Supplementary Information for:

Radiological identification of near-surface mineralogical deposits using low altitude unmanned aerial vehicle

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Supplementary Methods:

Radiological Data Processing

Gamma-Ray Spectroscopy:

The High Purity Germanium (HPGe) detection system for gamma-ray emission analysis was a cryogenically (LN$_2$) cooled Broad Energy Germanium Detector (BEGE) from Mirion Technologies, with a detectable gamma-ray energy range of 3 keV to 3 MeV (greater than that of the SIGMA-50 deployed for aerial measurements), a relative detection efficiency of 34% and Full Width at Half Maximum (FWHM) peak resolution at 1,332 keV of 1.90 keV (0.72 keV at 122 keV). For spectral measurements, a sealed beaker containing approximately 50 g of this ore material (gently crushed) was placed in direct contact with the 65 cm^2 cross-sectional area and 30 mm thick crystal, with data obtained over an 8-hour collection period. During the analysis, both the detector and sample material were fully encased within a lead 'castle' to neglect against the detrimental detection of gamma-rays not associated with the ore material. Control of the detector was performed using the instruments associated counting software from Mirion, with the Genie 2000 Gamma analysis software package (also from Mirion) employed for the subsequent peak-fitting, nuclide identification and contribution quantification via the software's in-built reference libraries. Prior to analysis, a calibration of the system was undertaken to determine the gamma-ray energy per detection channel (4096) relationship, with a 'multi-source' reference standard (containing amongst other nuclides, ^{137}Cs, ^{241}Am, ^{113}Sn, ^{88}Y, ^{85}Sr and ^{60}Co) placed under the detector and the emissions aligned following a 2-hour exposure period.

Scanning Electron Microscopy and Energy Dispersive Spectroscopy:

Compositional analysis and high-resolution imaging of the collected surface vein material was undertaken using a scanning electron microscope (SEM) equipped with an energy dispersive (x-ray) spectroscopy (EDS) system. The SEM used for both was a Zeiss SIGMA™ Variable Pressure (VP) Field Emission (FE) instrument equipped with secondary electron (SE2), backscattered electron (BSE), Variable Pressure (VP)/Cathodoluminescence (CL) and InLens detectors – with the BSE detector used predominantly during this work to identify regions within the sample composed of high Z (atomic) number, i.e. uranium-rich grains,

ahead of compositional analysis. The attached EDS system comprised an EDAX (Ametek Inc.) Octane Plus Si-drift EDS detector alongside the associated TEAM control and spectral analysis software. For examination, a small fragment of slightly crushed ore material was placed onto the surface of a standard SEM pin-stub using an adhesive carbon (Leit™) disc and installed into the microscopes chamber before being evacuated to a vacuum of greater than 10^{-5} mbar. A consistent accelerating voltage of 20 kV and beam current of 1.7 nA (120 μm aperture) and working distance of 9 mm were used during all analysis (imaging and EDS) to ensure consistent results throughout. EDS analysis was performed using both (single) point and mapping functions to determine the elemental composition and variations in distribution. To negate against the non-conductive samples electrical charging under the electron beam, the variable pressure (VP) function of the instrument was utilised, flowing a constant stream of N_2 gas over the sample to remove charge accumulation on its surface.

Raman Spectroscopy:

Supporting phase determination on portions of the mineralogy within the crushed vein samples was determined via Raman spectroscopy. Measurements were made using a Renishaw Ramascope™ 2000 with the excitation wavelength set to 514 nm. Samples were illuminated through a 50x Olympus objective (BH2-UMA). The power at the sample was approximately 8 mW with a 30 s acquisition time for each spectrum over the wavenumber range 100 cm^{-1} to 4000 cm^{-1}. Prior to analysis, the spectrometer was calibrated using a monocrystalline silicon standard specimen to ensure appropriate peak identification, with subsequent peak fitting and deconvolution of the Raman spectra performed using the GRAMS32 analysis software. In each instance, the fluorescence background and high-frequency noise components were computationally removed from the raw spectra by sequentially processing via low-pass and high-pass fast Fourier Transform (FFT) filters.
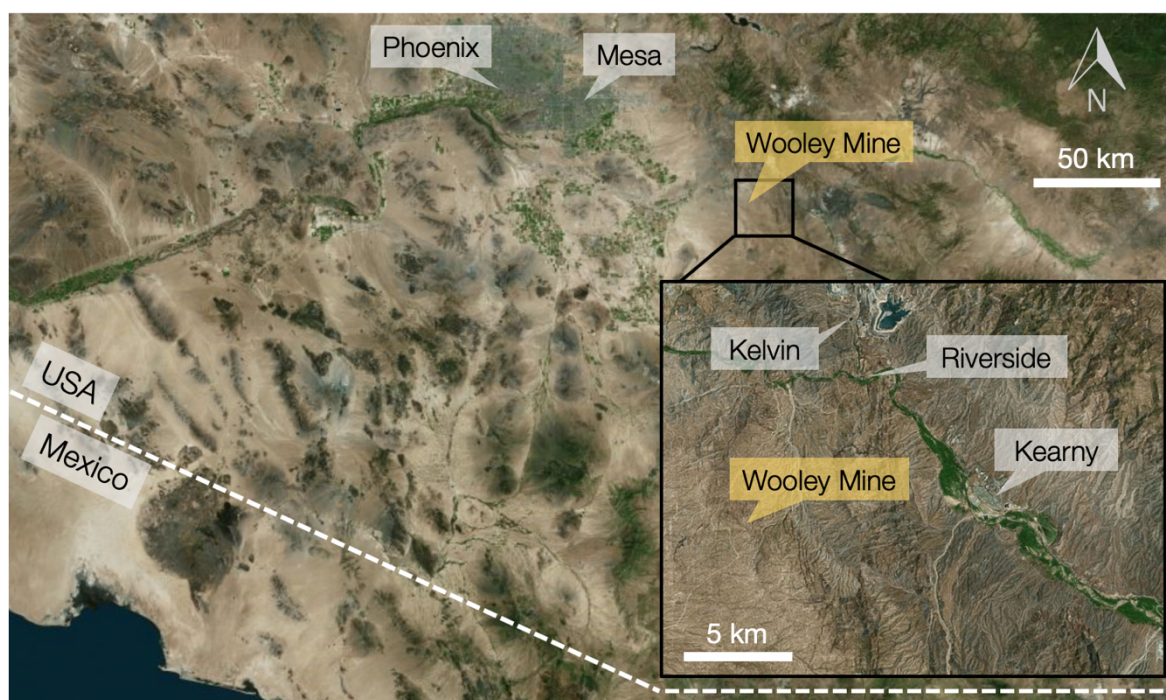
Supplementary Figures:

Figure S1: Satellite maps detailing the location of the Wooley Mine site in relation to nearby population centres. Modified from DigitalGlobe™.

