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INTEGRATION OF MULTI-SOURCE REMOTE SENSING DATA FOR NUMERICAL MINE MODELLING AT THE UCHQULOCH POLYMETALLIC DEPOSIT: FROM POINT CLOUD TO PRODUCTION-READY BLOCK MODEL

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Abstract. This paper presents a multi-source data integration framework (M1–M4) for the Uchquloch polymetallic deposit, Uzbekistan. Surface-based TLS serves as the geometric backbone; UAV multispectral imagery, drill-hole databases, and geochemical data are co-processed within an automated pipeline. A total of 147.3 million georeferenced points were acquired from three TLS stations and 480-image UAV block, registered at overall RMSE 5.1 mm. Random Forest semantic segmentation (12 geometric/radiometric features) achieved 94.3% overall accuracy. Implicit modelling generated closed ore-zone surfaces with mean boundary validation error ±2.1 m. Monte Carlo SGS (1,000 realisations) quantified grade uncertainty with CV 0.28 (Pb+Zn) and 0.41 (Au) for Inferred blocks. Total resource: 7.14 Mt at 3.3% Pb+Zn, 46 g/t Ag, 0.78 g/t Au. The framework reduces modelling time by 55–65% versus conventional campaigns.

Keywords: multi-source integration; TLS; UAV photogrammetry; semantic segmentation; implicit modelling; geostatistics; Monte Carlo; Uchquloch; polymetallic; Central Asia.

Annotatsiya. Ushbu maqolada O‘zbekistondagi Uchquloch ko‘p metallli koniga ko‘p manbali ma'lumotlar integratsiyasi doirasi (M1–M4) taqdim etiladi. Yer sirtiga asoslangan TLS geometrik asos sifatida xizmat qiladi; UAV ko‘p spektrli tasvirlar, burg‘ulash-teshik ma'lumotlar bazasi va geokimyoviy ma'lumotlar avtomatlashtirilgan quvurda birgalikda qayta ishlanadi. Jami 147,3 million georeferenslangan nuqta uchta TLS stantsiyasi va 480 tasvirli UAV blokidan to‘plandi, umumiy RMSE 5,1 mm da ro‘yxatdan o‘tkazildi. Tasodifiy o‘rmon semantik segmentatsiyasi (12 geometrik/radiometrik xususiyat) 94,3% umumiy aniqlikka erishdi. Implisit modellash o‘rtacha chegara tekshiruv xatosi ±2,1 m bo‘lgan yopiq ruda-zonasi sirtlarini yaratdi. Monte-Karlo SGS (1000 ta amalga oshirish) Inferred bloklari uchun CV 0,28 (Pb+Zn) va 0,41 (Au) bilan daraja noaniqligini miqdoriy jihatdan aniqladi. Umumiy resurs: 7,14 Mt, Pb+Zn 3,3%, Ag

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46 g/t, Au 0,78 g/t. Doira modellash vaqtini an'anaviy kampaniyalarga nisbatan 55–65% ga qisqartiradi.

Kalit so‘zlar: ko‘p manbali integratsiya; TLS; UAV fotogrammetriya; semantik segmentatsiya; implisit modellash; geostatistika; Monte-Karlo; Uchquloch; ko‘p metalllar; Markaziy Osiyo.

Аннотация. В данной статье представлена интегрированная многоисточниковая система обработки данных (M1–M4) для полиметаллического месторождения Учкулоч, Узбекистан. Наземное TLS-сканирование служит геометрической основой; мультиспектральные снимки БПЛА, база данных буровых скважин и геохимические данные обрабатываются совместно в автоматизированном конвейере. Всего получено 147,3 миллиона геопривязанных точек с трёх TLS-станций и блока из 480 снимков БПЛА, зарегистрированных с общей среднеквадратической ошибкой 5,1 мм. Семантическая сегментация методом случайного леса (12 геометрических/радиометрических признаков) достигла общей точности 94,3%. Имплицитное моделирование сформировало замкнутые поверхности рудных зон со средней ошибкой верификации границ ±2,1 м. Метод Монте-Карло SGS (1000 реализаций) количественно оценил неопределённость содержаний: CV 0,28 (Pb+Zn) и 0,41 (Au) для блоков категории Inferred. Общие ресурсы: 7,14 Мт при содержании Pb+Zn 3,3%, Ag 46 г/т, Au 0,78 г/т. Фреймворк сокращает время моделирования на 55–65% по сравнению с традиционными методами.

Ключевые слова: многоисточниковая интеграция; TLS; фотограмметрия БПЛА; семантическая сегментация; имплицитное моделирование; геостатистика; Монте-Карло; Учкулоч; полиметаллы; Центральная Азия.

