xine

The Spectral Advantage in Mineral Exploration

Alteration mineral mapping from orbit: identifying, classifying and ranking hydrothermal systems at 8 metre resolution.

Mineral Exploration

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Contents

Introduction

This paper sets out how hyperspectral imaging supports mineral exploration, and how Axine Laboratories turns satellite spectroscopy into alteration mineral maps, assemblage classifications and ranked exploration targets. It is written for exploration managers, consulting geologists and technical services teams evaluating where remote spectroscopy fits in a modern target generation workflow.

Motivation: doing more with a smaller exploration dollar

Global nonferrous exploration budgets totalled 12.40 billion US dollars in 2025, a third consecutive year of decline in nominal terms[1]. Within that shrinking pool, capital has rotated decisively toward known ground. Minesite exploration reached a record 45 per cent of global budgets, while grassroots exploration fell to a record low share of about one fifth[1]. The pipeline of genuinely new discoveries is thinning at precisely the moment demand is accelerating.

The demand side is unambiguous. The International Energy Agency projects that mined supply from announced projects falls short of 2035 demand by roughly 30 per cent for copper and 40 per cent for lithium under stated policy settings, and estimates that around 500 billion US dollars of new mining capital will be required by 2040[2]. With an average of sixteen years between discovery and production[1], the deposits that supply the 2040s need to be found now.

Discovery economics have moved in the other direction. Analysis of long term discovery performance puts the cost per significant discovery at roughly 142 million US dollars in the decade to 2019, up from about 41 million in the 1980s in constant terms, with unit gold discovery costs doubling from 27 to 62 dollars per gold-equivalent ounce between the 2000s and the 2010s[3]. A substantial part of that escalation is structural rather than cyclical: the search has moved under cover, and increasing the average depth of cover from 25 to 75 metres roughly doubles discovery cost[4].

The response across the industry has been to demand better evidence earlier. Every dollar spent narrowing a search area before mobilisation is a dollar not spent testing ground that a better dataset would have deprioritised. This is where imaging spectroscopy has become operationally relevant rather than merely interesting.

Why alteration mineralogy is the right search target

Hydrothermal ore deposits are small. The alteration systems that formed them are not. A porphyry centre may be a few hundred metres across, while the zoned assemblage of alunite, kaolinite, white mica, chlorite and epidote produced by the same fluid commonly extends for kilometres. A satellite sensor that could never resolve an orebody can comfortably resolve the mineralogical footprint of the fluid that made it, and can map that footprint across an entire belt in a single acquisition.

That is the physical basis for the entire discipline. Axine Laboratories exists to make it operational: to deliver mineral-specific, validated alteration maps at a spatial resolution fine enough to act on, over any terrain, without mobilising a crew.

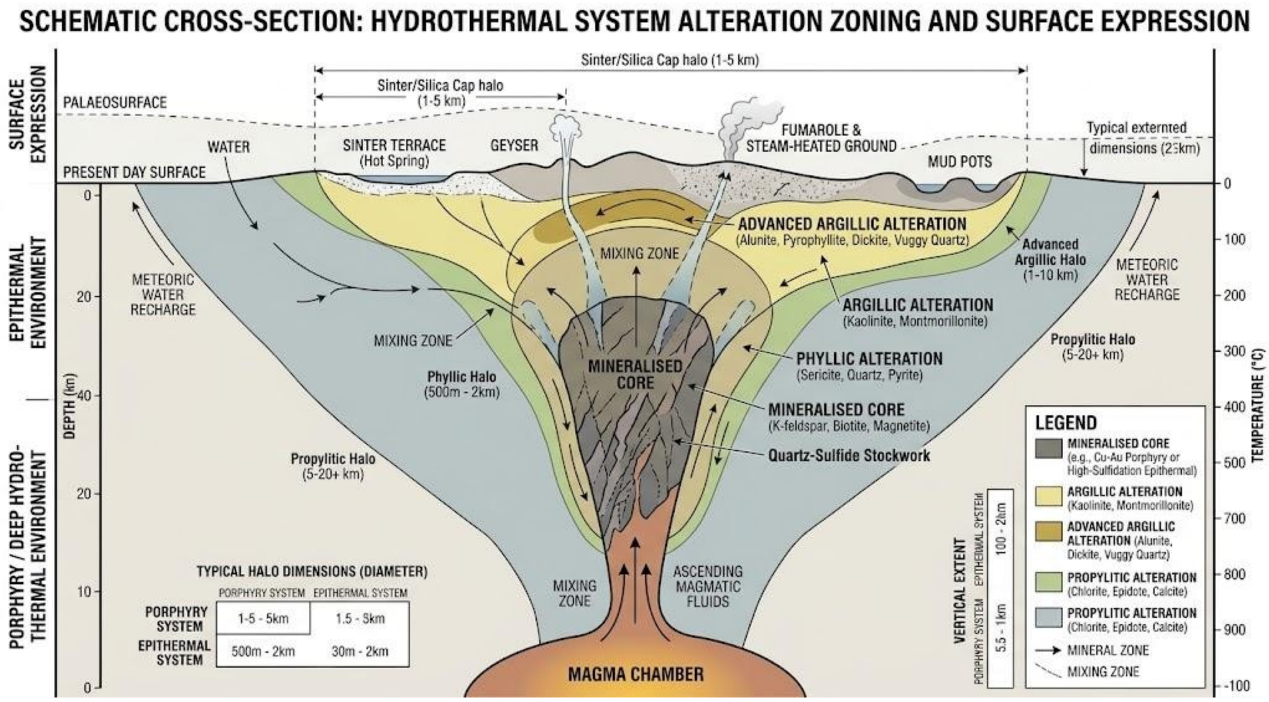

Figure 1 — *Zoned alteration in a hydrothermal system. The mineralised core is a few hundred metres across; the advanced argillic, argillic, phyllic and propylitic halos the same fluid produced run to kilometres and reach the surface, where a satellite can measure them.*

What is hyperspectral imaging?

