



Nanoparticles of uranium and rare earth elements in polymetallic mine waste

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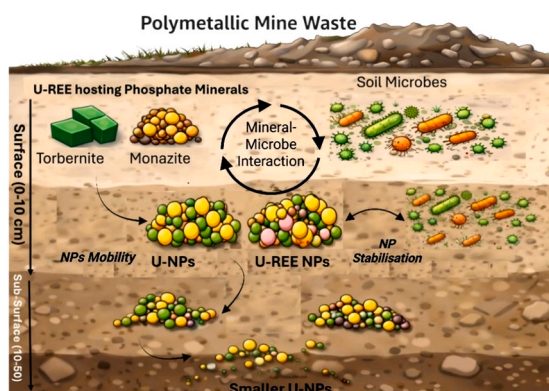
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HIGHLIGHTS

- U and REE occur as mobile nanoparticles in polymetallic mine waste.
- Nanoparticle abundance and U mass per particle decreases with soil depth.
- Composite U–REE–Fe nanoparticles dominate near the surface.
- REE partitioning occurs at nanoscale among particle types.
- Microbial activity promotes U–REE nanoparticle formation/stabilisation at surface.

GRAPHICAL ABSTRACT



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ABSTRACT

Waste from metal mining is a global and escalating issue. Risks are particularly severe for reactive minerals, which, upon exposure to oxygen, water and/or microbial activity, can cause widespread contamination (e.g., acid drainage from sulfide oxidation). This study investigates the nature of colloids within historic U-REE-Cu-rich mine wastes from Mount Painter in the Northern Flinders Ranges, South Australia. The primary mineralogical hosts of uranium (torbernite) and rare earth elements (monazite-(Ce)) are phosphate minerals, which are insoluble phases typically considered to limit U and REE mobility in groundwater. However, single particle ICP-MS analysis revealed substantial concentrations of polymetallic nanoparticles enriched in U-REE(Fe) and concentrated within the surface layers (0–10 cm) of the waste. Microbial diversity is highest near the surface, which is interpreted to promote the dissolution of phosphate minerals and the transformation of liberated metals into nanoparticles. This correlation suggests the potential for microbial consortia to extract metals from stable minerals and transform them into environmentally mobile colloidal forms, with significant implications for the

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1. Introduction

Waste from metal mining is a global and escalating issue, currently impacting 479,200 km of river channels and 164,000 km² of floodplains [1,2]. Polymetallic mine wastes are a major by-product of mining operations, often enriched with economically critical elements such as uranium (U) and rare earth elements (REEs) [3]. As a result of continuing global development, the transformation of the world's energy infrastructure away from fossil fuels, and the electrification of transport infrastructure, demand for base metals such as copper (Cu); critical minerals such as REE; and energy minerals such as U is increasing. Consequently, the volume of mining waste generated is predicted to increase dramatically, a reality compounded by steadily decreasing ore grades [4]. Most REE deposits are associated with substantial U and/or Th contents, and the U-REE-Cu-(Au,Co) association is characteristic of iron-oxide copper gold (IOCG) deposits, such as the super-giant Olympic Dam Cu-U-Ag-(REE) deposit in South Australia [3,5–8]. In many cases, U and Th are not recoverable economically, and are released into the waste stream.

The Mount Painter region in South Australia (Fig. 1) provides a natural laboratory for understanding the long-term (>50 years) fate of

radionuclides, REE, and associated metals in semi-arid environments, in both natural and anthropogenic settings [9]. Known for its historic U-rich mines associated with the 'Radium Boom' of the 1910–1930's, this region presents a semi-arid environment with high natural background radiation levels, heavy metal contamination, and low nutrient availability [10–13], as well as mine tailings rich in U, REE and Cu. These environments, while toxic to plants and animals harbour specialised microbial communities that influence the geochemical fate of U and REEs through processes such as biosorption, redox transformations, and biomineralisation (e.g., [14]). A key outcome of these interactions is the formation of biogenic nanoparticles, nanoscale materials with unique physicochemical properties and significant environmental and technological implications [15,16].

Little information is available about the nature of nanoparticles associated with U-REE-rich mine waste. To address this, we used single particle inductively coupled plasma mass spectrometry (SP ICP-MS) to characterise U- and REE-bearing nanoparticles within historic mining waste that has been subjected to natural weathering for over 80 years [9, 17]. SP ICP-MS is a powerful analytical technique that can detect individual particles and extract information on element mass distributions. Furthermore, when equipped with a time-of-flight mass analyser (i.e., SP ICP-TOFMS), the capabilities extend to being able to identify single particles consisting of multiple elements [18,19]. This technology is particularly useful for naturally formed nanoparticulate matter like that resulting from the interactions between ore minerals and microbial communities in polymetallic mine wastes. Here, SP ICP-TOFMS data are correlated with microbial community data to investigate the possible biological drivers on particle formation. This information provides new fundamental insights regarding the mobility of toxic and radioactive critical elements such as U and REE on the nano- or micro-scale in (semi-)arid environments.

2. Materials and methods

2.1. Site description and sampling

The Mount Painter region is located in the Northern Flinders Ranges of South Australia (Fig. 1, top inset). Samples were obtained from the polymetallic mine tailings enriched with U and REEs at the historic Number 6 Workings (Latitude -30.236047° and longitude 139.337039°). Number 6 was mined intermittently for radium, a decay product of uranium, from its discovery in 1910 to the 1930's [20]. Due to its remoteness and inclusion in the Arkaroola Wilderness Sanctuary in 1967, the site has remained mostly undisturbed since then [21]. The uranium-REE-copper mineralisation is hosted in hematite-rich breccia [17,22,23], and consists mainly of the phosphate minerals torbernite-meta-torbernite ($\text{Cu}^{2+}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 8-12\text{H}_2\text{O}$) and monazite-Ce (REEPO_4). A torbernite concentrate was produced and exported to the UK for processing, but due to rudimentary, water-free ore treatment methods, the tailings still contain high levels of torbernite (Fig. 2c). Geologically, Number 6 Workings are located in the Mount Painter Inlier (Fig. 1, lower inset); this basement unit is rich in U-Th-K-rich Mesoproterozoic gneisses [13,23,24], which are responsible for numerous small U-rich prospects and generally elevated U-Th contents in soils (Fig. 1). Although the basement-hosted Number 6 type orebodies have not led to large-scale U mining, the Cretaceous and Cenozoic sediments of the Lake Frome embayment hosts U-mines that have been producing yellow cake since late 2011 (Fig. 1; [12,13]).

Samples of mine tailings were obtained from five different locations at the Number 6 Workings, as described by Sanyal et al. [9]. In short, MP1, MP3 and MP4 (Fig. 2a) are samples from tailings containing

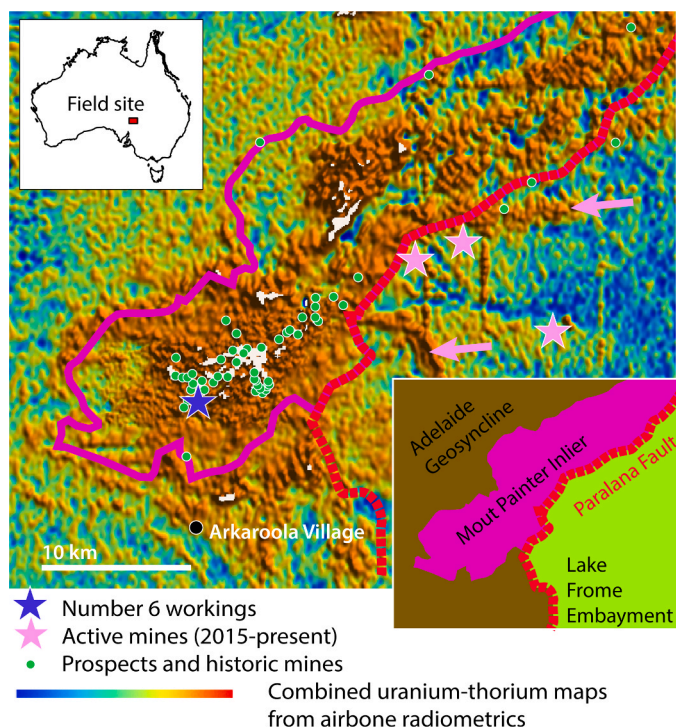


Fig. 1. Geological and geochemical framework of the study site, Number 6 Workings, in the Flinders Ranges of South Australia. The background map shows a combined map of U and Th radiometrics (white has highest concentrations). Uranium-rich mines and prospects are shown together with the outlines of the major geological units. Insets show the location in Australia and the geological architecture: the ancient, Mesoproterozoic crystalline, radioactive (K-Th-U-rich) rocks of the Mount Painter Inlier are raised (tectonic window) above the sediments of the Lake Frome Embayment (East) and Adelaide Geosyncline (West). Stars indicate economic sediment-hosted U deposits within the Lake Frome Embayment, exploited via in-situ recovery; arrows point to major drainage from the Mount Painter Inlier, radioactive due to high concentrations of U- and Th-bearing heavy minerals. Data source: <https://map.sarig.sa.gov.au>, retrieved 24/1/2025.

decreasing amounts of U; each of these three locations was sampled at four different depths (0–10 cm; 10–20 cm; 20–30 cm; and 30–50 cm). Sample MP0 is a background sample collected on a nearby ridge (Fig. 2a). Samples N0–6 (two separate samples) were collected underground (~90 m from the entrance) within a gallery located at the same elevation as sample MP4, and consist of strongly weathered, poorly consolidated, torbernite-rich ore. The samples were collected in 5 mL falcon, sealed, and kept refrigerated until DNA and particle extraction.