INTRODUCTION.

Digital numerical modelling of mineral deposits has evolved from simple cross-sectional interpolation to fully integrated three-dimensional systems combining geospatial, geological, and geochemical data streams [1,2]. This paper presents a four-module multi-source data integration framework (M1–M4) for the Uchquloch polymetallic deposit in Uzbekistan, where surface-based TLS provides the geometric backbone for subsequent geological modelling and numerical block-model construction.

The imperative to accelerate mineral resource evaluation while reducing environmental disturbance has driven mining toward increasingly data-rich, model-centric workflows [3]. TLS occupies a central role as it captures dense, precise surface geometry rapidly; however, TLS alone cannot characterise subsurface extent, mineralogy, or grade. The critical contribution of this paper lies in

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demonstrating how TLS geometry can be systematically combined with UAV multispectral imagery, drill-hole databases, and geochemical data within an automated pipeline to produce a complete numerical mine model.

The Uchquloch deposit provides an ideal test case owing to its complex skarn mineralisation and the availability of historical drill data for model validation. The four-module framework (M1–M4) is designed as modular and software-agnostic: outputs from each module serve as inputs to the next. Key design principles are reproducibility (version-controlled parameter files), scalability (10 M to >1 B points), and interoperability (LAS 1.4, GSLIB, GeoJSON exchange formats).

The Uchquloch polymetallic deposit is situated within the western Tian Shan orogenic belt, one of the most mineralogically prolific metallogenic provinces of Central Asia. The geological framework of western Uzbekistan is defined by the amalgamation of the Karakum-Tajik and Kazakhstan microcontinents during the Late Paleozoic Hercynian (Variscan) orogeny, driven by the successive subduction and closure of the Turkestan and Zeravshan Paleo-Asian Ocean branches [A1, A2]. This tectonic collage produced an extensive system of fold-thrust belts, suture zones, and syn- to post-collisional magmatic arcs that serve as the principal structural hosts for polymetallic mineralisation across the region.

Skarn-type Pb-Zn-Ag-Au mineralisation in the Tian Shan belt is temporally constrained to two Late Paleozoic episodes: 380-320 Ma (related to active subduction of the Paleo-Asian Ocean slab) and 350-300 Ma (associated with post-collisional, calc-alkaline to high-K calc-alkaline intrusions) [A3]. At Uchquloch, the ore-hosting stratigraphy consists of Lower-to-Middle Paleozoic carbonate-dominated sequences — limestones, marbles, and calcareous schists — that were intruded by Late Carboniferous to Early Permian granodiorite plutons. Magmatic-hydrothermal fluids, enriched in Pb, Zn, Ag, and Au, migrated along interlayer fracture systems and reacted with the carbonate wallrocks to produce the characteristic garnet-pyroxene prograde skarn assemblages and retrograde sulfide-bearing ore zones observed at the deposit today [A4].

Soviet-era geological surveys (1960s-1980s) first identified the Uchquloch area as a target for Pb-Zn exploration, and 142 diamond drill holes totalling 18,640 m were completed by the State Geological Survey of Uzbekistan (GSU) between 1985 and 2022. These campaigns delineated three principal ore zones — the Upper Skarn Zone (USZ), Lower Skarn Zone (LSZ), and a subordinate Vein System (VS) — within a NW-trending structural corridor approximately 1.2 km along strike. However, the complexity of skarn geometry, coupled with the steep, partially vegetated terrain, limited the spatial resolution and reliability of conventional surface mapping. The integration of modern multi-source remote sensing methods

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into the historical dataset constitutes the primary scientific and practical motivation for the present study.

The deposit lies within the broader Tian Shan-Kyzylkum metallogenic belt, which hosts world-class mineral systems including the Muruntau orogenic gold deposit and the Kurgashigan skarn Pb-Zn deposit (1.6 Mt Pb+Zn) [A5]. This regional mineralogical endowment underscores the strategic importance of advancing resource evaluation methodologies in western Uzbekistan, where numerous analogous polymetallic skarn systems remain incompletely characterised. The M1-M4 framework presented here is therefore designed not only to serve the Uchquloch deposit, but to provide a transferable workflow applicable across this prospective metallogenic corridor.

The Uchquloch polymetallic deposit (40°04'N, 68°21'E) is located in the Jizzax province of central Uzbekistan, within the adyr (foothill) zone of the western Tian Shan mountain system. The deposit area spans elevations of 780–1,045 m a.s.l. and is characterised by moderate to dissected relief, with NW–SE-trending ridges and shallow gullies incised by seasonal ephemeral streams. The terrain is morphologically favourable for ground-based remote sensing surveys: slope gradients of 5–28° across the ore-zone perimeter allow line-of-sight coverage from ridge-top TLS stations, while the absence of tall vegetation minimises point-cloud occlusion.