Every material interacts with light in a way determined by its chemistry. Minerals containing hydroxyl, water or carbonate groups absorb energy at specific wavelengths in the short-wave infrared through vibrational overtone and combination modes. Iron-bearing minerals absorb in the visible and near infrared through electronic transitions. The positions, depths and shapes of those absorption features constitute a spectral signature that identifies the mineral rather than merely describing its colour.

Conventional satellite imagery cannot resolve those features. An RGB sensor records three broad bands. A multispectral sensor records between four and twenty, each tens of nanometres wide. Hyperspectral sensors divide the spectrum into hundreds of contiguous narrow bands, each typically under 10 nm wide, producing a continuous spectrum for every pixel in the scene rather than a handful of averaged brightness values.

A comparison of RGB, multispectral and hyperspectral imagery.

Type	Number of bands	Bandwidth (FWHM)	Wavelength range
RGB	3	~50-70 nm	450-700 nm
Multispectral	4-20	~15-35 nm	400-2350 nm, discontinuous
Hyperspectral	100-500+	Under 10 nm	400-2500 nm, contiguous

The practical difference is discrimination. Kaolinite produces a characteristic doublet near 2160 and 2205 nm. Alunite absorbs near 2170 nm. White mica absorbs near 2200 nm, and the exact position of that feature shifts with aluminium content. A sensor with 100 nm wide bands averages all three into a single reading that something in the pixel absorbs around 2200 nm, which is true of most clays, most micas and a good deal of unaltered rock. A hyperspectral sensor separates them, names them, and reports the variant.

Spectral resolution determines which minerals can be distinguished. Spatial resolution determines how small a feature can be distinguished. Both matter, and they are independent. A 60 metre pixel covers 3,600 square metres of ground, so a narrow alteration corridor crossing that pixel contributes only a fraction of the measured signal. At 8 metres the same corridor dominates its pixel. This is why Axine pairs free archive imagery for regional reconnaissance with tasked high-resolution acquisition for detailed work.

Exposed rock on a cliff line. Reflectance spectroscopy measures whatever the surface presents to the sensor, so bare outcrop is the ground it reads best; open water, cloud and vegetation are screened and reported as not evaluated.

The tasked acquisition tier

For detailed mapping, Axine acquires imagery from a commercial hyperspectral constellation of six identical microsatellites offering:

- 472 contiguous spectral bands across the full visible to short-wave infrared range, 400 to 2500 nm.
- 8 metre ground sample distance in the hyperspectral channels, the finest commercially available hyperspectral resolution currently in orbit.
- 3 metre panchromatic imagery co-acquired for spatial context and sharpening.
- Revisit of up to daily for most locations worldwide, with directed tasking over a defined area of interest.

The complete SWIR range matters as much as the resolution. Carbonate and magnesium-hydroxyl features sit between 2300 and 2400 nm, beyond the reach of sensors that stop short of 2400, and they carry the propylitic and carbonate-host information that completes a zoned interpretation.

Challenges in mineral exploration

Exploration teams are being asked to generate more targets, defend them more rigorously, and do both on flat or falling budgets. The constraints below are the ones that spectral mapping is well positioned to relieve.

Ground like this ridge line sits a long way from a road head and a long way down the queue for a field season. Wall-to-wall coverage from orbit puts it on the same evidential footing as a block that has been walked.

+ **A depleting surface search space:** The near-surface search space in mature terranes has been substantially depleted, pushing programmes toward deeper cover and more remote ground, both of which raise unit discovery cost sharply. Datasets that extract more information from surface exposure improve the return on the ground that remains directly observable.
+ **Uneven ground truth:** Ranking a tenement package typically happens against uneven information. Some blocks are mapped, some carry historical soil grids of unknown provenance, some carry nothing. Consistent, wall-to-wall coverage puts every block on the same evidential footing.
+ **Field cost and seasonality:** Geological mapping and soil sampling are bounded by how much ground a crew can cover in a season, and field windows are compressed by wet seasons, permitting, access agreements and heritage clearance. Work completed before mobilisation is time recovered.
+ **Time-boxed commercial decisions:** Farm-in and option decisions run to calendar deadlines. Where a window is short and the ground is remote, a desktop dataset that can be produced in days rather than months materially changes the quality of the decision.
+ **Distinguishing alteration from weathering:** Supergene and weathering processes generate clays in ground that never hosted a hydrothermal fluid. Mineral-specific detection and

assemblage logic separate a zoned hydrothermal footprint from a generic clay anomaly, which is the difference between a target and a field trip.