2.2. Nanoparticle extraction

Particles were extracted in tetrasodium pyrophosphate (TSPP, 2.5 mM, pH 9.6) in accordance with Gao et al. [25]. Approximately 500 mg of sample material was added to 50 mL of the TSPP solution, held at 25 °C in a water bath and shaken for 30 min. Following this, the samples were sonicated for a further 30 min and left to stand overnight to allow large micro-scale particles to settle. The supernatant was then filtered through 0.22 µm syringe filters (Nylon Filter, Watman, GE Healthcare Life Sciences, UK) and diluted in MilliQ water. An identical sample was prepared without the addition of solid material to act as a control. This approach reflects the fraction of particles which are “extractable”. It has been recognised that sample preparation strategies such as filtration can result in significant particle loss. However, assuming comparable conditions, this approach enables relative comparisons, in which numbers and mass distributions of particles are compared over a set of similar locations [26].

2.3. Nanoparticle analysis via SP ICP-TOFMS

A Vitesse ICP-TOFMS (Nu Instruments, Wrexham, UK) was used in single particle mode (dwell time: 104.6 µs, mass range: 35–248 m/z) for the analysis of the extracted nanoparticles. A 100 nm Au nanoparticle standard (nanoComposix, San Diego, CA, USA, in 2 mM citrate buffer) and an ionic Au standard solution (10 µg·L⁻¹, TraceCERT) were used for the determination of the transport efficiency. A transport efficiency of 3.5% was calculated based on the “size method” described by Pace et al. [27], with an uptake rate (0.45 mL·min⁻¹) being determined gravimetrically.

The open-source single event processing software, SPCal (v.1.2.0, <https://github.com/djdt/spcal/releases/>; [28,29]) was used for data processing. This included the application of compound Poisson statistics ($\alpha = 10^{-6}$) for the determination of detection limits, hierarchical agglomerative clustering (HAC, distance threshold = 5%; [30]) to investigate composite particle compositions, and a non-target screening strategy [31], which enabled the identification of particles with unexpected compositions (10 ppm, 1 million events). Elements of interest found above the calculated detection threshold were calibrated using their respective ionic responses, which was determined by monitoring a blank and ionic standards of 10 µg·L⁻¹. Note that it was not possible to identify U and P on single particles by SP ICP-TOFMS, due to the challenges associated with simultaneous detection of U and P, which arise from the significant mass difference between the elements and a generally poorer detection limit for P.

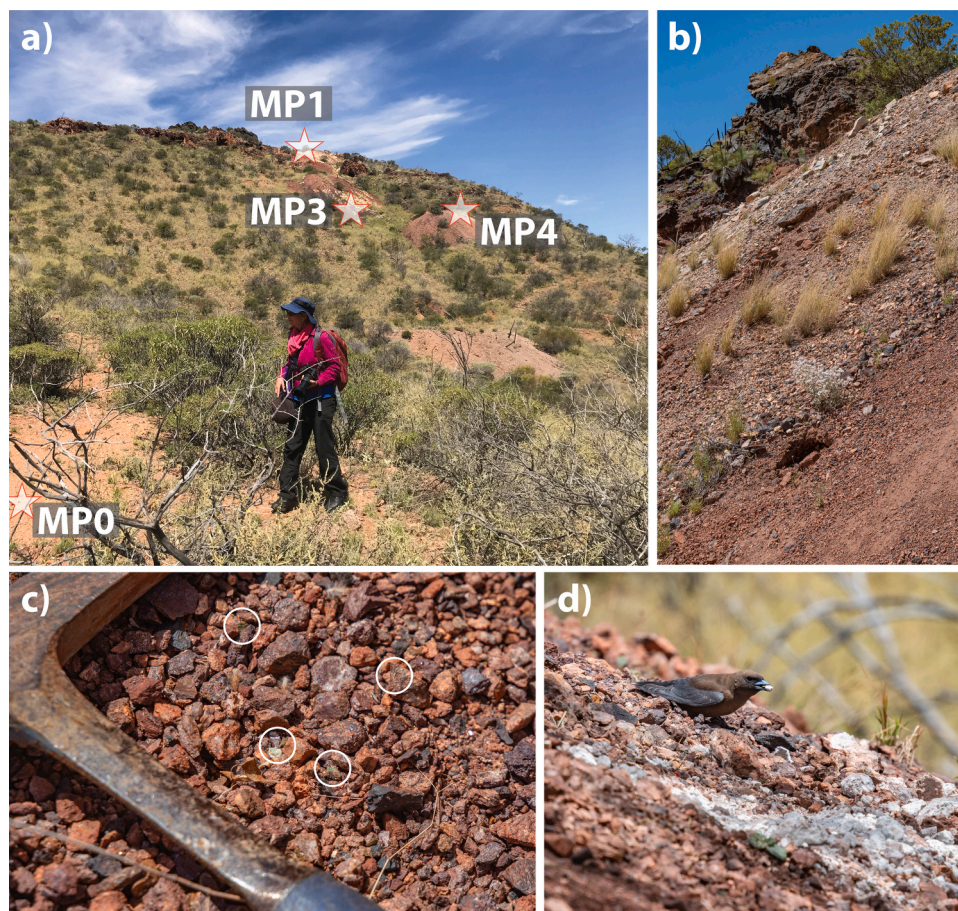


Fig. 2. Location and environmental settings of the studied samples. (a) View towards the historic Number 6 Workings, from the ridge where background sample MP0 was collected. The approximate locations of the mine dump samples are shown. (b) View of MP1 sample location. Note pioneering vegetation. (c) Most mining waste has no significant soil cover; the top waste pile (sample MP1) contains numerous fragments of green uranyl phosphate minerals (torbernite-autunite; highlighted by circles). (d) Little Woodswallow (*Artamus minor*) ingesting clay minerals from the U-rich mine waste near sample MP4.

2.4. Soil microbial community analysis

A 250 mg aliquot of each sample was aseptically transferred into individual glass bead tubes provided in the DNeasy PowerSoil Pro Kit (DNA Extraction) (Qiagen, USA). To enhance microbial cell lysis, particularly for cells adhering to aggregated tailings particles, the bead tubes were vortexed horizontally at maximum speed for 15 min. DNA extraction was then performed according to the manufacturer's protocol. The extracted DNA was quantified using a NanoDrop UV-vis spectrophotometer (NanoDrop Technologies, Wilmington, DE). High-throughput sequencing (HTS) was subsequently conducted, targeting the V3–V4 region of the 16S rRNA gene, using the MGISEQ-2000 sequencing platform (MGI Tech Co. Ltd). This system employs DNBseq™ technology, where sequencing begins with DNA anchor hybridisation, followed by the attachment of a fluorescent probe to the DNA Nanoball (DNB) using combinatorial probe anchor sequencing (cPAS) chemistry. A high-resolution imaging system then captures the fluorescent signal, which undergoes digital processing to generate high-quality, high-accuracy sequencing data. Raw sequencing data were processed using the established pipeline described in Sanyal et al. [32], including quality filtering, chimera removal, and clustering into operational taxonomic units (OTUs) at 97% sequence similarity. Taxonomic assignment was performed against a curated reference database. To quantitatively assess microbial diversity across sampling sites both surfaces and depths, α -diversity indices including Shannon, Simpson, and Fisher's alpha were calculated using standard ecological metrics implemented in QIIME2 (vegan package). These indices were used to evaluate richness and evenness patterns and to enable direct comparison with nanoparticle abundance and distribution. To further explore potential relationships between microbial community structure and nanoparticle characteristics, correlation analysis (Pearson correlation) was performed between α -diversity metrics and nanoparticle abundance/complexity across depth intervals. DNA sequencing data is deposited in the National Centre for Biotechnology Information (NCBI) under BioProject ID: PRJNA1398411 (<http://www.ncbi.nlm.nih.gov/bioproject/1398411>).

2.5. Rock and mineral chemical analyses

For bulk chemical analyses, the remaining samples from the 5 mL tubes were crushed in an agate mortar. The resulting powder was placed in a 2.5 cm diameter Teflon container with a thin mylar film, and measured with a portable X-Ray Fluorescence (pXRF) analyser (Vanta, Olympus, 50 kV, Rh anode). The U and REE contents of minerals from a typical high grade ore sample collected at location MP1 were measured by Laser Ablation ICP-MS at the School of Earth, Atmosphere and Environment, Monash University, using a Thermo iCAP-Q triple quadrupole ICP-MS coupled with an ASI Resolution 193 nm excimer laser equipped with a dual volume Laurus Technik S155 ablation cell. The laser operated at a repetition rate of 10 Hz, 30 μ m spot size and approximately 3.0 mJcm⁻² of laser energy at the sample. Internal standards used were ²³⁸U for torbernite (51 wt% U, corresponding to stoichiometric U content; error on concentrations <10%) and ⁵⁷Fe for the hematite-rich ore (between 70 wt% and 20 wt%, depending on quartz content; error on concentrations 50%). LA-ICP-MS provides accurate element ratios (<5% errors) for small sample volumes. In addition, total organic carbon (TOC), total inorganic carbon (TIC) and total nitrogen (TN) were determined on all samples following methods adapted from Rayment and Lyons (2011). Briefly, samples were oven-dried at 40 °C, sieved to < 2 mm, and analysed with limits of reporting (LOR) of 0.02% for TN, < 0.05% for TOC, and < 0.01% for TIC. Soil pH was measured in a 1:5 (w/v) soil-to-deionised water suspension using a calibrated pH electrode, following standard procedures [33]. Samples were equilibrated for 1 h with intermittent stirring prior to measurement to ensure stable readings. Mineral LA-ICP-MS and pXRF whole rock analyses are available via Mendeley Data at DOI: 10

.17632/fk8s39t57p.1. In addition, pXRF data and supporting data for Fig. 4 are provided as Supplementary Files S2 and S3.

