage, as their structures may undergo a series of time dependent transformation that have major effects on their stability. The University of Glasgow's School of Geographic and Earth Sciences (GES) has been leading studies on the impact of radiation damage to mineral stability, with analytical support from the Imaging Spectroscopy and Analysis Centre (ISAAC), in GES, and the Kelvin Nanocharacterisation Centre (KNC), in the School of Physics & Astronomy (P&A). This research links to activity in thermochronology (i.e., study of the thermal evolution of a region of the Earth's crust) in GES, measuring the accumulation of radiation damage in minerals to assess their detailed thermal histories. The powerful combination of these centres and associated expertise at the University of Glasgow is unique in the UK.

ISAAC's imaging capability enables a detailed assessment of the behaviour of zircon in a variety of crustal environments, providing realistic analogues for comparing behaviour of radioactive elements encapsulated in minerals over exceptionally long time scales and for assessing their reaction history and stability. Only by using natural analogues can the behaviour of these mineral systems as hosts for nuclear waste storage be realistically modelled. This project demonstrates the thorough characterisation of mineral grains that is required to understand their long-term geochemical behaviour, whether assessing the role of radiation damage on element mobility, the detailed pathways of fluid migration through rocks, or the evolution of porosity and permeability in hydrocarbon reservoir sandstones.

Mineral Characterisation Techniques – Measuring Radiation Effects on Zircon

ISAAC's field-emission analytical SEM was a key instrument for this research project, with its capability for very high resolution examination of zircon in-situ within polished thin sections of rocks. (For studying rocks and minerals, GES offers highly-skilled sample preparation capabilities, which are not widely available in the UK.) Several sophisticated SEM techniques were used, including backscattered electron (BSE) imaging to determine the average atomic number of mineral grains, energy-dispersive X-ray analysis (EDX) to identify the chemical elements in very small samples, and EDX element mapping to show the distribution of particular elements in individual grains. Along with these techniques, cathodoluminescence (CL) imaging provided detailed maps of trace element variation within each zircon grain. Electron backscatter diffraction (EBSD) and Raman spectroscopy were two additional techniques ISAAC utilised to assess the integrity of the mineral structure (i.e., the degree of radiation damage to the crystal lattice).

KNC's focused ion beam (FIB) milling and transmission electron microscopy (TEM) complemented ISAAC's SEM work with a synergistic suite of techniques that allowed even higher resolution examination of mineral behaviour at an atomic scale.

A Pioneering Approach to Solving Future Challenges

The University of Glasgow's expertise in GES, combined with state-of-the-art scientific analysis available through ISAAC and KNC, enables it to address the major challenges involved in the safe long-term storage of radioactive nuclides. As highlighted in this study of zircon, very sophisticated multi-disciplinary, integrated investigations are required to understand mineral behaviour in ancient crustal environments. Through such studies, radiation damage has been demonstrated to significantly impact host mineral stability and must be considered when designing safe storage facilities for radioactive waste materials.

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Images

1a. *Backscattered electron (BSE) image of chemically altered (dark) and unaltered (bright) zircon grain*
1b. *Cathodoluminescence (CL) image of zircon grain with bright areas highlighting areas of crystal lattice without radiation damage*
1c. *Electron backscatter diffraction (EBSD) image of zircon grain depicting lattice quality, with dark areas representing metamict (radiation-damaged zircon structure)*
2a. *BSE image of chemically altered (dark) and unaltered (bright) zircon grain*
2b. *EBSD image of zircon grain depicting lattice quality, with red-orange areas representing areas of the crystal lattice without radiation damage and blue-green shades the damaged zones*
2c. *X-ray distribution map showing concentrations of the chemical element zirconium (Zr)*
3a. *Etched apatite crystal (transmitted light image) showing individual fission tracks and damage generated by natural fission of uranium*
3b *Merged secondary electron (SE) and BSE image of grain boundaries of quartz and apatite showing extensive pitting associated with dissolution during the passage of hydrothermal fluids*