+ **Auditability of target generation:** Boards, joint venture partners and regulators increasingly ask how a target was generated and how the method was tested. Evidence with a documented validation regime behind it is materially easier to defend than an unpublished score.
+ **Integration with existing geoscience:** Modern exploration integrates magnetics, radiometrics, gravity, geochemistry and terrain. A mineralogical layer with genuine mineral specificity adds an independent axis of evidence rather than another correlated proxy.

Hyperspectral imagery in action

Integrating hyperspectral imagery into exploration workflows addresses these constraints directly. Across the value chain, the imagery supports three fundamental capabilities.

- **Detection:** Identifying the presence of specific alteration minerals, iron oxides and hydrothermal indicators across the full extent of a scene, including in ground that has never been walked.
- **Classification:** Grouping detected minerals into alteration assemblages, resolving compositional variants within a mineral species, and separating hydrothermal footprints from lithological and weathering backgrounds.
- **Quantification:** Measuring absorption feature depth and spatial extent to characterise the intensity and geometry of an alteration system, and to track how those measures change between acquisitions.

The table below sets out the spectral regions Axine works in, the minerals diagnosed in each, and their significance for exploration. Feature positions are given as ranges because exact positions shift with composition, crystallinity and grain size.

Diagnostic spectral regions, minerals detected, and exploration significance.

Band group	Wavelength (nm)	Minerals	Significance
VNIR	450-900	Hematite, goethite (ferric iron)	Gossan and oxidised cap mapping; iron oxide zoning across a system
VNIR	580, 745, 800	Neodymium-bearing phases	Sharp, narrow features associated with rare earth element indicators
SWIR	1400, 1900	Hydrated phases, molecular water	Hydration state; supports crystallinity and hydrated silica assessment
SWIR	~1480	Alunite	Paired with the 2170 nm feature to confirm advanced argillic alteration
SWIR	2160-2210	Kaolinite (2 variants), alunite, muscovite (4 variants), smectite	The principal alteration window. Feature position separates argillic, advanced argillic and phyllic assemblages
SWIR	~2200	White mica composition	Feature position tracks aluminium content and

Band group	Wavelength (nm)	Minerals	Significance
			provides a vector toward higher temperature zones
SWIR	2250-2260	Chlorite, epidote, hydrated silica	Propylitic alteration and silicification
SWIR	2300-2400	Calcite, dolomite, epidote, Mg-OH phases	Carbonate host rocks, carbonate alteration and the outer propylitic margin

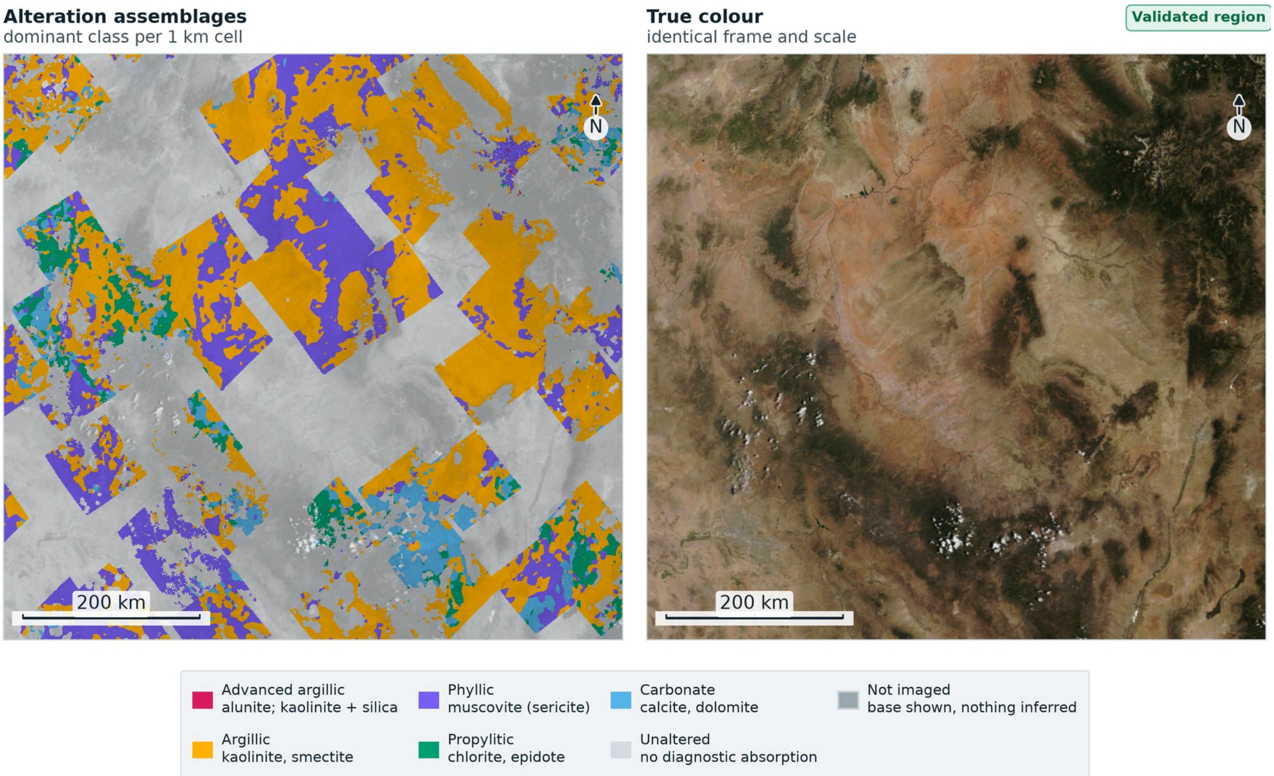

Figure 2 — *Alteration assemblages across a validated region, dominant class per 1 km cell, beside the identical frame in true colour at the same scale. Nothing in the optical view separates argillic ground from phyllic.*