2.6. In-vitro microbe-uranyl interaction experiments

A bacterial consortium was enriched from the M4 soil (0–10 cm depth) using Tris Minimal Medium (TMM) following the protocol described in Sanyal et al. [9]. The enriched microbial culture (5 mL) was harvested by centrifugation to form a cell pellet, and the supernatant was discarded. Cell pellets were washed twice with sterile Milli-Q (MQ) water to remove residual media components and insoluble debris. Washed cells were resuspended in an isotonic NaCl solution containing 500 ppm uranyl nitrate [U(VI)] and incubated at room temperature for 24 h on an orbital shaker to allow microbe–uranium interactions. This experimental setup was designed as a controlled in-vitro proof-of-concept system to evaluate the capacity of indigenous microbial consortia to interact with dissolved U(VI), rather than to directly replicate natural conditions. Elevated dissolved U(VI) concentrations were used to ensure sufficient elemental signal and spatial resolution for downstream SEM–EDS analyses. In natural system, mineral–microbe interactions occur within microenvironments (e.g., redox, pH, and ligands) that control metal speciation. Episodic weathering events (e.g., rainfall or redox fluctuations) can generate transient increases in dissolved U(VI) that are not captured by bulk measurements [34]. No external phosphate source was added to the incubation system. Phosphorus detected in the resulting mineral phases is therefore inferred to originate from microbial biomass (e.g., intracellular contents or extracellular polymeric substances). To assess potential artefacts and isolate microbial effects, control experiments were conducted under identical conditions: (i) a biological negative control consisting of bacterial cells suspended in isotonic NaCl without added U(VI), and (ii) an abiotic control containing 500 ppm uranyl nitrate in isotonic NaCl without microbial biomass. These controls were used to verify that mineral precipitation was specifically associated with the presence of both microbial biomass and dissolved U(VI). After incubation, the reaction was terminated by centrifugation (12,000 $\times$ g, 1 min), forming a bacteria–U pellet, and the supernatant was removed. The pellets were washed twice with MQ water and fixed in 2% (v/v) glutaraldehyde for 24 h. Fixed bacterial–U samples were prepared for scanning electron microscopy (SEM) following methods from Sanyal et al. [35]. Pellets from the bacterial-only control were processed identically.

3. Results and discussion

3.1. Extracted nanoparticles

Extractable U-bearing particles were detected in all the samples associated with U-rich ore, including the three tailing samples (MP1, MP3, MP4) and the underground samples (NO6) (Table 1). Particle number concentrations ranged from $1.3 \cdot 10^7$ ($\pm 0.3 \cdot 10^7$) to $3.9 \cdot 10^8$ ($\pm 0.2 \cdot 10^8$) extracted particles·kg⁻¹ soil. In contrast, no U-bearing particle was detected in the background sample (MP0; Fig. 2c). The median mass of U per particle was between 1.28 and 13.7 fg. Particle size estimates ranged from 50 to 110 nm assuming densities corresponding to phosphate compounds (e.g., chernikovite; monazite; see below). Since P could not be measured concurrently with U, mixed oxide-phosphate particles cannot be excluded and size estimates are to be interpreted with caution. For this study, however, the critical information resides in the metal contents of the nanoparticles.

A major benefit of a TOF mass analyser for particle analysis is being able to identify the co-existence of several elements on a single particle (Table 1). Particles in which U is the only detected metal were the most abundant particulate types, and U was the dominant metal in multi-elemental particles. In samples MP4 and NO6-A, U co-occurred together with lanthanides, with some particles being enriched in light REE (e.g., La, Ce, Nd), others in heavy REE (e.g., Y, Dy, Ho, Er); 7% of

Table 1

Nature and numbers of nanoparticles (extracted from 500 mg of material) present in U-rich tailings from the Northern Flinders Ranges, South Australia. Shown are particle number concentrations (PNC), the different particle compositions which were identified and the percentage that each unique particle type made up of the total PNC for that sample as well as the median mass of particles. Limit of detection = 0.4 fg U.

Sample Location	Sampling depth [cm]	PNC [particles•(kg ⁻¹ soil), •10 ⁸]	Particle Composition	% occurrence	Median Mass [fg]
MP1	0–10	1.43	U	100	13.7
	10–20	0.122	U	100	3.51
	20–30	0.128	U	100	3.56
MP3	0–10	0.206	U	100	10.2
	20–30	0.582	U	80	9.64
MP4	0–10	3.94	U, Fe, Ba, Y	20	2.94
			U	37	
			U, Y	27	
			U, Mn, Fe, Y	15	
			U, Dy, Ho, Er	12	
	10–20	2.38	U, K, Ba, La, Ce, Nd, Th	6	2.18
			U, Dy	3	
			U	56	
			U, Y	22	
			U, Dy, Ho, Er	10	
	20–30	0.0935	U, La, Ce, Nd, Sm	7	1.68
			U, Ce, Er, Tm, Yb	5	
	30–50	0.0712	U	100	1.28
			U	100	
NO6-A	-	4.87	U	55	3.13
			Fe, Mn, Y, Ce, U	12	
			Dy, Ho, Er, Sm, U	9	
			Dy, U	5	
			Y, U	4	
			Sm, U	3	
			Dy, Ho, U	3	
			Th, U	3	
			Ce, U	2	
			Ce, Y, U	2	
			Mn, Y, Ce, U	2	
			U	100	
NO6-B	-	0.499	U	100	5.2
MP0 (control)	0–10	0	-	-	-

particles from MP4 (10–20 cm depth; Table 1) contain Ce together with heavy REE (Er, Tm, Yb). Thorium (Th) was also detected in a small population of particles in MP4 (0–10 cm) and NO6-A.

Beyond confirming that particles were present, it was possible to consider sample depth as a second factor in the analysis (Fig. 3). The highest particle numbers were found within the first 10 cm (0–10 cm) at MP1 and MP4 and elevated in the top 30 cm in MP3. Taking MP4 as an example site, there was a 40% drop in extracted particles from the soil taken at a depth of 10–20 cm when compared to the 0–10 cm samples. Furthermore, soil taken from between 30 and 50 cm of depth were found to contain $7.1 \cdot 10^6$ extracted particles·kg⁻¹ soil, which is 98% lower than the particle count found in the top section ($3.94 \cdot 10^8$). Therefore, particles were detectable throughout the 50 cm of sampled soil, and it is clear that sample depth is a driving factor in terms of particle numbers. As particle numbers decreased with depth, so did U mass per particle and, therefore, likely particle size. This drop in particle mass was evident at all sampled sites with the exception of MP3 which showed a depleted particle number concentration in the 0–10 cm section relative to the other sites (Table 1). At MP4 the median particle mass dropped from 2.9 fg (0–10 cm) to 1.3 fg (30–50 cm). An equivalent drop was seen at MP1 with the median particle mass dropping from 14 fg (0–10 cm) to 3.6 fg (20–30 cm). This is indicative of a size fractionation which results in the particles with lowest masses, and likely lowest sizes, being found at greater depths because of their increased mobilities in this environment. This suggests that most of the particles form near the surface (top 20 cm). Naturally, the trend which saw particle numbers decrease with depth can only consider particles above the instrumental detection limits.

At sites MP1 and MP3 the detected particles appeared to only contain U, within the bounds of the detection limits for this analysis. However, at site MP4, where the highest number of particles were detected, U was found alongside some more common elements such as Fe as well as REE

including La, Ce, Dy, Ho, and Er. However, similar to the trends with particle number and particle mass, the most complex particles were found closer to the surface. In the first 10 cm of MP4, 58% of all detected particles were composite particles that included U and other elements, typically REE; this dropped to 47% in the 10–20 cm fraction and to 0% when combining the final 30 cm of soil. The relationship between particle counts and total U contents is complex: MP4 and NO6-A have the highest particle counts, despite relatively low U contents (<600 ppm), but in general samples with higher U contents show increased particle counts in MP1 and MP3 (Fig. 3b).

Samples NO6-A and B were collected underground in the same collapsed ore at the end of a tunnel, and thought to be very similar in terms of composition. They also occur in a sheltered, relatively stable environment with limited variability in humidity and temperature. However, they differ remarkably in terms of U content (540 vs 1080 ppm; Fig. 3) as well as quantity and diversity of nanoparticles, with NO6-A containing 4.87 extracted particles·(kg⁻¹ soil) with a great diversity of mixed metal particles, and NO6-B containing an order of magnitude less (0.499) U-only particles. We interpret this to suggest highly heterogeneous, mineral-grain scale controls on nanoparticle production.

