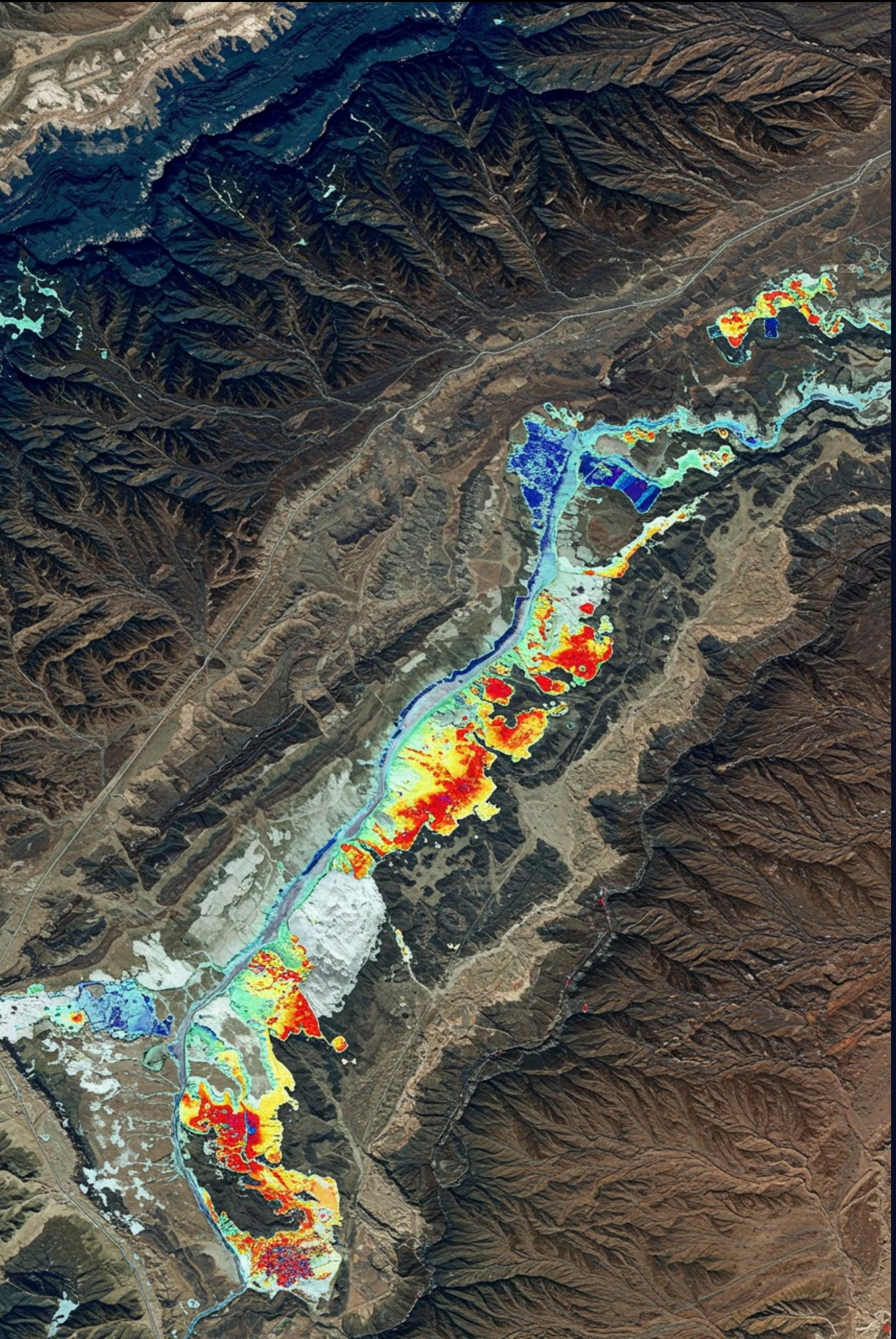
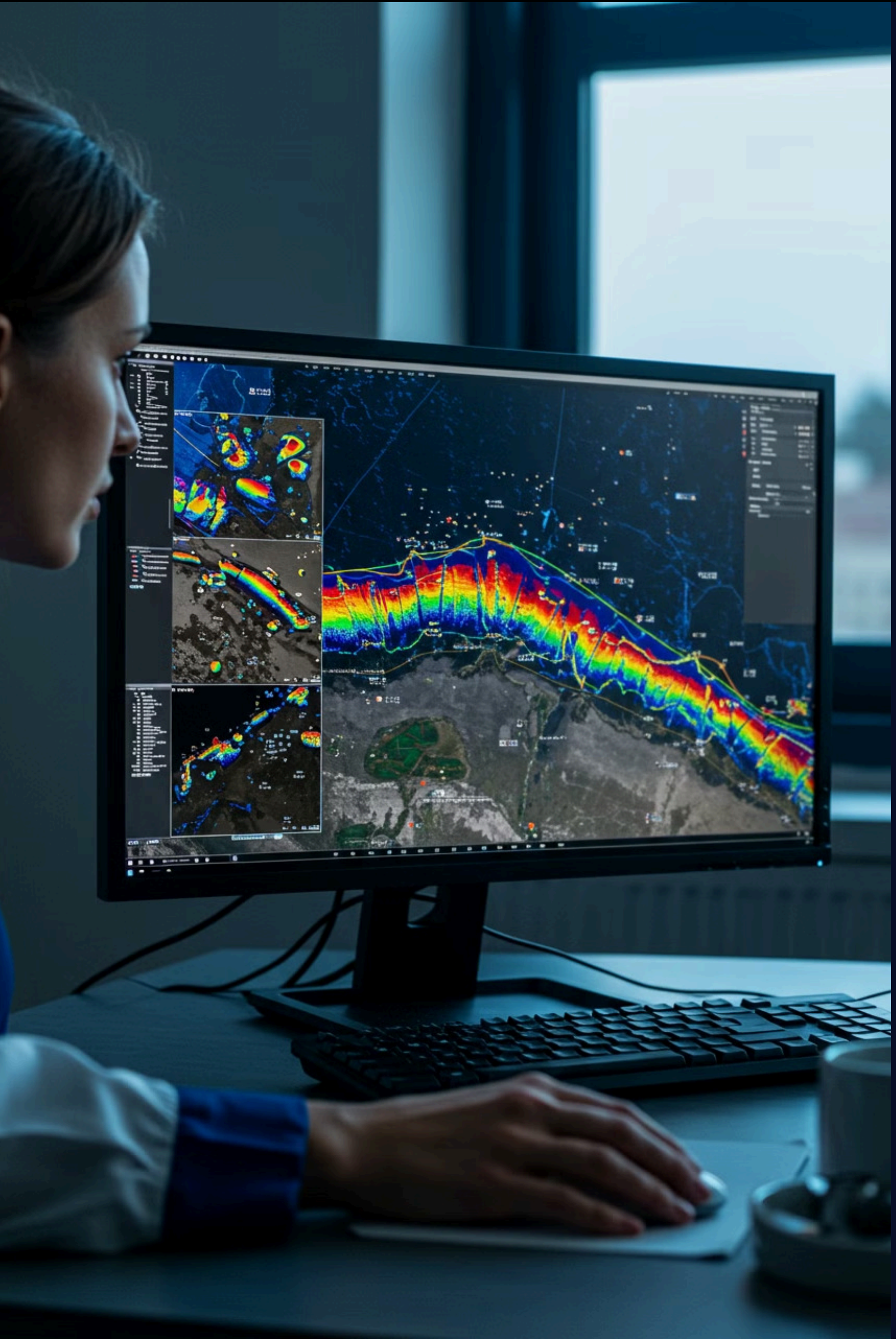


Advanced Spectral Survey Methodology for Copper-Gold Mineral Exploration

This methodology integrates Sentinel-2 VNIR-SWIR spectral data with subsurface gas anomalies (He, CH_4, CO_2) to map alteration minerals and deep fluid pathways, thereby improving the targeting of concealed copper-gold mineralisation. By combining these complementary datasets, exploration teams can identify prospective areas with greater precision and cost-effectiveness.