Hyperspectral versus multispectral imaging in exploration

Multispectral imagery provides a foundational view of surface characteristics and remains valuable for context, land cover and change. Hyperspectral imagery answers a different class of question, because mineral identification requires bands narrower than the absorption features themselves.

Parameter	Multispectral imaging	Hyperspectral imaging
Mineral identification	Broad mineral groups and indices	Specific minerals identified against measured library spectra
Compositional variants	Not resolvable	White mica composition and kaolinite crystallinity resolved as separate classes
Alteration assemblages	Generic clay and iron oxide indices	Zoned assemblages classified and mapped as coherent systems
Mixed pixels	Dominant response only	Up to three co-occurring minerals resolved per spectral window
Carbonate discrimination	Grouped where SWIR coverage allows	Calcite and dolomite separated
Iron oxide mapping	Iron oxide index	Ferric mineralogy mapped with assemblage context
Rare earth indicators	Not resolvable	Narrow neodymium features detectable where spectral resolution permits
Spatial detail	10-30 m typical	8 m in the tasked tier, with 3 m panchromatic context
Change monitoring	Land cover and disturbance	Compositional change between acquisitions

The comparison is a matter of physics rather than vendor preference: mineral discrimination requires narrow contiguous bands, and narrow contiguous bands are what defines a hyperspectral sensor.

The Axine analytical method

Axine runs a deterministic, physics-based detection layer. Mineral identification is performed by measuring absorption features and fitting them against the USGS splib07a spectral library, currently across twelve minerals and twenty-one variant spectra. No trained classifier decides what a pixel contains. The consequence is an output that is reproducible, sensor agnostic, and traceable to a measured feature and a reference spectrum at every pixel.

Reflectance and masking

Imagery from any supported sensor is reduced to surface reflectance and screened for vegetation, water, cloud, shadow and atmospheric water vapour absorption. Screened ground is reported explicitly as not evaluated, so that every coloured pixel on an Axine map is a measurement rather than an assumption.

Continuum removal and absolute band depth

Each spectral window is continuum removed so that absorption features are measured independently of overall brightness and slope. Features are quantified as absolute band depths, which is materially more reliable on mixed pixels than comparing whole-spectrum shapes.

Iterative residual pursuit

Real pixels contain mixtures. Once a mineral is fitted, its modelled contribution is removed and the residual is searched again, resolving up to three co-occurring minerals per spectral window. This is what allows an assemblage rather than a single dominant mineral to be reported, and it is the step that turns mineral detection into geological interpretation.

Per-pixel noise floor

Detection thresholds are derived from the radiometric uncertainty of the specific sensor at the specific wavelength, calculated per pixel from instrument characteristics. Thresholds are set from physics rather than tuned to produce a desired result, which is what makes a detection at one site comparable to a detection at another.

Assemblage classification and cluster detection

Detected minerals are grouped into advanced argillic, argillic, phyllic, propylitic and carbonate assemblages, and assemblages are aggregated into district-scale clusters. Cluster detection requires an advanced argillic anchor, which concentrates attention on systems carrying evidence of a magmatic-hydrothermal centre.

Prospectivity ranking

In regions calibrated against known occurrence datasets, a Bayesian hierarchical model with region-varying intercepts ranks alteration clusters by their association with known mineralisation. Axine holds calibration datasets at the scale of hundreds of thousands of occurrences, including 107,196 Western Australian records with commodity, deposit model and host geology attribution, and 304,632 United States records. Region-specific calibration is a deliberate design choice: geology varies between belts, and a model calibrated to the belt it is applied in produces a ranking a geologist can reason about.

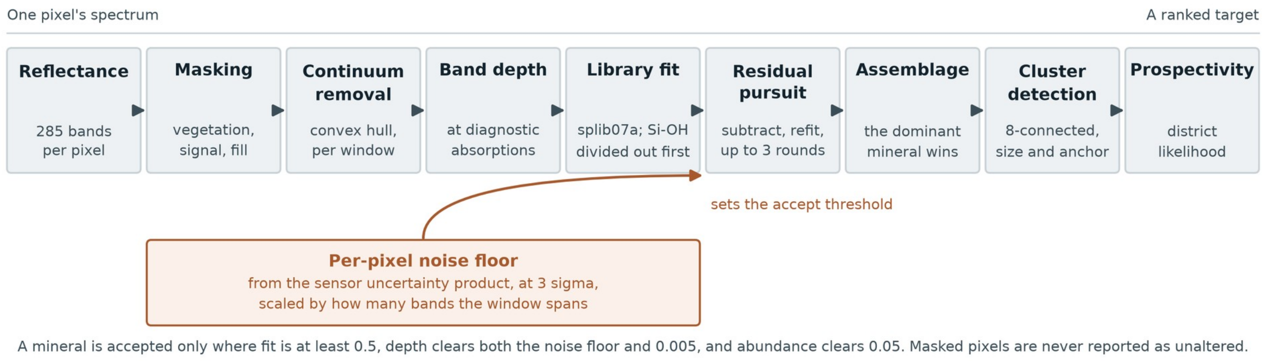

Figure 3 — *The processing chain, from one pixel's spectrum to a ranked target. The per-pixel noise floor enters as a separate branch and sets the accept threshold.*