3.2. Microbial community structures in the polymetallic mine tailings

The near-surface formation of heterogeneous nanoparticles may be linked to their production via bio-induced processes leading to the alteration of the main phosphate ore minerals, torbernite and monazite [9,36,37]. Alteration of torbernite is the likely source of U-only particles (Fig. 4). The only phase significantly enriched in Th is monazite; magmatic monazite contains up to > 10 wt% Th (e.g., [38]), and the hydrothermal monazite in Number 6 workings type ores contains lower, but significant Th (mostly ≤ 2 wt% Th; Hore et al., 2020). These

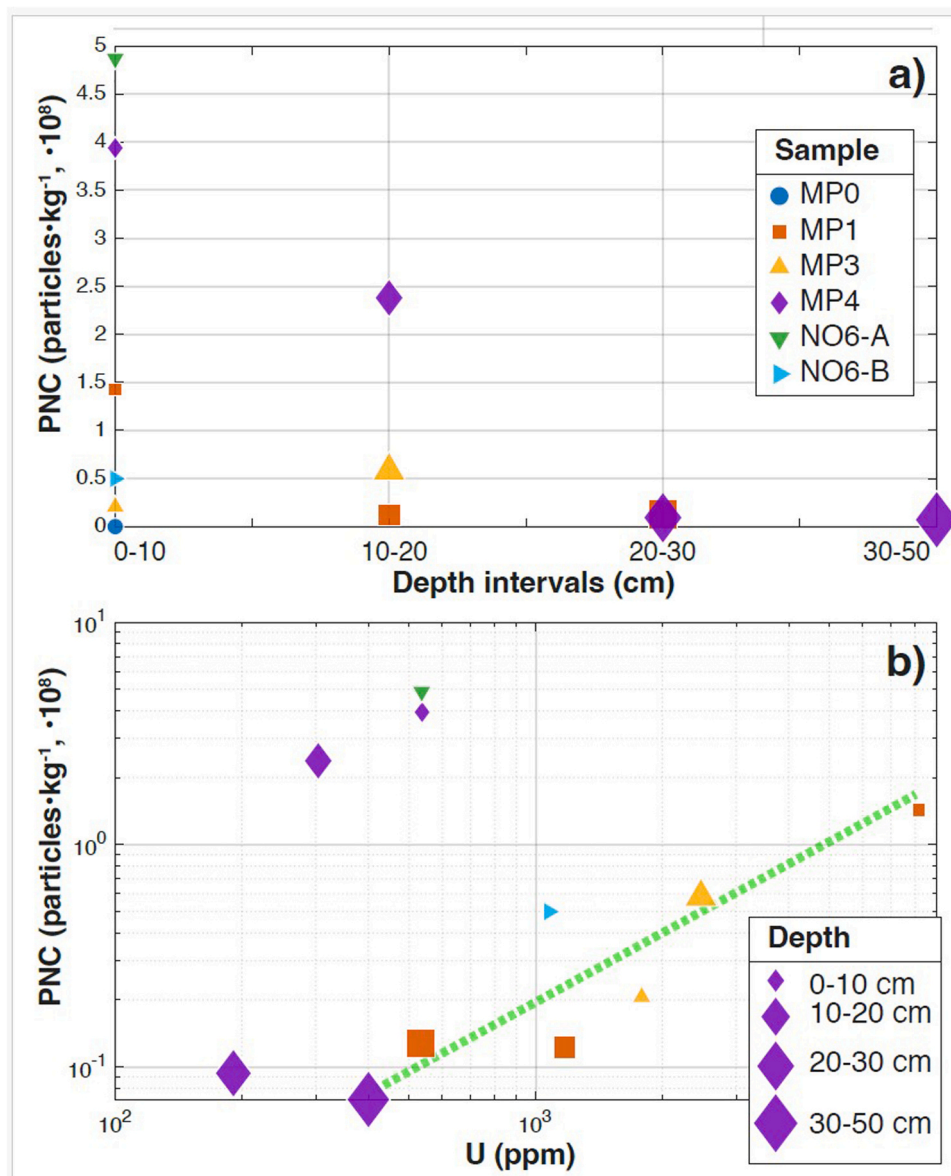


Fig. 3. Particle number concentrations (PNC) versus top depth (a) and U concentrations (b).

monazites are relatively poor in U (72% of the grains have <400 U; Hore et al., 2020), but they are highly enriched in light REE (Fig. 4). The Th-light REE association is reflected by the Th-bearing particles found in MP4 (0–10 cm; Table 1). Somewhat unintuitively, monazite is also the most likely source of heavy REE; torbernite is enriched in heavy REE relative to light REE, but concentrations are an order of magnitude lower than in monazite (Fig. 4). Microbial activity is one of the main factors affecting the stability of phosphate minerals in the regolith (e.g., [11,39,40]). To test for a possible microbial role in nanoparticle formation, we compare microbial community and diversity to the nanoparticle counts.

3.2.1. Surface microbial community patterns across sites

High throughput 16S rRNA gene sequencing showed that the surface microbial communities (0–10 cm depth) at polymetallic mine waste sites (MP1, MP3, MP4, and N0–6B in the Mount Painter region) are composed mainly of Actinobacteriota and Proteobacteria, though their proportions vary between sites (Table 2; Fig. 5). At MP1, Actinobacteriota and Proteobacteria dominated, which is consistent with the ability of these groups to survive in arid, metal-rich environments and participate in phosphate mineral solubilisation [9]. Moving to MP3,

bacterial phylum Acidobacteria evenly dominates with Actinobacteria and Proteobacteria. For MP4, there was a clear shift toward greater Proteobacterial (52.3%) abundance and a notable increase in Firmicutes (17.5%). Proteobacteria, especially members of the Gammaproteobacteria, are metabolically versatile and well-suited for dynamic surface environments, while the rise of Firmicutes at MP4 likely reflects adaptation to environmental disturbance or metal stress, given their capacity for spore formation and stress resistance [42,43]. The declining dominance of Actinobacteriota from MP1 to MP4 at the surface level may indicate a community response to local substrate depletion, increased competition, or changing geochemical conditions [44]. In contrast, the underground sample (N0–6B) exhibited a more even distribution among Actinobacteriota, Proteobacteria, Firmicutes, and Bacteroidota, suggesting a more stable environment with lower selective pressure from rapid changes in temperature and humidity levels [45,46].

3.2.2. Microbial community changes with depth at MP4

The vertical profile at MP4 revealed clear depth-related changes in microbial communities and their geochemical impacts (Fig. 6a, Supplementary Fig. S2). Across all depths, total organic carbon (TOC:

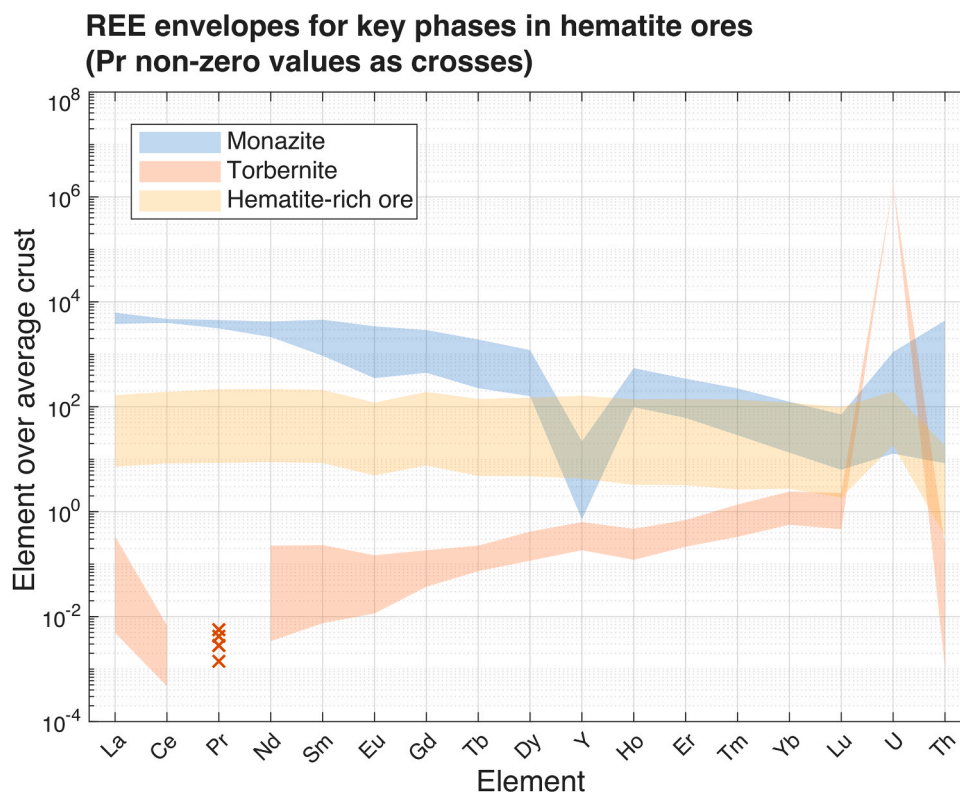


Fig. 4. REE contents of monazite (Hore et al., 2020), hematite-rich ore, and torbernite from Number 6 workings, normalised to the composition of the average crust [41].

Table 2

Summary of dominant microbial Phyla, U-P concentrations, and uranium–rare earth element nanoparticle complexity across mine waste samples and depths.

Sample	Depth/ Setting	TOC & TIC (%)	TN (%)	Soil pH	U [ppm]	P [ppm]	P:U (molar ratio)	Dominant Microbial Phyla	NP Complexity
MP1	Surface (0–10 cm)	0.09 & /< 0.01	< 0.02	6.52	8173	2788	3	Actinobacteriota (~35%), Proteobacteria (~30%)	U-only dominates, moderate NP numbers (~10 ⁸ kg ⁻¹)
MP3	Surface (0–10 cm)	0.20 & < 0.01	< 0.02	6.77	1788	1626	7	Proteobacteria (~20%), Actinobacteriota(20%) & Acidobacteriota (20%)	Mostly U; some Fe; REEs minor (Y); NP number between 10 ⁷ –10 ⁸ /kg soil
MP4	Surface (0–10 cm)	0.09 & < 0.01	< 0.02	7.01	537	1734	25	Proteobacteria (~52%), Firmicutes (20%), Actinobacteriota (~10%)	Most complex NPs: U, Fe, Mn, La, Ce, Dy, Ho, Er; highest NP number ranging from ~ 10 ⁸ –3 × 10 ⁸ /kg soil; 58% are composite
	Sub-surface (10–20 cm)	0.09 & < 0.01	< 0.02	6.66	304	1463	37	Actinobacteriota (~30%) & Proteobacteria (~20%), Acidobacteriota (~20%)	Composite NPs: U, Fe, La, Ce, Dy, Ho, Er; NP numbers from ~10 ⁷ –10 ⁸ /kg soil; 47% are composite
	Sub-surface (20–30 cm)	0.06 & < 0.01	< 0.02	6.98	191	1521	61	Actinobacteriota (~32%) & Proteobacteria (~48%),	U-only dominates; low NP numbers < 10 ⁷ / kg soil; no composite or REE-bearing NPs
	Sub-surface (30–50 cm)	0.08 & 0.01	< 0.02	7.02	400	1091	21	Actinobacteriota (~32%) Proteobacteria (~30%), Firmicutes (~10%)	U-only dominates low NP numbers < 10 ⁷ /kg soil; no composite or REE-bearing NPs
N0–6B	Mine adit	0.08 & < 0.01	< 0.02	6.85	1077	3518	25	Proteobacteria (~30%), Actinobacteriota (30%) & Firmicutes (15%)	U-only dominates (~10 ⁸ kg ⁻¹)