Introduction to Spectral Analysis in Mineral Exploration

1 Cost-Effective Screening

Remote sensing data in VNIR and SWIR spectral ranges provide a cost-effective initial screening tool to highlight key alteration minerals and secondary products associated with copper-gold systems.

2 Sentinel-2 Advantages

Sentinel-2 imagery offers free global coverage and moderate spatial resolution (10-20 m), making it well-suited for mapping mineral assemblages related to ore deposits.

3 Integrated Approach

When combined with subsurface gas anomaly data (He, CH_4, CO_2), which can indicate deep crustal fluid pathways and magmatic/metamorphic processes, integrated spectral-gas analysis significantly improves the accuracy of identifying prospective Cu-Au targets.

Theoretical Background of Spectral Analysis

VNIR-SWIR and Mineral Identification

Minerals and alteration products formed in hydrothermal environments often display diagnostic absorption features in the VNIR-SWIR range. By comparing pixel spectra from Sentinel-2 data to reference libraries, one can identify minerals linked to hydrothermal alteration zones, oxidation caps, and secondary enrichment, all of which are relevant to Cu-Au mineral systems.

Indirect Detection of Sulfides

Primary sulfides (e.g., chalcopyrite, arsenopyrite) rarely exhibit distinct VNIR-SWIR absorption features. Their presence is inferred indirectly through alteration minerals (clays, iron oxides), secondary copper minerals, and geochemical or gas data that indicate fluid flow and deep-seated mineralisation processes.

Sentinel-2 Spectral Characteristics

VNIR Bands

Sentinel-2's MSI sensor provides VNIR bands (B2, B3, B4, B8) that are useful for identifying iron oxides and some alteration minerals associated with Cu-Au systems.

SWIR Bands

Key SWIR bands (B11, B12) are particularly valuable for differentiating clay, carbonate, and iron-oxide bearing minerals, enabling the identification of hydrothermal alteration zones potentially associated with Cu-Au systems.

Spatial Resolution

With 10-20m resolution, Sentinel-2 provides sufficient detail to map mineral assemblages at a regional scale, making it ideal for early-stage exploration targeting.

Data Preparation and Preprocessing

Data Acquisition

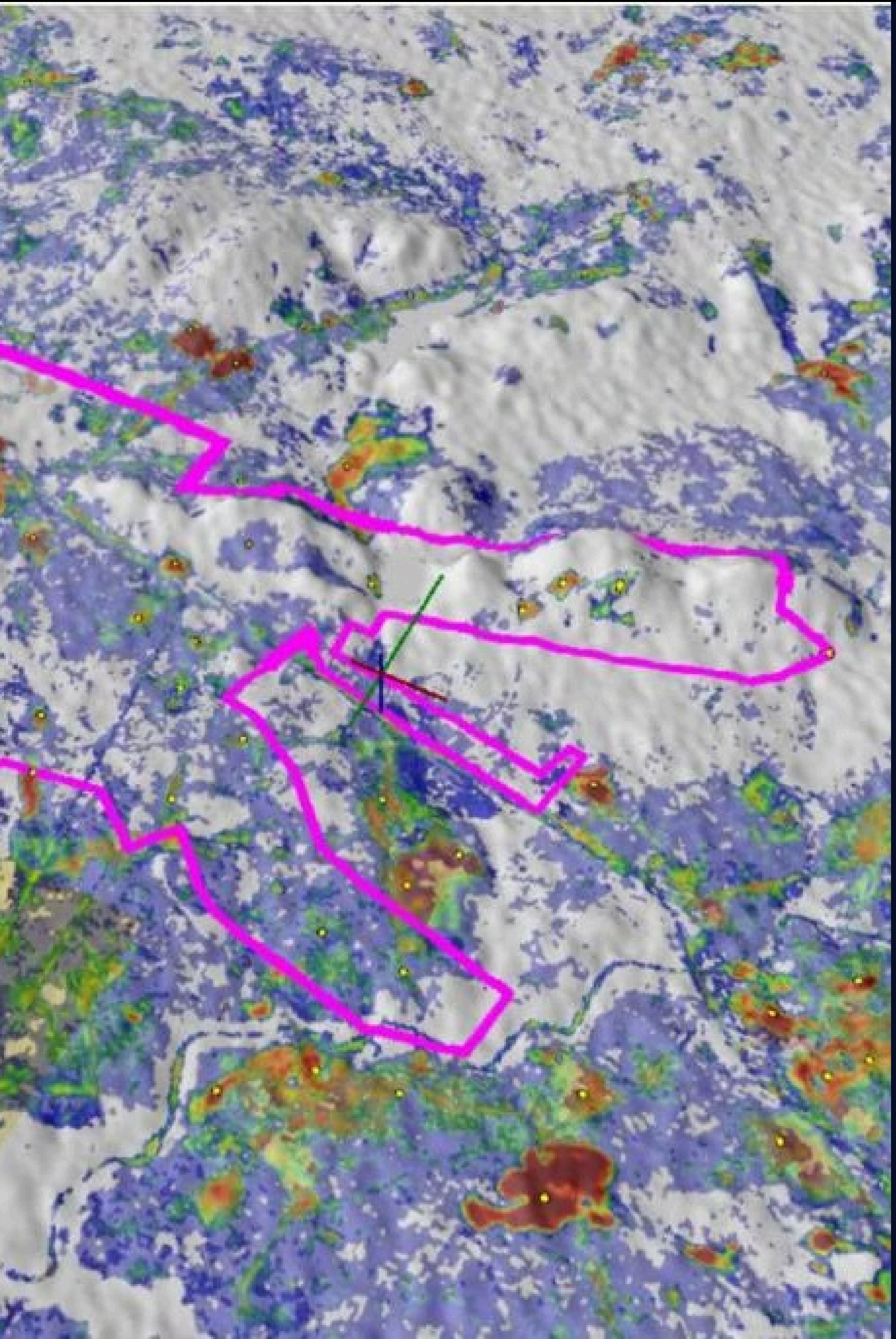
Download Sentinel-2 Level-1C images and apply atmospheric correction (Sen2Cor) to reach Level-2A surface reflectance, ensuring accurate spectral measurements.

Masking and Calibration

Use NDVI to mask dense vegetation and focus on exposed rocks. Ensure geometric and radiometric calibration is correct to maintain spatial accuracy across the study area.

Spectral Analysis in ENVI

Apply MNF (Minimum Noise Fraction) and PPI (Pixel Purity Index) transforms, then utilize the n-D Visualizer to isolate pure spectral pixels. Compare these endmembers against spectral libraries to identify specific minerals.



Selected Mineral Endmembers and Their Significance

Endmember	Correlation	Geological Significance	Cu-Au Targeting Relevance
Hematite	0.96	Iron oxide formed by oxidation	Indicates oxidized zones above potential sulfide deposits
Illite	0.54	Clay mineral in phyllic alteration	Marker of zones often associated with porphyry Cu-Au
Chrysocolla	0.95	Secondary copper mineral	Direct Cu indicator, signals potential Cu enrichment
Arsenopyrite	0.99	Fe-As sulfide	Direct geochemical proxy for Au mineralisation

These endmembers collectively help delineate hydrothermal halos, oxidized caps, secondary enrichment zones, and potential feeder structures. The combination provides a robust spectral signature for Cu-Au targeting.