Use cases across the exploration lifecycle

Exploration: identifying and ranking systems

+ **Regional reconnaissance:** Wall-to-wall mineral mapping across a belt or tenement package, producing a consistent mineralogical dataset over ground that has and has not been previously covered. Free archive sources support this at regional scale at no cost to the client.
+ **Alteration assemblage mapping:** Classification of advanced argillic, argillic, phyllic, propylitic and carbonate assemblages, with the spatial arrangement between them mapped. A zoned sequence is a far stronger target than an isolated anomaly, and zoning is visible on a map before it is visible on the ground.
+ **Vectoring by mica composition:** The position of the aluminium-hydroxyl feature near 2200 nm tracks white mica composition. The same vectoring logic long applied to drill core spectroscopy can be extended across surface exposure, giving a regional view of a vector that otherwise exists only along drill traces.
+ **Iron oxide and gossan mapping:** Ferric mineralogy mapped in context with the SWIR assemblages, supporting gossan identification and oxidation zoning.
+ **Prospectivity ranking:** Ranked alteration clusters within calibrated regions, delivered with the validation regime and performance figures attached, so that a ranking can be carried into an investment committee.
+ **High-resolution follow-up:** Where narrow structures, small outcrops or fine-scale zoning are the question, 8 metre tasked acquisition resolves features that regional imagery averages away.

Design and planning

+ **Field programme design:** Sampling traverses, mapping priorities and ground spectrometer visits placed against a mineralogical map rather than against topography and access. The saving here is measured directly in crew days.
+ **Tenement and farm-in triage:** Consistent mineralogical coverage across an entire package under a short decision window, putting blocks with rich historical data and blocks with none onto a comparable footing.
+ **Integration with geophysics:** Alteration mineralogy delivered as a georeferenced layer alongside magnetics, radiometrics and geochemistry, adding an independent evidence axis to an existing targeting model.

Operations

+ **Pit and stockpile mineralogy:** Compositional mapping of active faces, stockpiles and waste dumps, supporting material characterisation between conventional sampling rounds.

+ **Change monitoring:** Repeat acquisition against a baseline, with compositional change reported between epochs. Daily revisit availability in the tasked tier supports genuine monitoring cadence rather than annual snapshots.
+ **Tailings surface composition:** Surface mineral composition of tailings storage facilities tracked over time, including iron mineral assemblage inference across the impoundment surface.

Dozers working a pit floor. Active faces, stockpiles and waste dumps can be characterised compositionally between conventional sampling rounds, without putting anyone on the bench.

Rehabilitation and closure

+ **Rehabilitation monitoring:** Vegetation recovery, soil surface composition and disturbance extent tracked against a pre-disturbance or post-closure baseline, packaged as a periodic report suitable for regulatory submission.
+ **Compliance evidence:** Documented, repeatable, time-stamped evidence of surface condition, generated without site access.