~0.06–0.09%) and total nitrogen (TN: ≤0.02%) remained extremely low, highlighting the strongly nutrient-limited nature of the tailings environment (Table 2). The surface layer (0–10 cm) was dominated by Proteobacteria (e.g., alpha & gamma proteobacteria), Firmicutes, and Bacteroidota, while Actinobacteriota remained present but less abundant (~12%). At increasing depths (10–20 cm, 20–30 cm, 30–50 cm), the community shifted towards taxa adapted to low-nutrient and low-oxygen conditions; Proteobacteria and Firmicutes became less abundant, while stress-tolerant Actinobacteriota (especially class

Actinobacteria), Acidobacteria (e.g., class Verrucomicrobiae) increased in proportion (Fig. 6a). Overall, the MP4 profile highlights a strong coupling between extreme nutrient limitation (low TOC and TN), microbial community adaptation. In these tailings systems, surface communities retain sufficient metabolic flexibility to mediate complex metal transformations, whereas deeper, more energy-limited zones favour stress-tolerant taxa [47].

Importantly, these depth-related microbial patterns closely paralleled trends in nanoparticle (NP) abundance and complexity measured

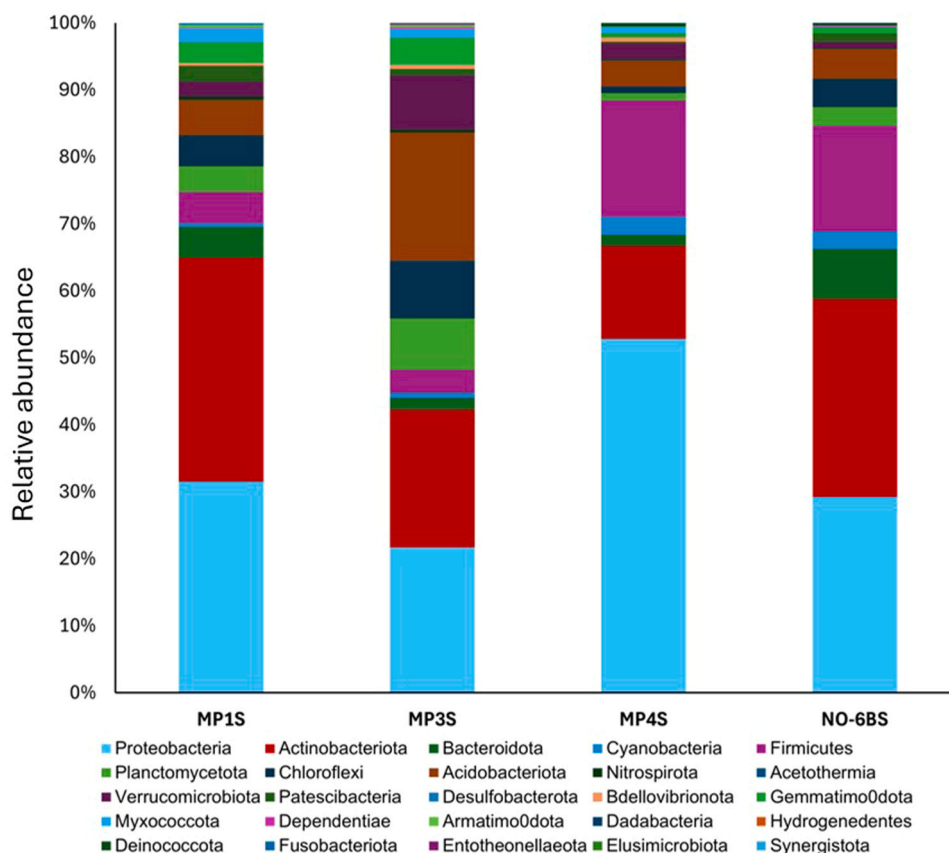


Fig. 5. Surface microbial community composition in U-REE-rich mine tailings. Relative abundance of bacterial phyla in surface samples (0–10 cm depth) from four mine waste sites (MP1S, MP3S, MP4S, NO-6BS). The surface communities are dominated by Proteobacteria, Actinobacteriota, and Bacteroidota, with notable site-specific variations. MP4S shows the highest relative abundance of Proteobacteria and Firmicutes, consistent with dynamic redox cycling and nanoparticle diversity at that site. In contrast, MP1S is enriched in Actinobacteriota. The underground site (NO-6BS) shows a more balanced distribution of Proteobacteria, Actinobacteria and Firmicutes.

by SP ICP-TOFMS. The surface (0–10 cm) not only had the greatest numbers of extractable U particles, but also the most chemically complex particles (e.g., REEs). Below ~20 cm, both NP abundance and complexity sharply decreased, with deeper layers yielding fewer and simpler, mostly U-only particles. These patterns are strongly supported by correlation analyses (Fig. 6b–c), which show a positive relationship between microbial diversity (Shannon index) and both median NP mass ($R \approx 0.96$) and NP particle abundance ($R \approx 0.92$). This indicates that more diverse microbial communities are associated with increased nanoparticle production and greater compositional complexity. Such relationships provide quantitative evidence linking microbial ecology directly to nanoparticle formation processes in these tailings systems. This pattern strongly implicates the surface-dwelling microbial community as a potential driver of phosphate mineral dissolution, metal liberation as well as nanoparticle formation. The predominance of heterotrophic Proteobacteria and Firmicutes in the surface horizon is likely to enhance the production of organic acids, chelators, and extracellular polymeric substances, all of which facilitate both the breakdown of primary phosphate minerals (torbernite, monazite) and the subsequent aggregation or stabilisation of liberated metals as nano-sized colloids [11,36].

With increasing depth, the attenuation of NP abundance and complexity reflects both the decline in microbial diversity and the shift toward oligotrophic, stress-tolerant taxa (e.g., Actinobacteriota, Acidobacteriota) under persistently low TOC and TN conditions. These communities are likely characterised by reduced metabolic rates and limited production of ligands or EPS required for active mineral dissolution and nanoparticle stabilisation. Consequently, in deeper, energy-

limited zones, metal cycling pathways simplify, resulting in the predominance of smaller, more mobile, and chemically simple U-only nanoparticles.

3.3. Influence of microbial interactions on particle heterogeneity

Surface soils across Mount Painter consistently exhibited the highest concentrations and greatest chemical diversity of nanoparticles (NPs), with both abundance and complexity declining sharply with depth. Additionally, surface samples (MP0S, MP1S, MP3S, MP4S, NO-6BS) exhibited higher species diversity compared to deeper layers, indicating more diverse and evenly distributed microbial communities at the surface (Table S1, Fig. S1). This spatial pattern directly mirrors the distribution of metabolically active microbial communities at these sites. Specifically, surface samples such as MP4, where Proteobacteria and Firmicutes collectively made up nearly 70% of the community, were associated with the largest number of composite nanoparticles containing U, REE (e.g., Ce, Dy, Ho), and transition metals (Fe, Mn). In contrast, subsurface layers, characterized by a higher proportion of Actinobacteriota and Proteobacteria, yielded fewer and simpler, predominantly U-only nanoparticles. The heterogeneity in NP abundance and composition among surface sites MP1, MP3, and MP4 correlates with differences in microbial community structure as well as localised mineral redistribution due to weathering. For example, MP1, dominated by Actinobacteriota, had moderate NP abundance and less chemical complexity, while MP4, with its higher relative abundance of Proteobacteria and Firmicutes, exhibited the highest concentration and diversity of composite nanoparticles.