Integration of Gas Anomalies in Regional African Context

1. **Enhanced Targeting**
   Combined spectral-gas analysis for precise Cu-Au exploration
2. **Gas Anomalies**
   He, CH_4, CO_2 as proxies for fluid migration
3. **Spectral Mapping**
   Mineral endmembers from Sentinel-2 VNIR-SWIR
4. **Geological Framework**
   African metallogenic provinces and tectonic structures

Helium (He), methane (CH_4), and carbon dioxide (CO_2) anomalies are invaluable proxies for understanding subsurface fluid migration, crustal architecture, and potential pathways for metalliferous fluids. Across different African metallogenic provinces, these gases highlight deep-seated structures and fluid conduits that can host diverse Cu-Au systems.

When these anomalies are integrated with VNIR-SWIR spectral data from Sentinel-2, endmember maps (e.g., arsenopyrite, hematite, chrysocolla, magnetite) can be correlated with tectono-magmatic processes and the styles of mineralisation characteristic of each region.

Carbon Dioxide (CO_2) Anomalies

Magmatic Association

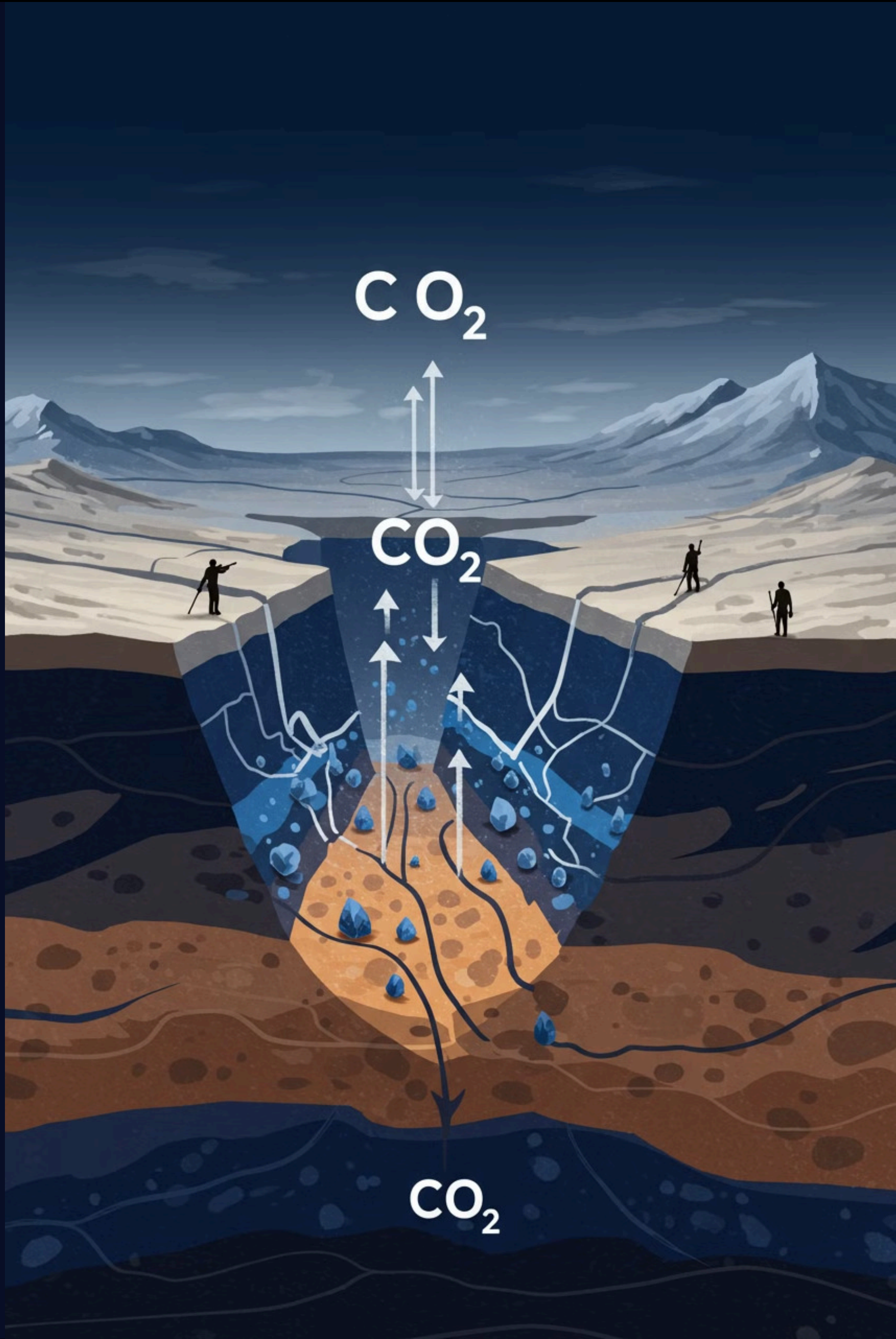
CO_2 anomalies are often associated with hydrothermal systems and magmatic intrusions. Elevated CO_2 levels may indicate the degassing of magmatic bodies, which are key drivers of hydrothermal fluid circulation.

Structural Indicators

CO_2 anomalies in the study area align with fault zones and shear structures, suggesting active or fossilized hydrothermal systems that may channel mineralizing fluids.

Carbonate Alteration

These zones may host gold and copper deposits, as CO_2 is commonly associated with carbonate alteration (calcite veins) in mineralized systems, providing a chemical environment favorable for metal deposition.



Methane (CH_4) Anomalies

Organic Interaction

Methane is a marker of organic material degradation or the interaction of hydrothermal fluids with organic-rich rocks, providing insights into fluid-rock interactions.

Fault System Markers

CH_4 anomalies are often linked to fault systems, where gas migration occurs through structural conduits, highlighting potential pathways for mineralizing fluids.

Artisanal Mining Correlation

High CH_4 concentrations in the Ruya River region coincide with artisanal workings and hydrothermally altered zones, suggesting interaction of hydrothermal fluids with organic-rich sedimentary layers.

Helium (He) Anomalies

Deep Crustal Indicator

Helium is a rare gas often associated with deep crustal or mantle-derived processes. It is commonly found in tectonically active regions where crustal degassing occurs, making it a valuable tracer for deep geological processes.

Fault System Marker

Elevated He levels in the study area indicate the presence of deep-seated faults and magmatic activity. These structural features often serve as conduits for mineralizing fluids from deep sources.

IOCG System Association

Helium anomalies are particularly significant for locating IOCG (Iron Oxide Copper Gold) systems, where mantle contributions play a role in fluid composition and metal enrichment processes.

Gas Anomaly Patterns and Correlations

1

Artisanal Mining Correlation

Elevated CO_2, CH_4, and He concentrations align with artisanal mining areas, confirming their association with known mineralized zones. This correlation validates the use of gas geochemistry as a predictive tool for locating new deposits.