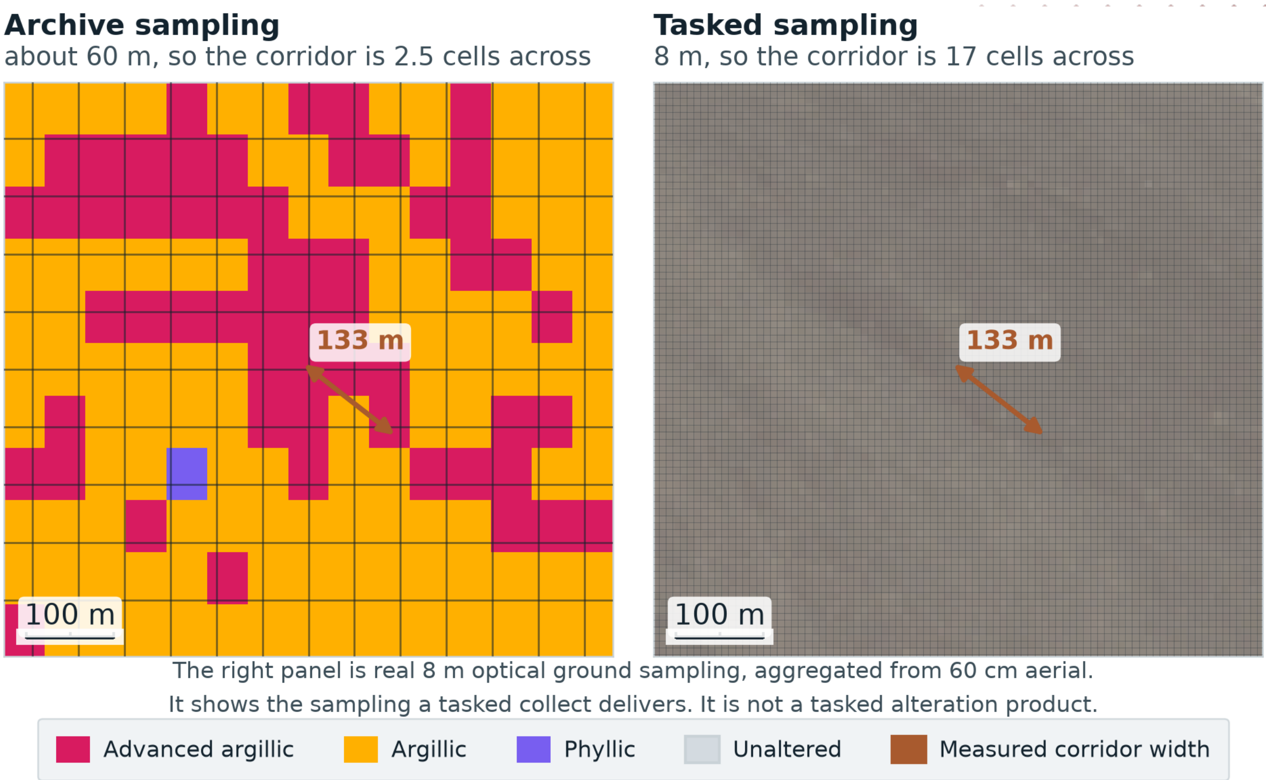

Figure 4 — *A 133 metre alteration corridor at archive and at tasked ground sampling. At about 60 m the corridor is 2.5 cells across; at 8 m it is 17.*

Validation and confidence

Axine treats validation as a product feature. Every output carries a stated validation posture, and every performance figure we publish is traceable to a documented test against an independent reference.

Independent reference comparison

- **Cuprite, Nevada:** Mineral maps compared directly against USGS Tetracorder products over the same scenes, at the reference site the discipline uses as its benchmark.
- **Marysvale, Utah:** A second independent comparison over a different alteration system, confirming that performance is a property of the method rather than of a single well-studied site.
- **EMIT L2B products:** Direct comparison against the independently produced EMIT Level 2B mineral products.

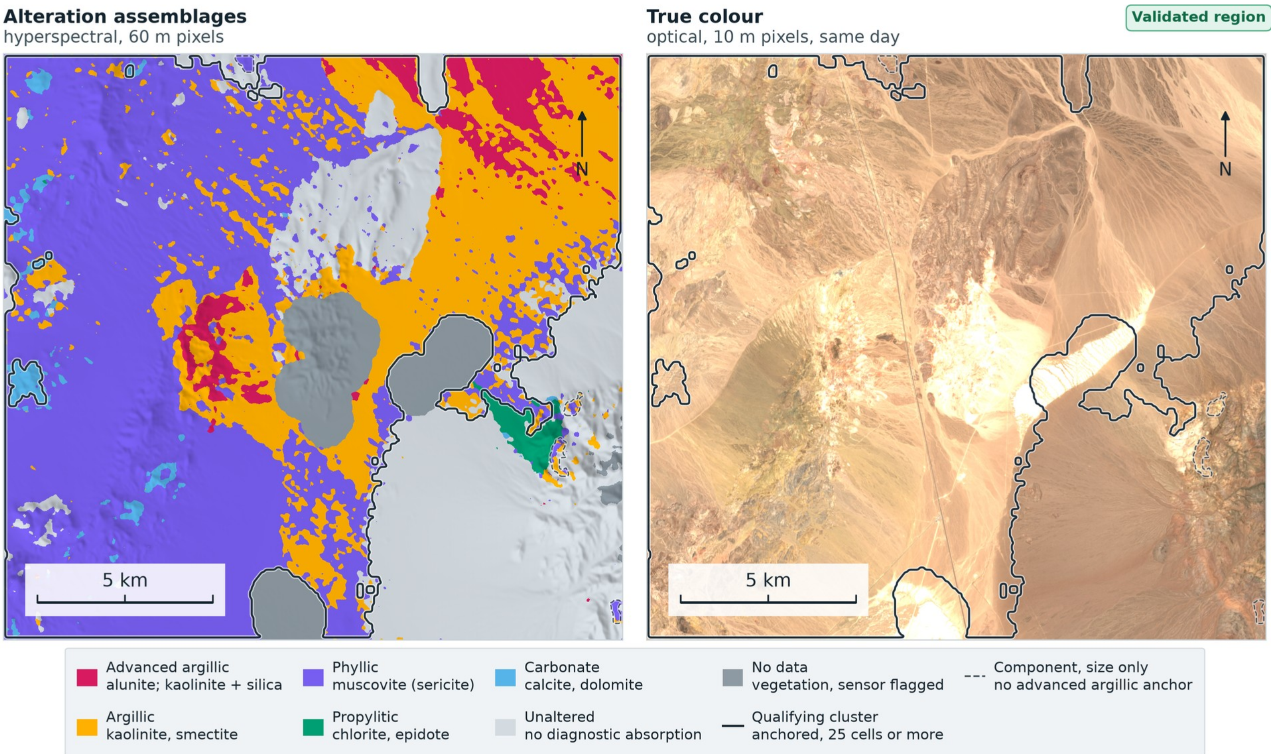

Figure 5 — *Cuprite, Nevada, the benchmark site for the discipline. Assemblages from 60 m hyperspectral data beside 10 m optical imagery of the same day, with qualifying clusters outlined in black.*

Results are reported as full confusion matrices with Cohen's kappa, balanced accuracy and cluster-scale pass gates, rather than as a single headline percentage. On an imbalanced mineral map a headline accuracy figure is dominated by the majority class and says very little about the minerals a client actually cares about.