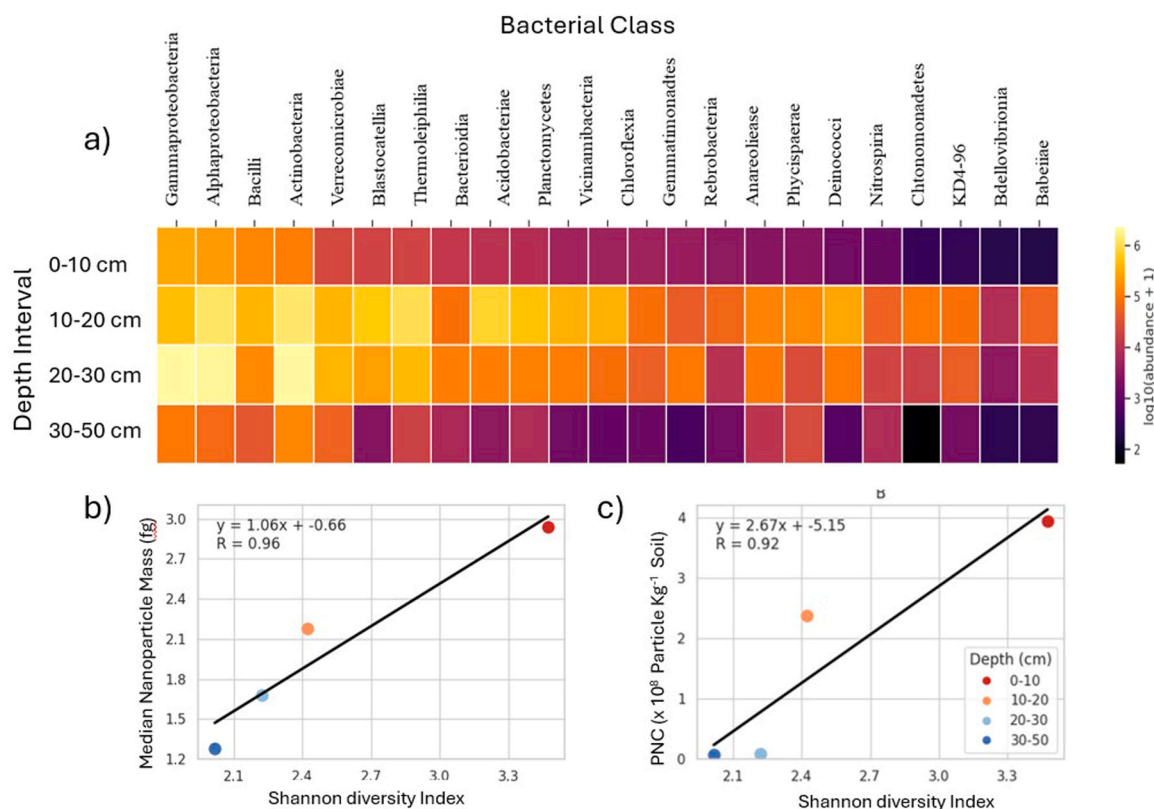


Fig. 6. Depth-resolved microbial community composition and its relationship with nanoparticle characteristics in MP4 tailings. (a) Heatmap showing the relative distribution of the top 15 bacterial classes, which collectively represent approximately 90% of the total community abundance, across depth intervals (0–10, 10–20, 20–30, and 30–50 cm). Values are shown as log₁₀-transformed absolute abundances. (b) Relationship between Shannon diversity index and median nanoparticle mass, showing a strong positive correlation ($R = 0.96$). (c) Relationship between Shannon diversity index and particle number concentration (PNC), also showing a strong positive correlation ($R = 0.92$). However, the 20–30 cm depth interval deviates from this trend, exhibiting lower PNC than expected based on its relatively high microbial diversity.

In contrast, subsurface layers of MP4 (10–50 cm) dominated by Actinobacteriota (Fig. 6a, Fig. S2 & Table 2) and exhibiting reduced overall microbial diversity, yielded fewer and chemically simpler nanoparticles, largely composed of uranium alone. Dominant bacterial classes within this phylum (e.g., Blastocatellia, Thermolephilia, Actinobacteria) are known for tolerating heavy metal toxicity, degrading organic matter, and mediating mineral transformation [48]. These depth-dependent trends suggest that active microbial metabolism, rather than passive geochemical processes alone, plays a key role in promoting nanoparticle heterogeneity at the mine waste surface.

In vitro U(VI)–microbe incubation experiment provides mechanistic support for this interpretation. SEM revealed extensive cell-associated mineralisation, with blade- and plate-like nano- to microcrystals forming directly on bacterial surfaces (Fig. 7a,b). Energy-dispersive X-ray spectroscopy (EDS) confirmed that these biominerals were enriched in U and P, indicating biologically mediated precipitation of U–P phases (Fig. 7c). SEM observations of the control samples showed only intact bacterial cells and associated extracellular polymeric substances (EPS), with no evidence of crystalline or mineral precipitates (Fig. S3). No mineral precipitation was observed in the absence of microbes (in

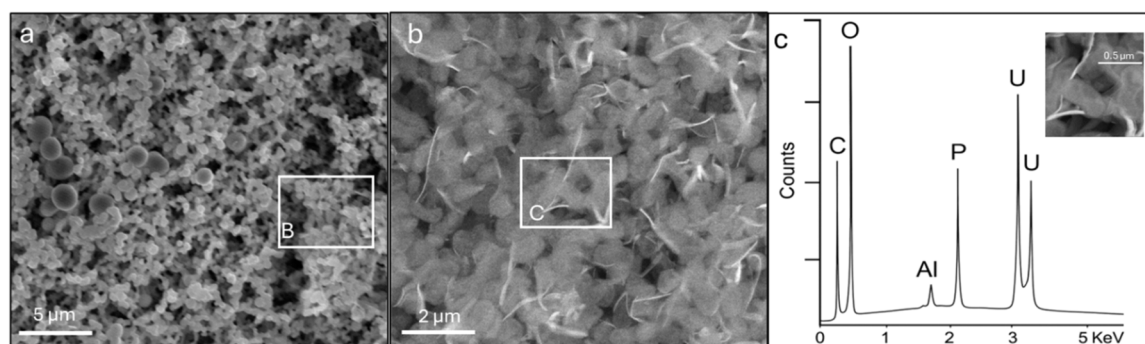


Fig. 7. SEM and elemental analysis of bacterially mediated U–P mineral formation. (a) Low-magnification SEM image showing the morphology of bacterial consortium after incubation with soluble U(VI). (b) Higher-magnification SEM (Back Scattered Electron) image highlighting cell-associated, blade- and plate-like micro crystal formation. Insets mark regions selected for detailed analysis. (c) Spectrum acquired from EDS analysis of the mineral-encrusted regions, showing dominant peaks for U and P along with O and minor C and Al (Background from Al stub used to mount the sample), confirming the formation of U–P mineral phases. The inset SEM image (scale bar: 0.5 μ m) shows the analysed area corresponding to the EDS measurement.

abiotic control). Therefore, the close spatial association between microbial cells and newly formed U–P minerals demonstrates that microbial activity can rapidly transform soluble U into compositionally distinct mineral particles in a micro-environment analogous to those found at the mine surface. Importantly, the formation of nano- to micro-scale U–P minerals *in vitro* mirrors the occurrence of chemically complex nanoparticles observed in surface soils, whereas environments with limited microbial activity predominantly yield simpler U-only particles. This experimental evidence supports the field-based inference that microbial consortia not only enhance U immobilisation but also drive mineralogical diversification through metabolic processes such as phosphate release, redox transformations, and localised pH modification. Differences in NP abundance and composition among surface sites (MP1, MP3, and MP4) likely reflect both variation in microbial community structure and site-specific weathering dynamics.

Overall, these findings suggest that microbial community composition and diversity are active drivers of nanoparticle heterogeneity in U-REE-P-rich environments. Sites and horizons dominated by metabolically versatile surface bacteria promote the dissolution of phosphate minerals and the stabilization of complex, multi-element nanoparticles. In contrast, deeper or more isolated settings i.e., under extreme nutrient limiting conditions, where microbial diversity is lower, support only limited NP formation and simpler particle types. This interplay between biology and geochemistry ultimately shapes the environmental risk and mobility of contaminants in mine waste landscapes.

3.4. Implications for U and REEs biogeochemical cycling and bioremediation

The interplay between U-REE nanoparticles and microbial diversity and dynamics in mine waste environments is crucial for predicting the long-term environmental behaviour of U and REEs. Surface microbial communities rich in metabolically flexible taxa such as Proteobacteria and Actinobacteriota drive key biogeochemical processes by influencing redox potential, producing organic acids, and altering local pH, therefore, collectively promoting the release and re-precipitation of nanoparticulate U and REEs. The diversity and functional capabilities of these microbial consortia are therefore directly linked to the creation and stabilisation of these nanoparticles. Such (biogenic) nanoparticle formation is environmentally significant as NPs are much more mobile than bulk minerals, increasing the potential for U and REE migration through wind dust and seepage especially during episodic rain events. For environmental monitoring and mine-site rehabilitation, this highlights the need for nanoparticle-focused risk assessments, especially in arid or semi-arid landscapes prone to episodic rainfall and flash flooding, which can rapidly transport these particles over long distances.

Research on the role of colloids in controlling the evolving risks associated with mining waste remains in its infancy, but evidence is mounting that this is a major pathway for the mobility of contaminants in such environments. For example, Tindale et al. [49] demonstrated that about 20% of arsenic in leachate for sulfidic mine waste is in particulate form (~7 nm), associated with Al and Fe. Lu et al. [50] showed that drying-wetting cycles facilitate the transport of metal-rich (Pb, Cu) nanoparticles in mine tailings. The role of biologically mediated mineral transformations forming mobile nanoparticles has recently been highlighted for tellurium [51] and cobalt [15]. At the Number 6 Workings, the metal sources are highly insoluble phosphate minerals, and their alteration is highly likely to be promoted by biological processes. A similar situation is observed for native gold and, to a lesser extent, platinum group elements, whose transformation from coarse insoluble minerals to nanoparticles is biomediated (e.g., [52,53]). In the case of gold, Rea et al. [54] showed a positive feedback loop, whereby the accumulation of colloids affected the microbial community structure, i.e. affecting the evolution of the microbe-waste material through time.

An important advance in the present study is the discovery of complex polymetallic nanoparticles enabled by SP ICP-TOFMS, including

evidence for strong partitioning among the REE. This highlights the importance of micro-environments (mineralogical, geochemical, and microbial) in controlling metal liberation. Understanding these controls could have important implications for mineral exploration and bioengineering, e.g. for separation of the valuable heavy REE from the much less valuable light REE in regolith-hosted minerals systems (e.g., [55]) and processing plants (e.g. [56,57]).

4. Conclusions and Outlook

The mobility of elements through arid landscapes can occur both in particulate and aqueous form. Nanoparticles are a potentially major mode of transport in such drought-prone environments, where average rainfall (250 mm per annum; [58]) is erratic and unpredictable, causing flash flooding and rapid dispersion of nanoparticles [59]. This study identified the occurrence of nanoparticulate U and other critical elements (La, Ce, etc.) in an area known to be rich in uranium-containing minerals. The work presented highlights the enhanced mobility of these nanoparticles throughout soil in an arid environment with the smallest, and likely most labile particles, being found in the deepest sampled sections. In the areas where particles were found to be most complex, in that they were often composite particles composed of several REE, there was also an indication that this may have been a result of higher microbial diversity. Therefore, this article emphasises the importance for considering nano-materials which form in the environment when considering the biogeochemical cycling of elements, such as U, and furthermore, the potential for these natural cycles of minerals to be influenced by complex microbial communities such as those found in the soils of Mount Painter.