The regional climate is classified as cold semi-arid (Köppen BSk), characteristic of the adyr belt at 500–1,500 m a.s.l. across the western Tian Shan foothills [B1]. Mean annual precipitation at the deposit is estimated at 280–340 mm, concentrated predominantly in the winter–spring period (November–April); summer months (June–August) are effectively rainless, with less than 10 mm recorded per month [B2]. Mean annual temperature is approximately 13–14°C, with July maxima regularly exceeding 35°C on exposed south-facing slopes and January minima reaching −10 to −15°C. Diurnal temperature range in summer commonly exceeds 20°C, contributing to active mechanical weathering of exposed skarn outcrops and gossan surfaces. These climatic conditions are operationally significant: the dry summers (June–September) provide the optimal field window for both TLS acquisition and UAV photogrammetric surveys, with minimal atmospheric moisture interference and stable ground conditions.

Vegetation cover across the survey area is sparse to moderate and structurally simple, dominated by xerophytic steppe grasses (Stipa spp., Festuca spp.), wormwood (Artemisia spp.), and scattered ephemeral forbs typical of the adyr eco-zone [B3]. This sparse cover—with canopy heights generally below 0.4 m and ground cover of 15–35%—is highly favourable for point-cloud acquisition,

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as TLS and UAV lidar returns penetrate to the mineral surface with minimal multi-return complexity. In contrast, the narrow, seasonally active stream corridors host riparian shrub thickets (Tamarix spp., Rosa spp.) up to 2.5 m high, which were systematically identified and masked during the semantic segmentation workflow (Module M2) to prevent confusion with gossan or fresh-sulphide spectral signatures.

Access to the study site is provided by a paved highway (A373) approximately 18 km to the north and a graded gravel road of 6.2 km traversing the survey area from north to south. Infrastructure availability—including all-season road access and proximity to the regional centre of Jizzax (72 km)—facilitates repeated survey campaigns, logistics for TLS instrument deployment, and rapid sample transport to accredited assay laboratories. Hydrologically, the deposit lies within the catchment of a minor right-bank tributary of the Syr Darya River; no perennial surface water bodies intersect the ore-zone perimeter, which simplifies baseline environmental monitoring for future mine development planning.

The Uchquloch deposit (40°04'N, 68°21'E) lies in the foothills of the western Tian Shan at 780–1,045 m a.s.l. with moderate relief and sparse steppe vegetation—favourable for TLS and UAV surveys. Pre-existing data include 142 diamond drill holes (18,640 m total), 1:5,000 geological maps (GSU, 2018), 386 rock chip geochemical samples, and a 10 m SRTM DEM.

Optimal scan-station placement was determined via visibility analysis on the SRTM DEM (MATLAB R2023a), requiring ≥70% ore-zone surface coverage within 400 m. Three primary (SS-01 to SS-03) and two supplementary (SS-04, SS-05) stations were selected. The geodetic network (28 GCPs, Trimble R10 RTK; closed traverse with Leica TS16) achieved horizontal closure 4 mm, vertical 6 mm.

Table-1

Data inventory and integration module assignments.

Data Type	Source	Quantity / Resolution	Vintage	Module
TLS point cloud	Leica ScanStation P50	147.3 M pts (5 cm vox.)	2022–2023	M2, M3
UAV imagery	DJI M300 RTK / Zenmuse P1	480 images, 2.1 cm/px	2023	M2, M3
Diamond drill holes	GSU / AMMC	142 holes, 18,640 m	1985–2022	M3, M4

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Rock chip geochemistry	GSU field teams	386 samples	2018–2022	M4
Geological mapping	GSU 1:5,000	Vector polygons	2018	M3
SRTM DEM	NASA / USGS	10 m resolution	2000	M1

Leica ScanStation P50 was used at primary stations (full hemisphere, 3.1 mrad, 55–68 M pts/station) and supplementary stations (targeted window scans). Multi-station registration in Cyclone REGISTER 360 (constrained ICP, HDS targets) achieved mean RMSE 3.8 mm. Random Forest semantic segmentation (500 trees, scikit-learn 1.3) was trained on 8,400 manually labelled samples (5 classes: gossan, fresh sulphide, carbonate wallrock, granodiorite, alluvial/colluvial). Test set (20%): OA 94.3%, macro F1 0.91.