2

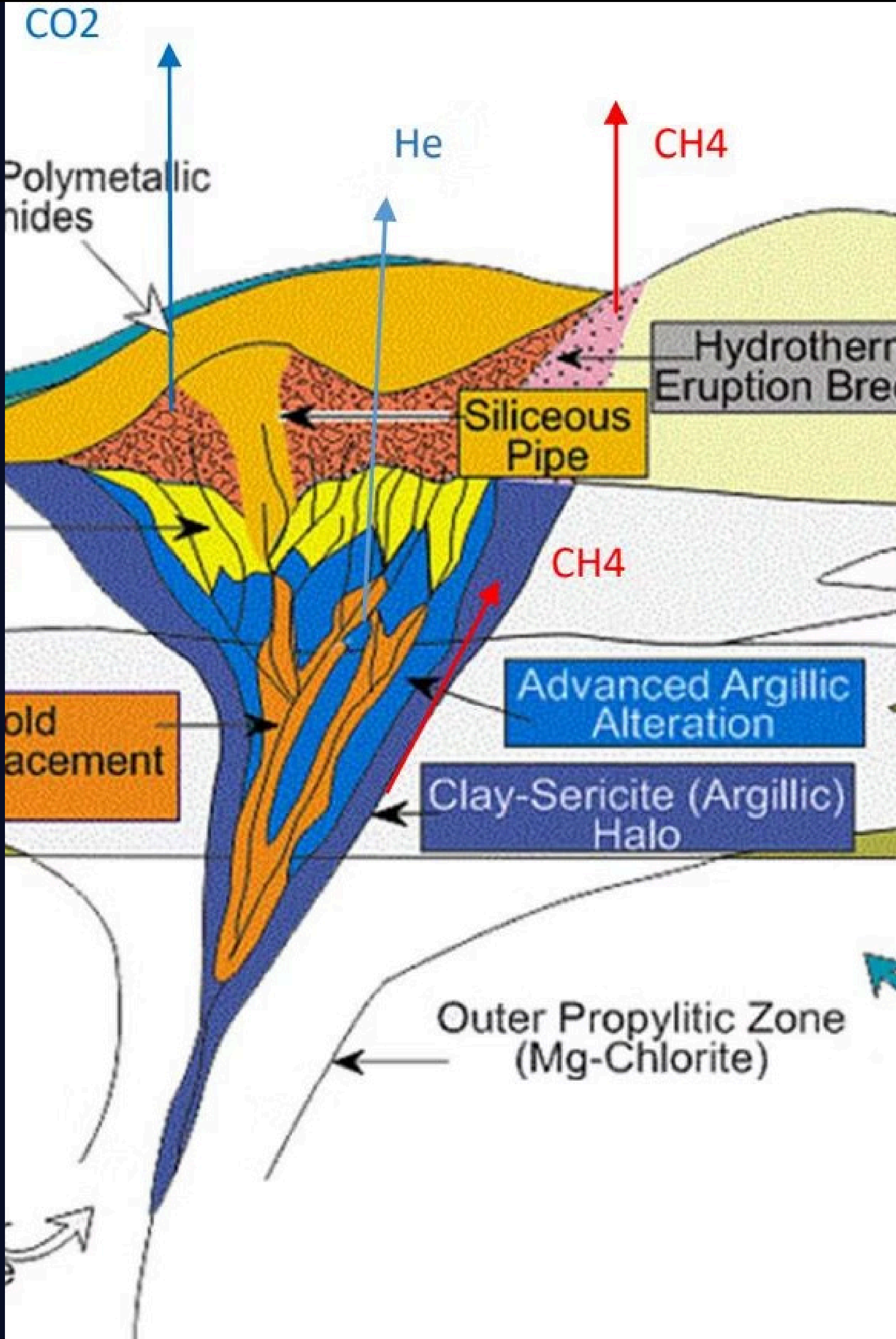
Structural Control

Gas anomalies are concentrated along fault zones, emphasizing the role of structural controls in fluid migration and mineral deposition. These structures serve as pathways for both gases and mineralizing fluids.

3

Hydrothermal Indicators

The coexistence of CO_2 and CH_4 anomalies highlights hydrothermal activity, while He anomalies suggest deeper crustal contributions, providing a comprehensive picture of the mineralizing system.



Key Findings from Gas Anomaly Analysis

1 Prospective Zones

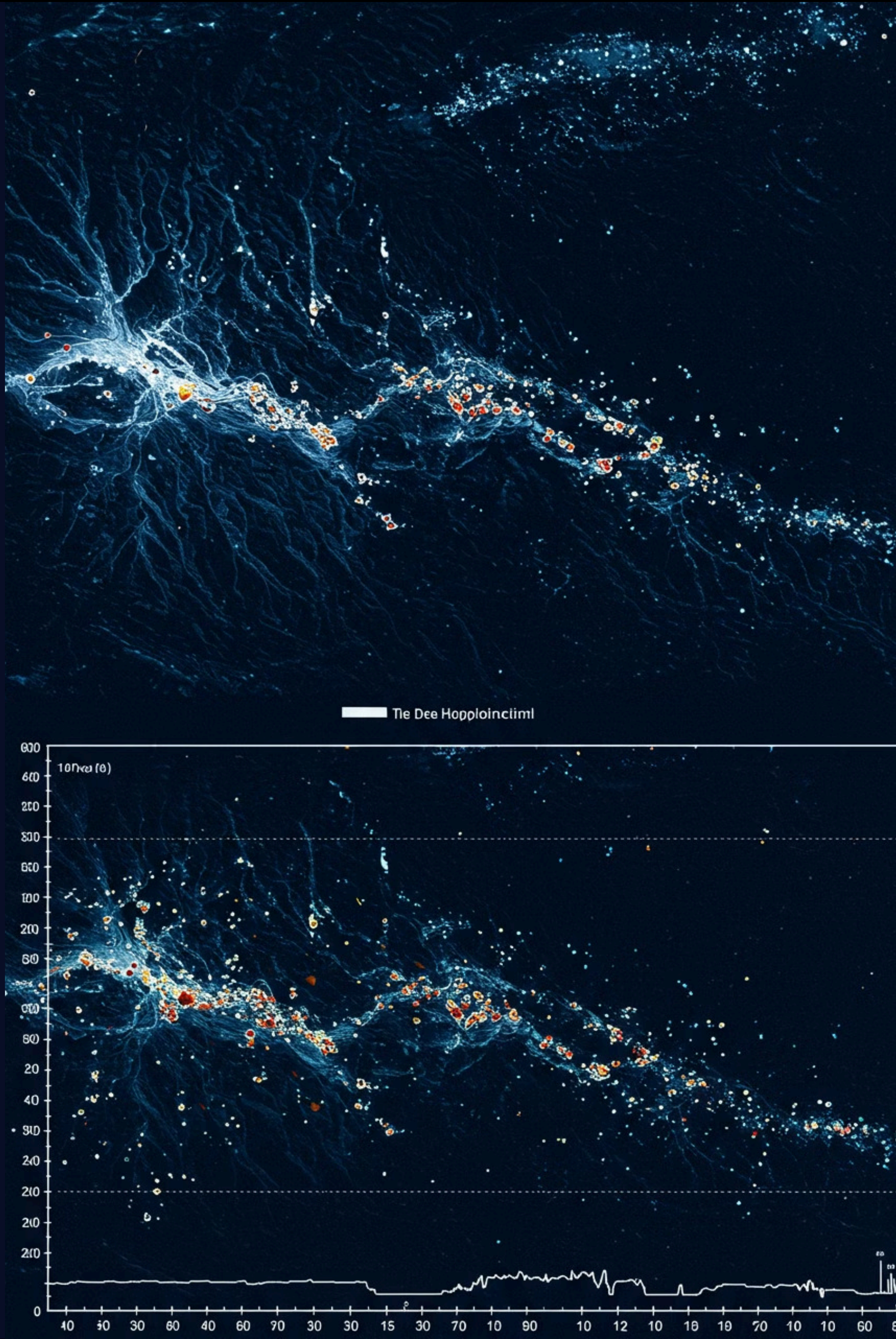
Zones with combined CO_2, CH_4, and He anomalies represent high-priority targets for exploration. These areas are likely to host mineralisation associated with hydrothermal and magmatic processes, providing a focused approach to target selection.