Figure S2: Photograph of the surface mineral vein, exhibiting elongated quartz-rich regions alongside associated Cu-rich green inclusions. The width of the image is 60 cm.
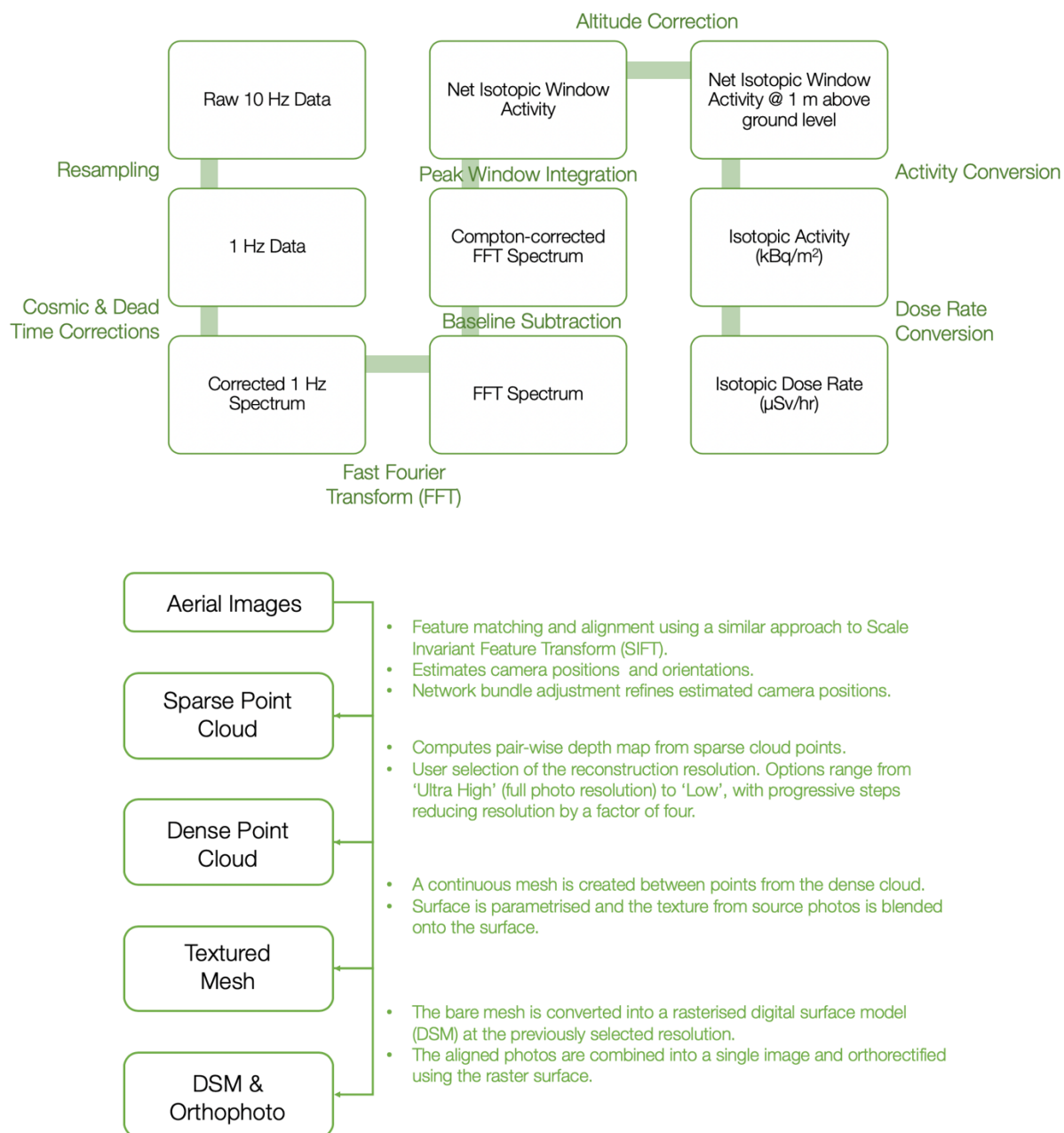
Flow chart (a) — radiological data processing

Raw 10 Hz Data

Resampling

1 Hz Data

Cosmic & Dead Time Corrections

Corrected 1 Hz Spectrum

Fast Fourier Transform (FFT)

FFT Spectrum

Baseline Subtraction

Compton-corrected FFT Spectrum

Peak Window Integration

Net Isotopic Window Activity

Altitude Correction

Net Isotopic Window Activity @ 1 m above ground level

Activity Conversion

Isotopic Activity (kBq/m²)

Dose Rate Conversion

Isotopic Dose Rate (μSv/hr)

Flow chart (b) — aerial imagery processing

Aerial Images

- Feature matching and alignment using a similar approach to Scale Invariant Feature Transform (SIFT).
- Estimates camera positions and orientations.
- Network bundle adjustment refines estimated camera positions.