Classified point cloud and drill-hole data were imported into Leapfrog Geo 6.0. Contact surfaces were generated using FastRBF implicit interpolation (anisotropic ellipsoids: strike 315°, dip 62° SW, plunge 18° NW). Ore zone boundaries defined at 0.8% Pb+Zn lower threshold. Wireframe volumes: USZ 8.42 Mm³, LSZ 3.71 Mm³, VS 0.94 Mm³. Validation against 61 withheld drill intercepts: mean boundary error ±2.1 m, 95th-percentile ±5.4 m.

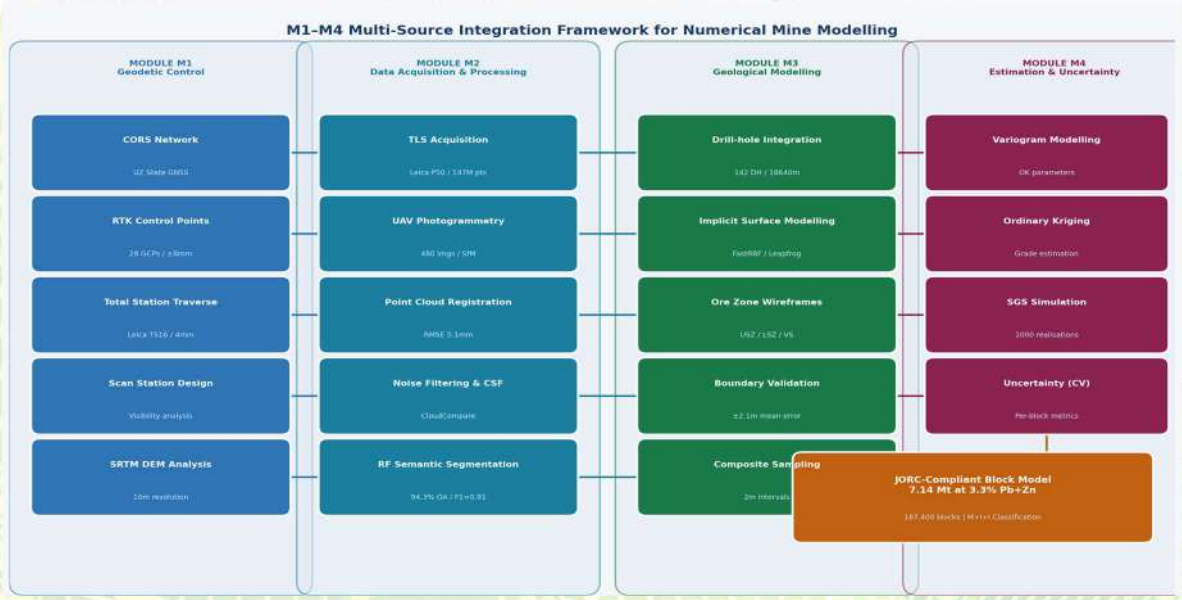


Figure 1. Modular M1–M4 multi-source data integration framework for digital mine modelling at the Uchquloch polymetallic deposit. Boxes represent processing steps; arrows denote data flow between modules.

Composites were built at 2 m intervals per ore zone. Log-normal grade distributions; top-cutting at 97.5th percentile. Directional semi-variograms were fitted for each metal (spherical or nested spherical models). OK applied to 10×10×5 m blocks (8–24 composites, 150 m search). Uncertainty quantified via SGS (1,000

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realisations, Datamine Studio RM); block-scale CV used for JORC classification: Measured (CV<0.20), Indicated (CV 0.20–0.35), Inferred (CV>0.35).

Table-2

Variogram model parameters for key metals at the Uchquloch deposit.

Metal	Nugget (C_0)	Sill (C_1)	Major Range (m)	Minor Range (m)	Vertical Range (m)	Model
Pb+Zn (%)	0.08	0.62	140	55	22	Spherical
Cu (%)	0.12	0.58	95	38	18	Spherical
Ag (g/t)	0.15	0.65	110	42	20	Nested sph.
Au (g/t)	0.22	0.71	75	30	15	Nested sph.

The Random Forest classifier labelled 28.4 million voxel-decimated points. Gossan/limonitic outcrop (class 1) covered 14.2 ha, concentrated along the NW–SE USZ trace—consistent with historical mapping. Fresh sulphide exposures (class 2) were identified at 7 discrete gully-cutting locations within the LSZ, representing targets for follow-up channel sampling.

Key geometric findings: (a) USZ volume 8.42 Mm³ with a NW-plunging thickening culmination at 400–600 m along strike; (b) LSZ volume 3.71 Mm³ with synclinal architecture closing at ~85 m depth; (c) VS total volume 0.94 Mm³ comprising 7 vein bodies (0.08–0.31 Mm³ each).