Indeed, the study site, Mount Painter, Northern Flinders Ranges provides a valuable natural laboratory to explore novel microbes and their biochemical pathways involved in U+REE transformation and nanoparticle stabilisation. It also opens opportunities for harnessing these native microbial processes in nanoparticle mobility management through accelerated biomineralisation as well as sustainable recovery of critical elements from waste.

Environmental implications

Uranium and rare earth elements in mine waste can occur as environmentally mobile nanoparticles, which are far more transportable than their bulk mineral forms. These particles, concentrated near the surface, pose a significant risk of dispersion through wind and runoff, especially in arid environments. Their formation is linked to the breakdown of phosphate minerals, with microbial activity playing a contributing role. These findings highlight the need for environmental monitoring and remediation strategies that specifically consider nanoparticulate phases as key vectors for contaminant mobility.

CRediT authorship contribution statement

Santonu K. Sanyal: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Barbara Etschmann:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Joël Brugger:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Raquel Gonzalez de Vega:** Writing – review & editing, Methodology, Investigation. **Thebny Thaise Moro:** Writing – review & editing, Methodology, Investigation. **Vanessa Wong:** Writing – review & editing, Resources. **Kaitlin Baggott:** Writing – review & editing, Methodology, Investigation. **David Clases:** Writing – review & editing, Visualization, Resources, Methodology, Investigation, Formal analysis. **Lhiam Paton:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jhazmat.2026.142213](https://doi.org/10.1016/j.jhazmat.2026.142213).

Data availability

All the data has been deposited to public domains.

References

- Macklin, M.G., Thomas, C.J., Mudbhakal, A., Brewer, P.A., Hudson-Edwards, K.A., Lewin, J., et al., 2023. Impacts of metal mining on river systems: a global assessment. *Science* 381 (6664), 1345–1350. <https://doi.org/10.1126/science.adg6704>.
- Owen, J.R., Kemp, D., Lechner, A.M., Ang Li Ern, M., Lebre, E., Mudd, G.M., et al., 2024. Increasing mine waste will induce land cover change that results in ecological degradation and human displacement. *J Environ Manag* 351, 119691. <https://doi.org/10.1016/j.jenvman.2023.119691>.
- Weng, Z.H., Jowitt, S.M., Mudd, G.M., Haque, N., 2015. A detailed assessment of global rare earth element resources: opportunities and challenges. *Econ Geol* 110 (8), 1925–1952. <https://doi.org/10.2113/econgeo.110.8.1925>.
- Jowitt, S.M., Mudd, G.M., Thompson, J.F.H., 2020. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Commun Earth Environ* 1 (1). <https://doi.org/10.1038/s43247-020-0011-0>.
- Anvia, M., Brown, S.A., McOrist, G.D., 2015. The deportment of uranium decay chain radionuclides during processing of an Australian monazite concentrate using a caustic conversion route. *J Radioanal Nucl Chem* 303 (2), 1393–1398. <https://doi.org/10.1007/s10967-014-3483-5>.
- Henriques, I., Böhm, S., 2022. The perils of ecologically unequal exchange: contesting rare-earth mining in Greenland. *J Clean Prod* 349. <https://doi.org/10.1016/j.jclepro.2022.131378>.
- Ram, R., Owen, N.D., Kalnins, C., Cook, N.J., Ehrig, K., Etschmann, B., et al., 2021. Understanding the mobility and retention of uranium and its daughter products. *J Hazard Mater* 410. <https://doi.org/10.1016/j.jhazmat.2020.124553>.
- Ram, R., Vaughan, J., Etschmann, B., Brugger, J., 2019. The aqueous chemistry of polonium (Po) in environmental and anthropogenic processes. *J Hazard Mater* 380, 120725. <https://doi.org/10.1016/j.jhazmat.2019.06.002>.
- Sanyal, S.K., Etschmann, B., Hore, S.B., Shuster, J., Brugger, J., 2024. Microbial adaptations and biogeochemical cycling of uranium in polymetallic tailings. *J Hazard Mater* 465. <https://doi.org/10.1016/j.jhazmat.2023.133334>.
- Fairbrother, L., Brugger, J., Shapter, J., Laird, J.S., Southam, G., Reith, F., 2012. Supergene gold transformation: Biogenic secondary and nano-particulate gold from arid Australia. *Chem Geol* 320, 17–31. <https://doi.org/10.1016/j.chemgeo.2012.05.025>.
- Kalintsev, A., Brugger, J., Etschmann, B., Ram, R., 2021. An *in situ*, micro-scale investigation of inorganically and organically driven rare-earth remobilisation during weathering. *Mineral Mag* 85 (1), 105–116. <https://doi.org/10.1180/mgm.2021.4>.
- Wülser, P.-A., Brugger, J., Foden, J., Pfeifer, H.-R., 2011. The sandstone-hosted beverley uranium deposit, lake frome Basin, South Australia: mineralogy, geochemistry, and a time-constrained model for its genesis. *Econ Geol* 106 (5), 835–867.
- Brugger, J., Long, N., McPhail, D.C., Plimer, I., 2005. An active amagmatic hydrothermal system: the Paralana hot springs, Northern Flinders Ranges, South Australia. *Chem Geol* 222 (1–2), 35–64. <https://doi.org/10.1016/j.chemgeo.2005.06.007>.
- Castelle, C.J., Hug, L.A., Wrighton, K.C., Thomas, B.C., Williams, K.H., Wu, D., et al., 2013. Extraordinary phylogenetic diversity and metabolic versatility in aquifer sediment. *Nat Commun* 4, 1–10, 2120.
- Missen, O.P., Mills, S.J., Thaise Moro, T., Villalobos-Portillo, E.E., Castillo-Michel, H., Lockwood, T.E., et al., 2024. Natural cobalt–manganese oxide nanoparticles: speciation, detection and implications for cobalt cycling. *Environ Chem* 21 (2). <https://doi.org/10.1071/en23093>.
- Bundschuh, M., Filser, J., Luderwald, S., McKee, M.S., Metreveli, G., Schaumann, G.E., et al., 2018. Nanoparticles in the environment: where do we come from, where do we go to? *Environ Sci Eur* 30 (1), 6. <https://doi.org/10.1186/s12302-018-0132-6>.
- Brugger, J., Wülser, P.-A., Foden, J., 2011. Genesis and preservation of a Uranium-Rich paleozoic epithermal system with a surface expression (Northern Flinders Ranges, South Australia): radiogenic heat driving regional hydrothermal circulation over geological timescales. *Astrobiology* 11 (6), 499–508. <https://doi.org/10.1089/ast.2011.0605>.
- Lockwood, T.E., Gonzalez de Vega, R., Du, Z., Schlatt, L., Xu, X., Clases, D., 2024. Strategies to enhance figures of merit in ICP-ToF-MS. *J Anal Spectr* 39 (1), 227–234. <https://doi.org/10.1039/d3ja00288h>.
- Paton, L., Moro, T.T., Lockwood, T., de Andrade Maranhão, T., Gössler, G., Clases, D., et al., 2024. AF4-MALS-SP ICP-ToF-MS analysis gives insight into nature of HgSe nanoparticles formed by cetaceans. *Environ Sci Nano* 11 (5), 1883–1890. <https://doi.org/10.1039/d3en00886j>.
- Brugger, J., Ansermet, S., Pring, A., 2003. Uranium minerals from Mt Painter, Northern Flinders Ranges, South Australia. *Aust J Mineral* 9, 15–31.
- Coats, R.P., Blissett, A.H., 1971. Regional and economic geology of the Mount Painter province. *Dep Mines Geol Surv South Aust Bull* 43, 426.
- Hore, S.B., Hill, S.M., Alley, N.F., 2020. Early Cretaceous glacial environment and paleosurface evolution within the Mount Painter Inlier, northern Flinders Ranges, South Australia. *Aust J Earth Sci* 67, 1117–1160. <https://doi.org/10.1080/08120099.2020.1730963>.
- Hore, S.B., Hill, S.M., Reid, A., Wade, B., Alley, N.F., Mason, D.R., 2020. U-Pb geochronology reveals evidence of a Late Devonian hydrothermal event, and protracted hydrothermal-epithermal system, within the Mount Painter Inlier, northern Flinders Ranges, South Australia. *Aust J Earth Sci* 67, 1009–1044. <https://doi.org/10.1080/08120099.2020.1793383>.
- Sandiford, M., McLaren, S., Neumann, N., 2002. Long-term thermal consequences of the redistribution of heat-producing elements associated with large-scale granitic complexes. *J Metamorph Geol* 20 (1), 87–98.
- Gao, Y.P., Yang, Y., Li, L., Wei, W.J., Xu, H., Wang, Q., et al., 2020. Quantitative detection of gold nanoparticles in soil and sediment. *Anal Chim Acta* 1110, 72–81. <https://doi.org/10.1016/j.aca.2020.03.005>.
- Paton, L., Kiesel, S., Steinhofel, G., Elinkmann, M., Moro, T.T., de Vega, R.G., et al., 2025. Assessing the impact of common sample preparation strategies for single particle ICP-MS regarding recovery and size distribution of natural single particles. *J Anal Spectrom* 40 (10), 2897–2908.
- Pace, H.E., Rogers, N.J., Jarolimek, C., Coleman, V.A., Higgins, C.P., Ranville, J.F., 2011. Determining transport efficiency for the purpose of counting and sizing nanoparticles via single particle inductively coupled plasma mass spectrometry. *Anal Chem* 83 (24), 9361–9369. <https://doi.org/10.1021/ac201952t>.
- Lockwood, T.E., Gonzalez de Vega, R., Clases, D., 2021. An interactive Python-based data processing platform for single particle and single cell ICP-MS. *J Anal Spectr* 36 (11), 2536–2544. <https://doi.org/10.1039/d1ja00297j>.
- Lockwood, T.E., Schlatt, L., Clases, D., 2025. SPCal – an open source, easy-to-use processing platform for ICP-TOFMS-based single event data. *J Anal Spectr* 40 (1), 130–136. <https://doi.org/10.1039/d4ja00241e>.
- Tharaud, M., Schlatt, L., Shaw, P., Benedetti, M.F., 2022. Nanoparticle identification using single particle ICP-ToF-MS acquisition coupled to cluster analysis. From engineered to natural nanoparticles. *J Anal Spectr* 37 (10), 2042–2052. <https://doi.org/10.1039/d2ja00116k>.
- Gonzalez de Vega, R., Lockwood, T.E., Paton, L., Schlatt, L., Clases, D., 2023. Non-target analysis and characterisation of nanoparticles in spirits via single particle ICP-TOF-MS. *J Anal Spectr* 38 (12), 2656–2663. <https://doi.org/10.1039/d3ja00253e>.
- Sanyal, S.K., Shuster, J., Reith, F., 2019. Biogeochemical gold cycling selects metal-resistant bacteria that promote gold particle transformation. *FEMS Microbiol Ecol* 95 (7). <https://doi.org/10.1093/femsec/fiz078>.
- Rayment, G.E., Lyons, D.J., 2011. Soil chemical methods: Australasia, 3. CSIRO publishing.
- Sanyal, S.K., Shuster, J., 2021. Gold particle geomicrobiology: Using viable bacteria as a model for understanding microbe–mineral interactions. *Mineral Mag* 85 (1), 117–124. <https://doi.org/10.1180/mgm.2021.19>.
- Sanyal, S.K., Reith, F., Shuster, J., 2020. A genomic perspective of metal-resistant bacteria from gold particles: Possible survival mechanisms during gold biogeochemical cycling. *FEMS Microbiol Ecol* 96 (7). <https://doi.org/10.1093/femsec/fiaa111>.
- Newsome, L., Morris, K., Lloyd, J.R., 2014. The biogeochemistry and bioremediation of uranium and other priority radionuclides. *Chem Geol* 363, 164–184. <https://doi.org/10.1016/j.chemgeo.2013.10.034>.
- Nie, X.Q., Dong, F.Q., Liu, M.X., He, H.C., Sun, S.Y., Bian, L., et al., 2017. Microbially mediated stable uranium phosphate nano-biomaterials. *J Nanosci Nanotechnol* 17, 6771–6780. <https://doi.org/10.1166/jnn.2017.14463>.
- Forbes, C., Giles, D., Freeman, H., Sawyer, M., Normington, V., 2015. Glacial dispersion of hydrothermal monazite in the Prominent Hill deposit: an exploration tool. *J Geochem Explor* 156, 10–33. <https://doi.org/10.1016/j.gexplo.2015.04.011>.