Sparse Point Cloud

- Computes pair-wise depth map from sparse cloud points.
- User selection of the reconstruction resolution. Options range from 'Ultra High' (full photo resolution) to 'Low', with progressive steps reducing resolution by a factor of four.

Dense Point Cloud

- A continuous mesh is created between points from the dense cloud.
- Surface is parametrised and the texture from source photos is blended onto the surface.

Textured Mesh

- The bare mesh is converted into a rasterised digital surface model (DSM) at the previously selected resolution.
- The aligned photos are combined into a single image and orthorectified using the raster surface.

DSM & Orthophoto

Figure S3: (a) Flow chart of the radiological data processing undertaken to convert UAV-derived measurements into standard (altitude corrected) values of activity and dose rate. **(b)** Flow chart of the aerial imagery processing undertaken to convert to overlapping photos into a 3-dimensional photo-realistic topographic site model.
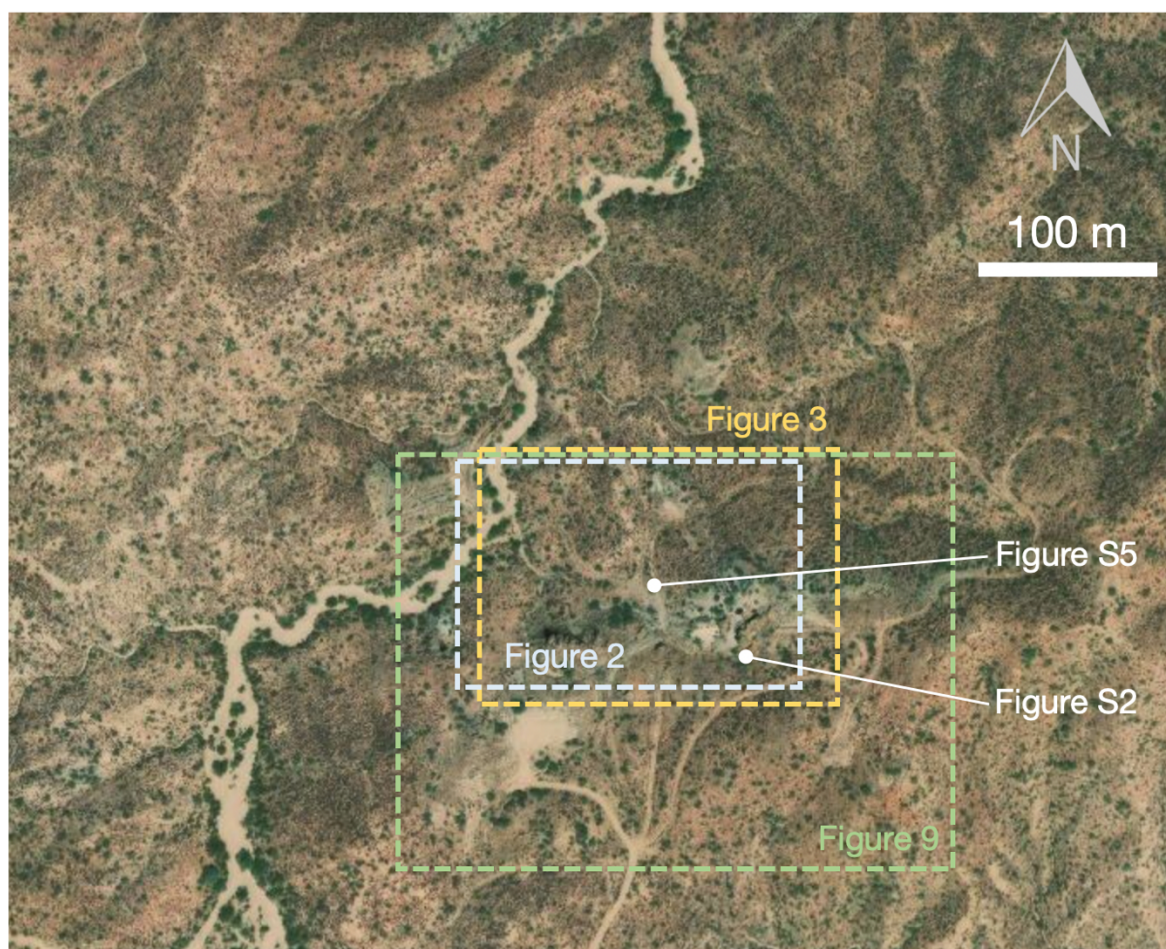
Figure S4: Overview aerial map of the Wooley Mine site, illustrating the relative locations of the figures presented within this manuscript. Modified from DigitalGlobe™.
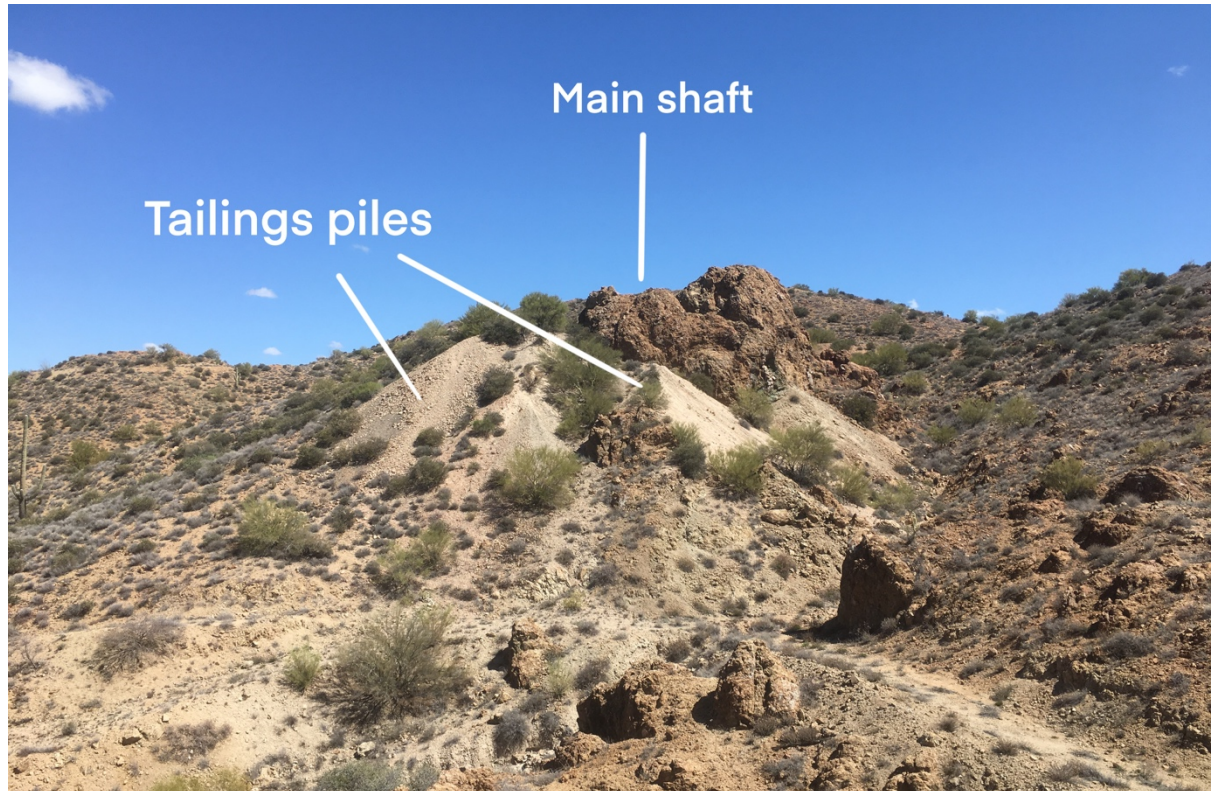
Figure S5: Photograph (facing north) of the topographic high on the Wooley Mine site, comprising the tailings piles and the former vertical (main) shaft entrance on the top of the hillside.