Protocol

+ **Pre-registration:** Test design, thresholds and success criteria are fixed and recorded before evaluation data is examined.
+ **Frozen parameters:** Detection parameters derive from instrument characteristics and are not adjusted after results are seen.
+ **Hash-sealed inputs:** Input imagery and library files are hashed, so any published result can be reproduced against the exact data that produced it.
+ **Stability testing:** Leave-one-region-out and single-site-removal runs confirm that reported performance is not carried by any single site.
+ **Leakage controls:** Label permutation runs confirm that measured performance collapses when labels are destroyed, the standard test for information leakage.
+ **Append-only logging:** Every comparison run is written to an append-only log, providing a complete audit trail behind any figure we quote.

Reported performance

Within calibrated regions, the prospectivity ranking model achieves an area under the ROC curve of 0.7465, with a 95 per cent credible interval of 0.663 to 0.819, under spatially blocked validation. Quoting the interval alongside the point estimate, and naming the validation regime that produced both, is standard practice in the statistical literature and rare in this market. It is how we would want a supplier to report to us.

Validation posture on every layer

Each analytical layer in the platform renders with an explicit posture: calibrated region, validated region, or screening. Deterministic band mathematics quotes no accuracy figure because none is claimed for it. Fitted and learned products quote accuracy where they have been tested against ground truth for that region. A client always knows which of the three they are looking at, which is what makes an Axine layer safe to put in front of a joint venture partner.

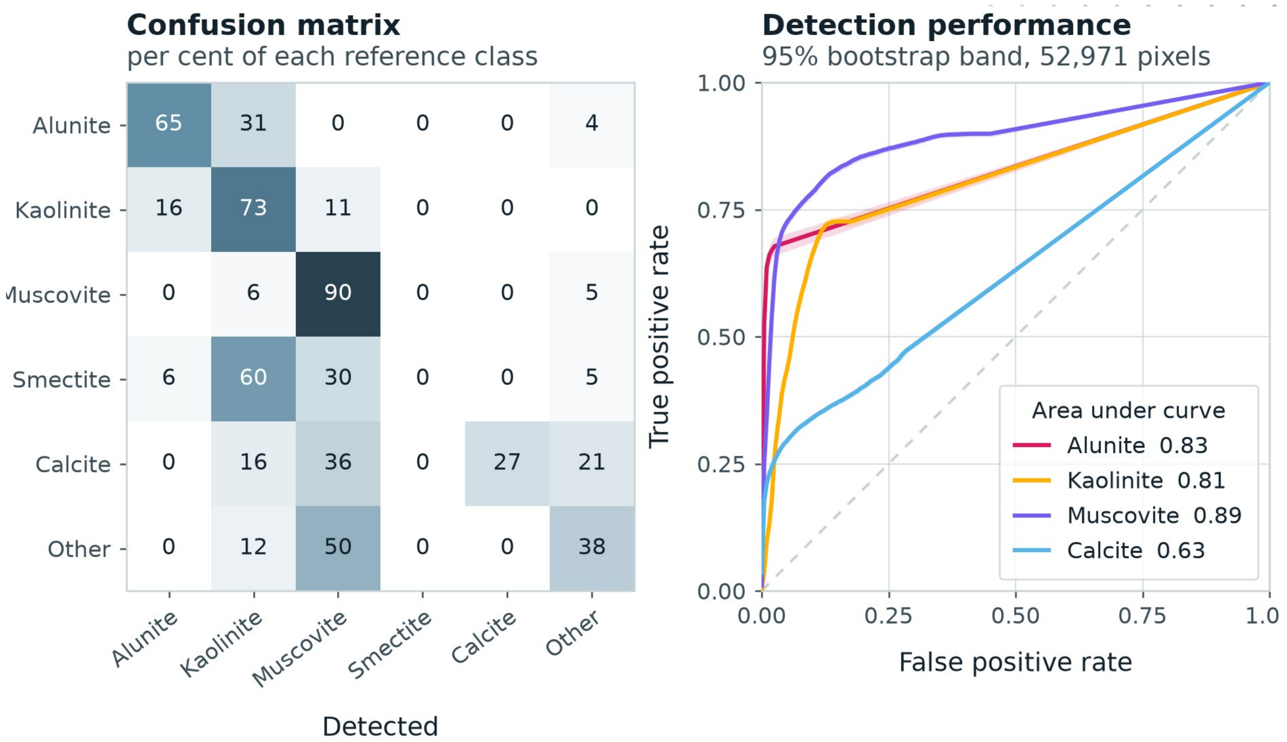

Figure 6 — *Per-class confusion matrix against the independent reference, and detection performance with 95 per cent bootstrap bands over 52,971 pixels.*