- [39] Voutsinos, M.Y., Banfield, J.F., Moreau, J.W., 2020. Secondary lanthanide phosphate mineralisation in weathering profiles of I-, S- and A-type granites. *Mineral Mag* 85, 82–93. <https://doi.org/10.1180/mgm.2020.90>.
- [40] Voutsinos, M.Y., West-Roberts, J.A., Sachdeva, R., Moreau, J.W., Banfield, J.F., 2024. Weathered granites and soils harbour microbes with lanthanide-dependent methylotrophic enzymes. *BMC Biol* 22. <https://doi.org/10.1186/s12915-024-01841-0>.
- [41] Rudnick, R.L., Gao, S., 2014. Composition of the continental crust. *Treatise Geochem* 1–51. <https://doi.org/10.1016/b978-0-08-095975-7.00301-6>.
- [42] Ho, A., Di Lonardo, D.P., Bodelier, P.L., 2017. Revisiting life strategy concepts in environmental microbial ecology. *FEMS Microbiol Ecol* 93(3). <https://doi.org/10.1093/femsec/fix006>.
- [43] Liu, L., Chen, Y., Shen, J.X., Pan, Y.X., Lin, W., 2023. Metabolic versatility of soil microbial communities below the rocks of the hyperarid Dalangtan Playa. *Appl Environ Microbiol* 89 (11). <https://doi.org/10.1128/aem.01072-23>.
- [44] Filippidou, S., Wunderlin, T., Junier, T., Jeanneret, N., Dorador, C., Molina, V., et al., 2016. A combination of extreme environmental conditions favor the prevalence of endospore-forming firmicutes. *Front Microbiol* 7, 1707. <https://doi.org/10.3389/fmicb.2016.01707>.
- [45] Hao, J.J., Chai, Y.N., Lopes, L.D., Ordoñez, R.A., Wright, E.E., Archontoulis, S., et al., 2021. The effects of soil depth on the structure of microbial communities in agricultural soils in Iowa (United States). *Appl Environ Microbiol* 87 (4). <https://doi.org/10.1128/aem.02673-20>.
- [46] Salazar-Hamm, P.S., Homan, F.E., Good, S.A., Hathaway, J.J.M., Clements, A.E., Haugh, E.G., et al., 2025. Subterranean marvels: microbial communities in caves and underground mines and their promise for natural product discovery. *Nat Prod Rep* 42 (3), 592–622. <https://doi.org/10.1039/d4np00055b>.
- [47] Diaby, N., Dold, B., Pfeifer, H.R., Holliger, C., Johnson, D.B., Hallberg, K.B., 2007. Microbial communities in a porphyry copper tailings impoundment and their impact on the geochemical dynamics of the mine waste. *Environ Microbiol* 9 (2), 298–307. <https://doi.org/10.1111/j.1462-2920.2006.01138.x>.
- [48] Shivlata, L., Satyanarayana, T., 2015. Thermophilic and alkaliphilic Actinobacteria: biology and potential applications. *Front Microbiol* 6, 1014. <https://doi.org/10.3389/fmicb.2015.01014>.
- [49] Tindale, K., Patel, P., Wallschläger, D., 2011. Colloidal arsenic composition from abandoned gold mine tailing leachates in Nova Scotia, Canada. *Appl Geochem* 26, S260–S262. <https://doi.org/10.1016/j.apgeochem.2011.03.119>.
- [50] Lu, C., Wu, Y., Hu, S., 2016. Drying–wetting cycles facilitated mobilization and transport of metal-rich colloidal particles from exposed mine tailing into soil in a gold mining region along the Silk Road. *Environ Earth Sci* 75 (12). <https://doi.org/10.1007/s12665-016-5812-1>.
- [51] Missen, O.P., Lausberg, E.R., Brugger, J., Etschmann, B., Mills, S.J., Momma, K., , 2022. Natural nanoparticles of the critical element tellurium. *Journal of Hazardous Materials Letters* 3. doi.org/10.1016/j.hazl.2022.100053.
- [52] Brugger, J., Etschmann, B., Grosse, C., Plumridge, C., Kaminski, J., Paterson, D., et al., 2013. Can biological toxicity drive the contrasting behavior of platinum and gold in surface environments? *Chem Geol* 343, 99–110. <https://doi.org/10.1016/j.chemgeo.2013.02.010>.
- [53] Reith, F., Fairbrother, L., Nolze, G., Wilhelmi, O., Clode, P., Gregg, A., et al., 2010. Nanoparticle factories: biofilms hold the key to gold dispersion and nugget formation. *Geology* 38 (9), 843–846. <https://doi.org/10.1130/G31052.1>.
- [54] Rea, M.A., Standish, C.D., Shuster, J., Bissett, A., Reith, F., 2018. Progressive biogeochemical transformation of placer gold particles drives compositional changes in associated biofilm communities. *FEMS Microbiol Ecol* 94 (6). <https://doi.org/10.1093/femsec/fiy080>.
- [55] Bamforth, T.G., Lampinen, H.M., Lynham, L., Reid, N., Thorne, R., Iglesias-Martínez, M., et al., 2025. Unsupervised geochemical characterisation of deeply weathered terrains and regolith-hosted REE deposits: rationale and benefits for exploration. *Ore Geol Rev* 181. <https://doi.org/10.1016/j.oregeorev.2025.106634>.
- [56] Levett, A., van der Ent, A., Ray Jones, T., Bolouri, K., Kelly, K., Vaughan, J., et al., 2024. Water-soluble rare earth elements (REEs) recovered from uranium tailings. *Miner Eng* 210. <https://doi.org/10.1016/j.mineng.2024.108675>.
- [57] Owen, N.D., Cook, N.J., Rollog, M., Ehrig, K.J., Schmandt, D.S., Ram, R., et al., 2019. REE-, Sr-, Ca-aluminum-phosphate-sulfate minerals of the alunite supergroup and their role as hosts for radionuclides. *Am Miner* 104 (12), 1806–1819. <https://doi.org/10.2138/am-2019-7116>.
- [58] BOM-Bureau of Meteorology, 2025. Climate Data from Arkaroola Weather Station. (http://www.bom.gov.au/climate/averages/tables/cw_017099.shtml). Retrieved February 2025. Bureau of Meteorology, Melbourne.
- [59] Cook, M., Etschmann, B., Ram, R., Ignatyev, K., Gervinskis, G., Conradson, S.D., et al., 2021. The nature of Pu-bearing particles from the Maralinga nuclear testing site, Australia. *Sci Rep* 11 (1). <https://doi.org/10.1038/s41598-021-89757-5>.