2 Validation of Spectral Analysis

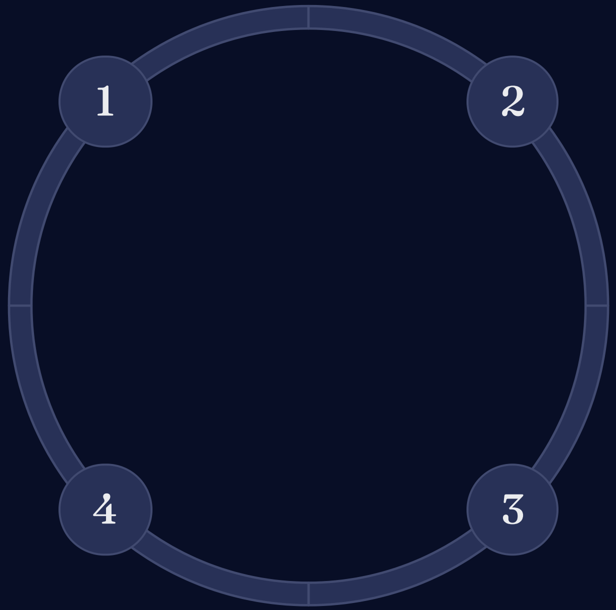
Gas anomalies complement spectral findings, providing additional evidence for the presence of copper and gold deposits. For example, areas with strong chalcopyrite spectral correlations also show elevated CO_2 and CH_4 levels, confirming the mineral identification.

3 Structural and Tectonic Insights

Gas geochemistry highlights the importance of faults and shear zones as conduits for mineralizing fluids and gas migration, enhancing structural understanding of the deposit area.



Structural and Tectonic Insights from Gas Anomalies



Fault Conduits

Gas geochemistry highlights the importance of faults and shear zones as conduits for mineralizing fluids and gas migration, providing structural context for exploration.

Geochemical Evidence

Gas anomalies of CO_2, CH_4, and He provide critical geochemical evidence for mineralisation in the Ruya River area, strengthening the geological model.

Deep-Seated Activity

Helium's indication of deep-seated tectonic activity makes it particularly valuable for delineating high-priority exploration zones with potential for significant mineralisation.

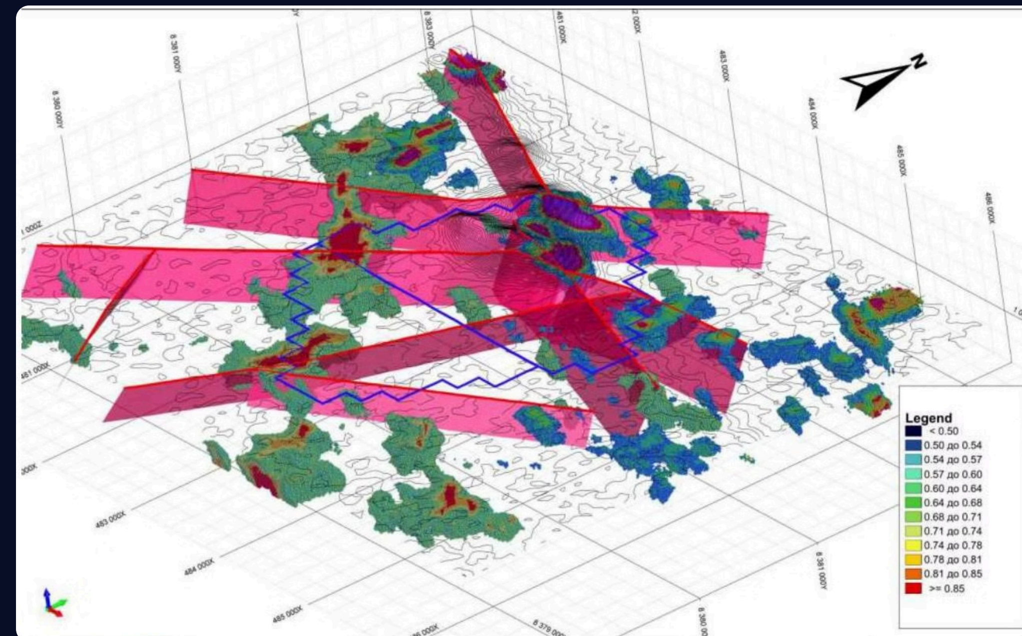
Fluid Interactions

Methane's link to hydrothermal fluid interactions with organic-rich rocks provides insights into the chemical processes involved in mineral deposition.

Case Study: Zambia Copper-Gold Exploration

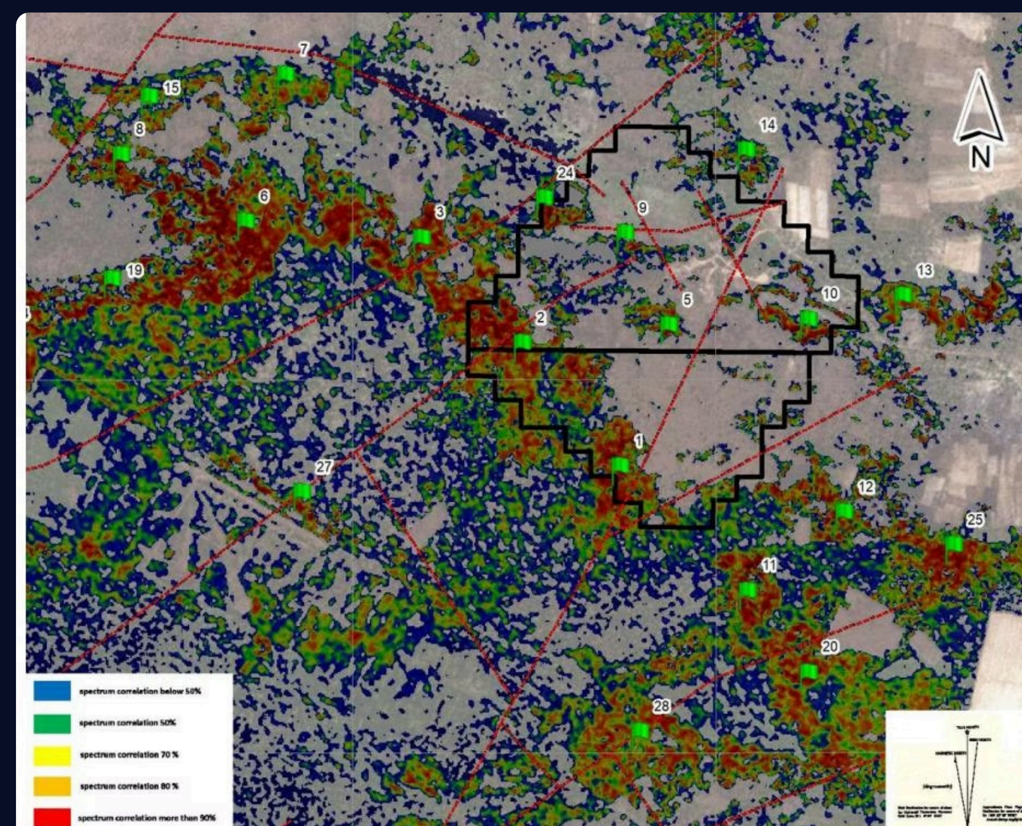
Deposit Types

Zambia hosts stratiform copper (Copperbelt), IOCG-like systems, porphyry-style, and shear-hosted Cu-Au deposits, making it an ideal region for applying integrated spectral-gas methodology.