Operational benefits

+ **Coverage ahead of mobilisation:** Regional mineral mapping is delivered as a desktop product in days, converting a question that would otherwise wait for a field season into one answered before mobilisation.
+ **Interpretable evidence:** Every detection traces to a measured absorption feature and a named library spectrum, inspectable pixel by pixel. Geologists can interrogate the evidence rather than accept a score.
+ **Scale and reach:** A single acquisition covers ground that would take a season to traverse, with no sensors to install, no access to negotiate and no crew exposure on unassessed terrain.
+ **Predictable economics:** Everything derived from public satellite data is free, permanently. Tasked acquisition is priced per square kilometre against a defined area of interest, so programme cost is known before commitment.
+ **Auditable decisions:** Pre-registered tests, hashed inputs and an append-only comparison log mean a target generation decision can be defended to a board, a partner or a regulator.
+ **Data sovereignty:** Areas of interest and results remain within Axine infrastructure. For most exploration clients the coordinates being examined are more commercially sensitive than the results themselves.
+ **One method across tiers:** The same pipeline runs on archive and tasked imagery, so a programme can screen regionally at no cost and escalate only the ground that earns it.

Stockpiled overburden above a cut bench. A single acquisition covers ground a crew would need a season to walk, with nothing to install, no access to negotiate and nobody exposed on an unassessed face.

Inherent product properties

Closed canopy. Vegetated ground is screened and reported as not evaluated rather than inferred, which is why the method is strongest over arid and semi-arid terrain with real exposure.

+ **Complete spectral coverage:** Contiguous narrow-band coverage from 400 to 2500 nm captures the full diagnostic range for alteration mineralogy, including the carbonate and magnesium-hydroxyl features above 2300 nm.
+ **Mineral-specific detection:** Identification against measured library spectra, with compositional and crystallinity variants resolved as separate classes rather than collapsed into mineral groups.
+ **High spatial resolution:** 8 metre hyperspectral ground sampling in the tasked tier, with 3 metre panchromatic context, resolving features that regional imagery averages into background.
+ **Deterministic and reproducible:** A physics-based detection layer produces the same answer on the same data every time, with no dependence on training data resembling the target area.
+ **Sensor agnostic:** One pipeline ingests EMIT, EnMAP, PRISMA, ASTER, Sentinel-2, Landsat and tasked high-resolution imagery, so results remain comparable as a programme moves between tiers.
+ **Analysis-ready delivery:** Cloud-optimised GeoTIFF outputs with per-pixel spectral inspection, API access and generated reports, designed to enter an existing GIS rather than to sit in a separate portal.
+ **Monitoring-capable:** Repeat acquisition against a baseline turns a static map into a compositional time series, with revisit of up to daily available in the tasked tier.

Optimal operating conditions

Reflectance spectroscopy measures exposed surface material, so the method performs best over arid to semi-arid terrain, exposed rock, outcrop, mine faces, waste and tailings surfaces, and areas of thin or residual cover. Vegetated ground is screened and reported as not evaluated rather than inferred. Where surface exposure is limited, Axine outputs are designed to be integrated with geophysical and geochemical layers as one independent axis of evidence within a broader targeting model.

Platform, access and data handling

The platform

Work is ordered and delivered through a web application. Users draw an area of interest on an interactive map, search available imagery, submit an order and follow it through a staged job queue. Results are served as cloud-optimised GeoTIFFs with map tiling, and any pixel can be opened to inspect its full spectrum, the features that were measured, and the library spectra those features were fitted against. Results are catalogued, reports are generated as PDF, and workspaces support teams, roles and notifications. An API is available for clients working in their own GIS environment.

Lisa

Lisa is a client-facing assistant that runs entirely on Axine infrastructure rather than on a third-party model service. She searches imagery, estimates pricing, retrieves results, saves and lists areas of interest, geocodes, and reports the current model version with its validation metrics. Order submission is confirmation-gated by design, and any request requiring judgement is escalated to a human analyst.

Self-hosting is a procurement decision rather than an engineering preference. Client areas of interest, which reveal where a company is looking, never leave Axine infrastructure and are never transmitted to an external model provider.

Access tiers

Tier	Coverage
Free	Everything derived from public satellite data: mineral maps, assemblage classification, prospectivity ranking within calibrated regions, visualisation, Lisa and API access. Axine does not charge for information obtained freely.
Tasked	Directed 8 metre hyperspectral acquisition over a defined area of interest, with full analysis, priced per square kilometre against a stated minimum area.
Monitoring	Scheduled repeat acquisition with change detection between epochs, on volume terms.

About Axine Laboratories

Axine Laboratories builds commercial hyperspectral analytics for the mineral exploration and mining industry, and for energy, agriculture and water monitoring applications. The company is registered in the United States and run by a technical team of geologists and engineers.

Our approach rests on three commitments. Detection is physics-based and reproducible, fitted against measured spectral libraries rather than inferred by an untraceable model. Every published figure is backed by a pre-registered test against an independent reference, with the validation regime stated alongside it. And analysis derived from public satellite data is free and will remain so, because we do not charge for information obtained freely.

Revenue comes from tasked high-resolution acquisition and the analysis performed on it, which aligns our interest with delivering imagery a client could not otherwise obtain rather than with metering access to imagery that is already public.

Axine Laboratories

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