Gas Integration

He anomalies along major basement-involved faults guide exploration towards IOCG or porphyry-like centers. CH4 and CO2 signals combined with iron oxide and secondary Cu minerals highlight potential metamorphic-magmatic fluid inputs contributing to stratiform Cu and possible Au enrichment.



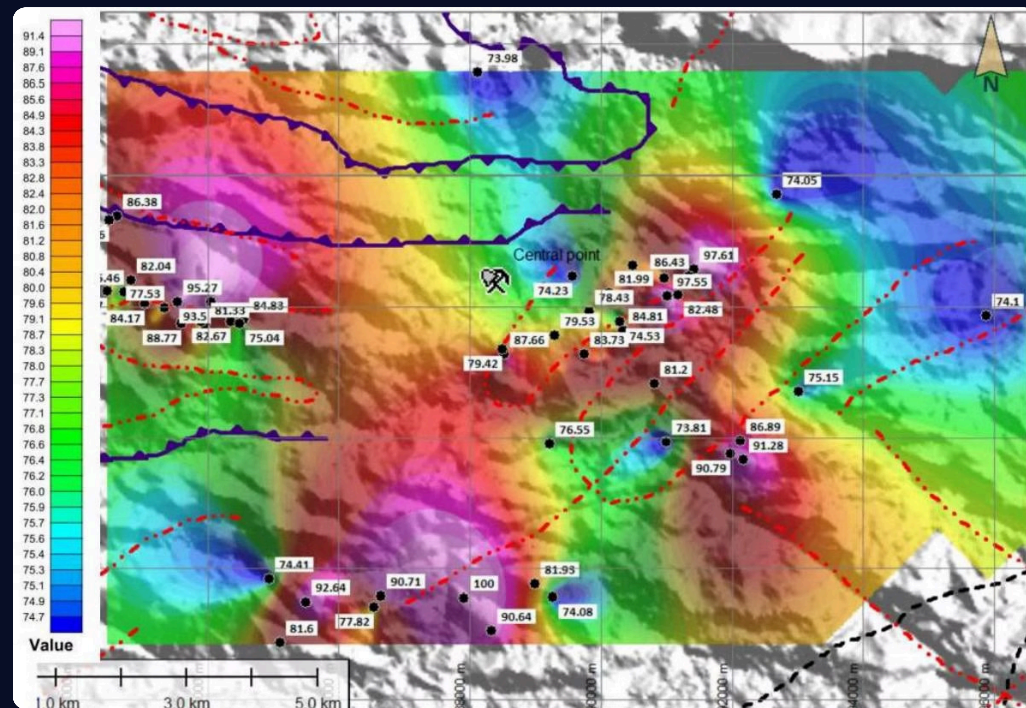
Case Study: Zimbabwe Gold Exploration

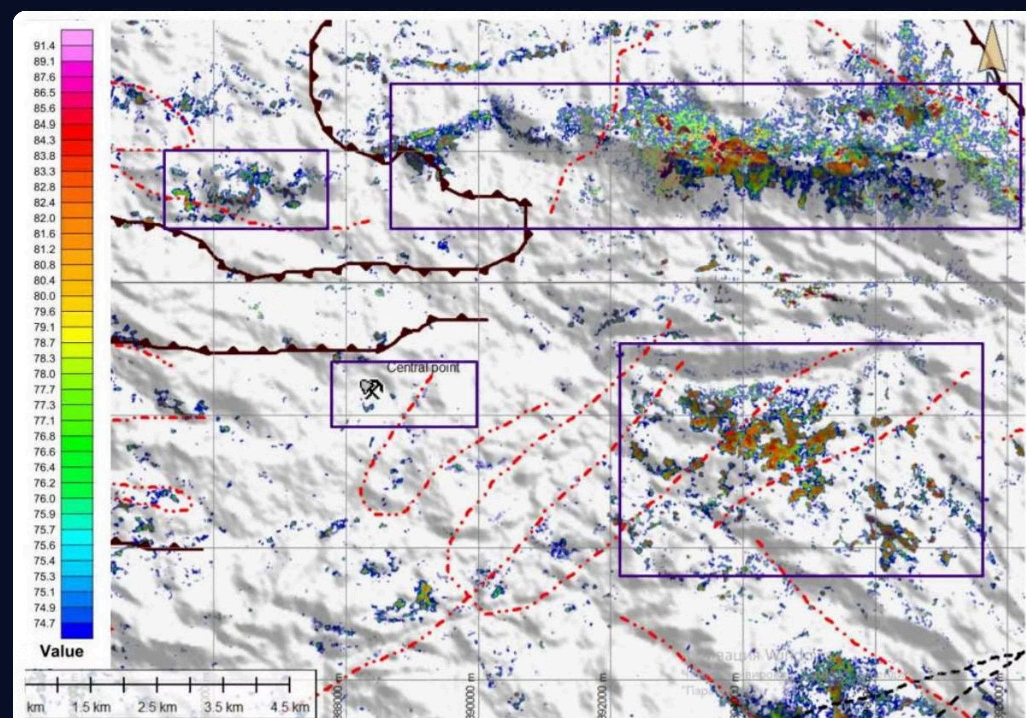
Deposit Types

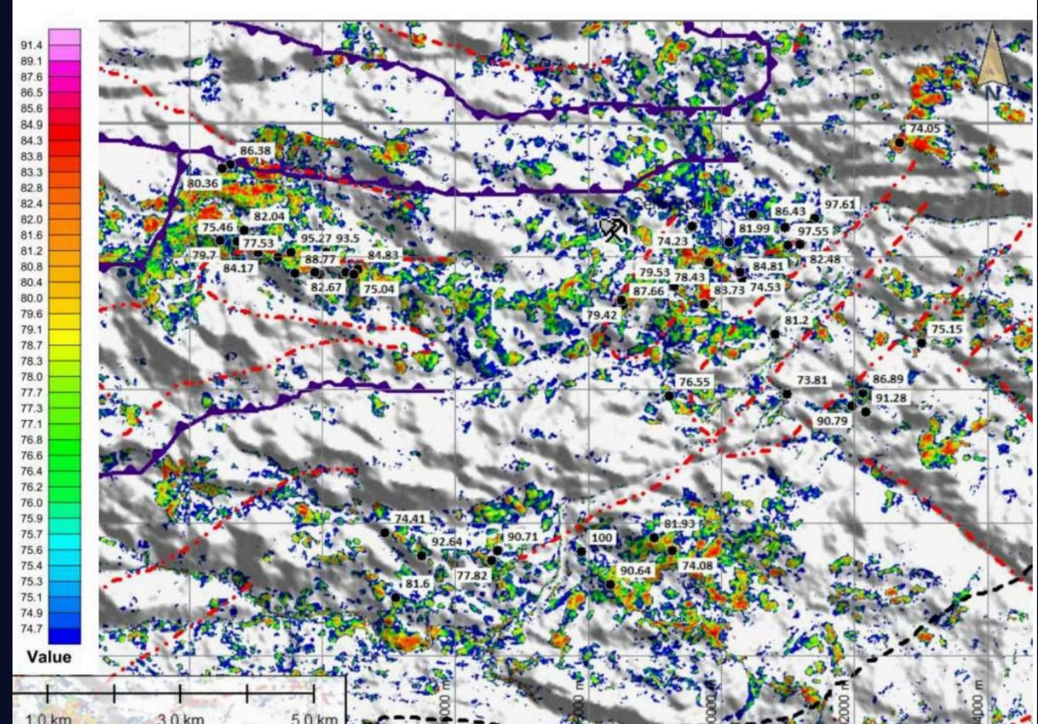
Zimbabwe features shear-zone hosted gold in Archean greenstone belts, BIF-hosted iron formations with associated Au, and possible IOCG variants, providing diverse exploration targets.

Gas Integration

Helium anomalies along greenstone belts' shear zones can pinpoint structures channeling gold-bearing fluids. CO2 anomalies in areas with carbonate alteration and arsenopyrite endmembers can signal the presence of orogenic gold systems. CH4 anomalies may reflect reduced fluid conditions in fracture networks controlling Au-Cu mineralisation.







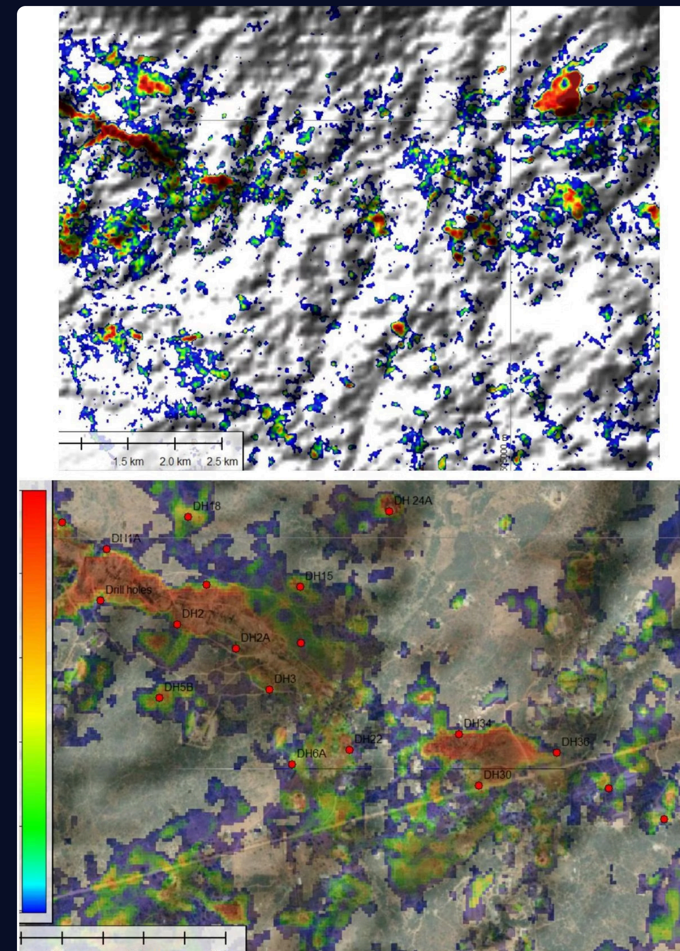
Case Study: Tanzania Gold Exploration

Deposit Types

Tanzania contains greenstone-hosted orogenic gold (Lake Victoria Goldfields), stratabound Cu mineralisation, and magmatic-hydrothermal systems in Proterozoic belts, offering multiple exploration targets.

Gas Integration

He anomalies mark deep crustal breaks, essential for localizing orogenic gold lodes. CH4/CO2 overlaps with illite/sericite or hematite endmembers can indicate magmatic fluids in porphyry-like or IOCG systems. Arsenopyrite correlation alongside He can highlight high-grade gold shoots in shear-hosted systems.

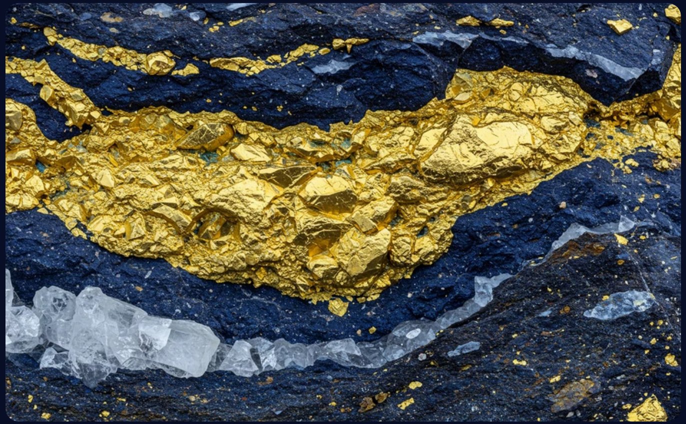


Lupa Gold Field / Spectral anomalies and Exploration drill holes

Case Study: Ghana Gold Exploration

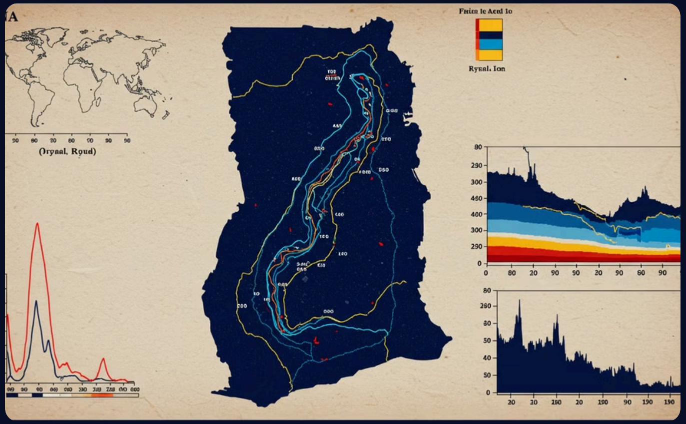
Deposit Types

Ghana hosts orogenic gold deposits (Ashanti Belt), disseminated sulfides within Birimian volcano-sedimentary sequences, and potential porphyry-like intrusions at depth, providing diverse exploration targets.



Helium Anomalies

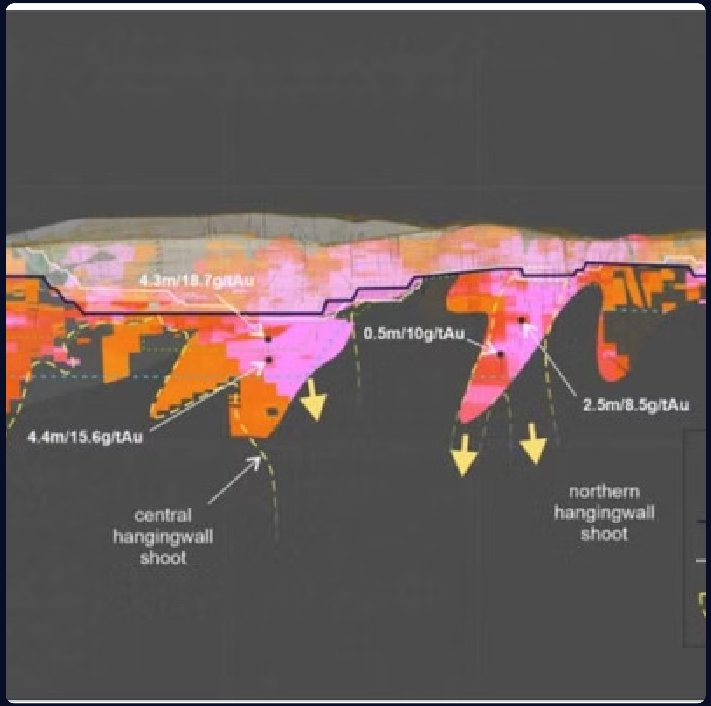
Helium anomalies superimposed on arsenopyrite and magnetite endmember maps can refine targeting of high-grade orogenic gold ore shoots, improving drill targeting efficiency.

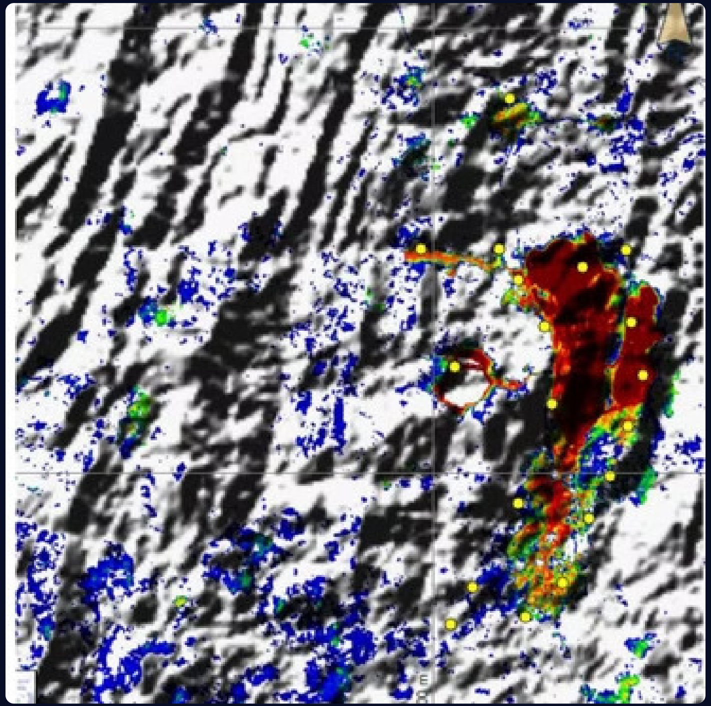


Carbon Dioxide and Methane

CO2 signatures may indicate carbonate alteration associated with gold-quartz veins. CH4 anomalies might help identify reduced fluid regimes that enhance gold precipitation in structural traps.

Case Study: Nigeria Polymetallic Exploration





Nigeria hosts polymetallic vein systems, shear-hosted gold in Proterozoic basement, possible IOCG-style deposits in rifted terrains, and lead-zinc sulfides in sedimentary basins. He anomalies aligned with basement shear zones can guide exploration towards Cu-Au ± Co mineralisation. CO_2 and CH_4 anomalies overlapping with jarosite or chrysocolla endmembers can indicate oxidized zones above deeper sulfide mineralisation, crucial in polymetallic vein settings where secondary copper minerals at surface hint at deeper Cu-Au potential.

The Segilola Gold Project demonstrates successful application of these techniques in identifying prospective zones for gold mineralisation in Nigeria's complex geological setting.

Applications by Deposit Type Across Regions

1 Shear-Zone Hosted Gold

In Zimbabwe, Tanzania, Ghana, and Nigeria, high He anomalies define crustal-scale faults. Arsenopyrite endmembers combined with CO_2 anomalies signify hydrothermal fluid-rock interaction typical of orogenic gold systems. Illite, sericite, and tourmaline endmembers help track fluid alteration halos.

2 Linear Stockworks and Porphyry Cu-Au

In Zambia and Tanzania, CH_4 or CO_2 anomalies indicate magmatic or metamorphic fluid inputs. Iron oxides and smectite-illite halos from spectral data mark potassic to phyllic alteration in porphyry-like systems. He anomalies along intersecting faults localize fluid upflow zones.

3 IOCG Deposits

In Zambia, He and CO_2 anomalies suggest deep magmatic or mantle-sourced fluids. Magnetite and hematite endmembers define iron oxide-rich cores typical of IOCG systems. Chrysocolla or jarosite near these structures points to supergene enrichment and surface oxidation halos.

4 Stratiform Mineralisation

In Zambia, CH_4 and He anomalies in sedimentary basins reflect fluid flow along permeable horizons. Overlapping endmembers like chrysocolla and jarosite confirm oxidative remobilization of copper and other metals within stratiform layers.

Practical Exploration Outcomes

1

Target Ranking

High He + arsenopyrite = prime Au targets in shear zones

2

Deposit Classification

CO_2 + magnetite/hematite = IOCG or magmatic-hydrothermal system

3

Regional Application

Same approach applies across multiple African countries

Integrating gas anomalies with mineral endmember maps allows explorers to efficiently rank targets and distinguish deposit styles. In Ghana's Ashanti Belt, orogenic gold is closely tied to shear-zone structures. He anomalies along these structures, combined with arsenopyrite spectral matches and CO_2 highs, create compelling drill targets where these parameters intersect.

In Tanzania's Lake Victoria Goldfields, correlating CH_4 and He anomalies with tourmaline and illite endmembers might reveal buried porphyry or intrusion-related systems underlying the greenstone-hosted orogenic gold belts. In Nigeria's polymetallic terrains, CO_2/CH_4 anomalies overlapping with chrysocolla or jarosite endmembers help delineate zones of supergene alteration above concealed Cu-Au bodies.

Practical Applications and Interpretations

1. **Integrated Analysis**
   Combined spectral-gas approach for precise targeting
2. **Structural Control**
   Fault-controlled mineralizing systems identified
3. **Mineral Indicators**
   Key minerals signaling Cu-Au potential

In a prospective region showing helium anomalies over a faulted block, overlaying the mineral map reveals chrysocolla (Cu indicator) and magnetite (IOCG signature) near these anomalies. Further, jarosite and hematite clusters define an oxidation cap possibly overlying sulfides. The combination suggests a structurally controlled IOCG system with Cu-Au potential.

Arsenopyrite, with its high correlation, if mapped near He anomalies, strongly points towards hidden Au mineralisation. In parallel, cobaltite presence might indicate complex metal enrichment, enhancing the exploration focus and providing multiple lines of evidence for mineralisation.

Validation and Further Work

Field Verification

Ground-truthing with sampling and portable spectrometry

Drill Testing

Targeted drilling of high-priority anomalies

Laboratory Analysis

XRD, XRF to confirm mineralogy and geochemistry

Geophysical Surveys

Magnetic or IP surveys to validate inferred features

Iterative Improvement

Machine learning for endmember refinement

The integrated spectral-gas methodology requires validation through multiple complementary techniques. Field verification involves sampling, portable spectrometry, and laboratory analysis to confirm the mineralogy and geochemistry indicated by remote sensing. Geophysical surveys can validate magnetite bodies and sulfide concentrations inferred from spectral-gas analysis, refining drill targets and providing additional subsurface information.

Limitations and Future Directions

1

Current Limitations

Sentinel-2's limited spectral range and broader bands may constrain fine mineral discrimination. Multiple vegetation endmembers highlight challenges in fully exposing rock surfaces in densely vegetated regions, potentially masking important spectral signatures.

2

Technical Advancements

Future hyperspectral imaging missions (e.g., CHIME) will enable more precise mineral identification with narrower spectral bands and greater sensitivity. AI-driven endmember extraction and classification algorithms can improve the accuracy and efficiency of mineral mapping from spectral data.

3

Monitoring Innovations

Continuous gas monitoring systems can provide dynamic insights into fluid pathways, capturing temporal variations in gas emissions that may indicate active mineralizing processes or changing subsurface conditions.

Conclusions

Powerful Integrated Approach

This advanced spectral remote sensing methodology, using Sentinel-2 VNIR-SWIR data integrated with gas anomaly indicators, provides a powerful approach for early-stage Cu-Au exploration, combining multiple lines of evidence for more confident targeting.

Mineral-Fluid Convergence

By identifying 16 key mineral endmembers and relating them to geological processes, explorers can pinpoint zones where mineral and fluid indicators converge, highlighting areas of highest potential for mineralisation.

Cost-Effective Exploration

The methodology enables more targeted and cost-effective follow-up work, reducing the need for extensive ground surveys and allowing exploration teams to focus resources on the most promising areas for detailed investigation.