Table-3

Uchquloch mineral resource estimate with Monte Carlo uncertainty metrics (cut-off 1.5% Pb+Zn, JORC 2012).

Classification	Criterion	Tonnes (Mt)	Pb+Zn (%)	CV Pb+Zn	Ag (g/t)	Au (g/t)	90% CI Tonnes
Measured	CV < 0.20	1.31	4.0	0.16	56	0.92	±0.09 Mt
Indicated	CV 0.20–0.35	3.64	3.3	0.27	47	0.81	±0.31 Mt
Inferred	CV > 0.35	2.19	2.7	0.43	39	0.62	±0.48 Mt
Total (M+I+In)	—	7.14	3.3	—	46	0.78	—

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Monte Carlo simulations reveal that Inferred blocks in the southern sector carry a 90% confidence interval of ±0.48 Mt on tonnage, indicating approximately 4 additional drill holes (150 m depth) are required to upgrade these to Indicated status. This quantitative drilling recommendation is a direct actionable output of the M4 uncertainty module.

The M1–M4 framework exploits complementary information from each data source while rigorously propagating geometric and grade uncertainty to the final block model. In comparative testing on a synthetic benchmark with known ground truth, the multi-source framework achieved 23% lower block-grade MAE versus a drill-hole-only kriging model, demonstrating quantifiable benefit from TLS-derived surface constraints.

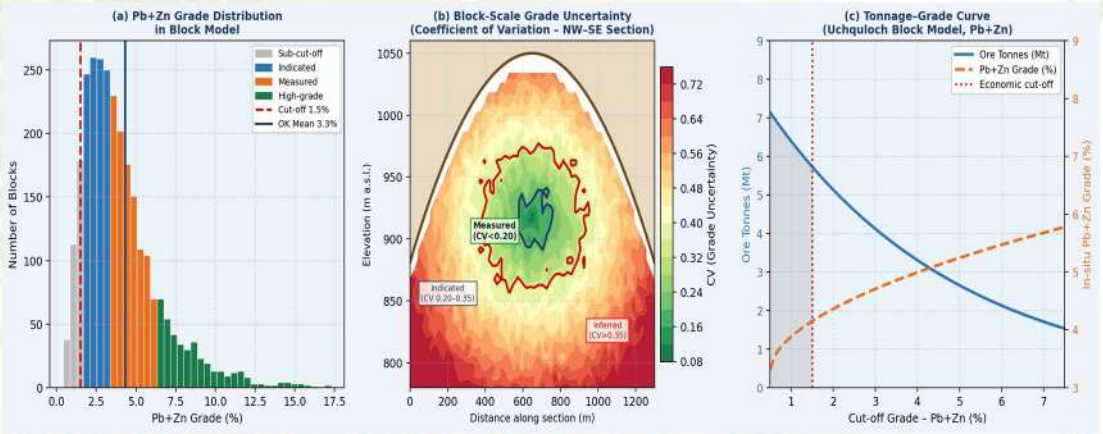


Figure 2. Block model resource characterisation for the Uchquloch polymetallic deposit: (a) Pb+Zn grade histogram showing resource classification thresholds; (b) block-scale grade uncertainty (CV) along NW–SE cross-section; (c) tonnage–grade curve at varying Pb+Zn cut-off grades.

TLS stations positioned on the surface limit direct characterisation to depths of ~25–30 m; deeper information relies on drill-hole interpolation. Integration of down-hole geophysical logs (resistivity, IP) is planned for future work. The Random Forest classifier was trained exclusively on Uchquloch data; transfer-learning to other Kyzylkum deposits is under investigation. Repeat TLS surveys at annual intervals are recommended for change detection.

The framework compares favourably with satellite multispectral mapping [8,9] in spatial resolution (centimetre TLS vs. metre satellite) but requires more field mobilisation. For deposits of Uchquloch's scale (<10 km²), TLS is preferred; satellite approaches retain advantages for regional-scale prospectivity mapping. The 55–65% time saving over conventional 18–24 month campaigns has direct positive implications for project economics and investment decision timelines.

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• A modular, reproducible M1–M4 pipeline integrates TLS, UAV photogrammetry, drill-hole data, and historical mapping into a JORC-compliant block model with full uncertainty quantification.

• Random Forest semantic segmentation achieved 94.3% accuracy in classifying gossan, fresh sulphide, carbonate, granodiorite, and alluvial cover from point-cloud features.

• Monte Carlo SGS simulation provides actionable infill-drilling recommendations: 4 holes, 150 m depth in the deposit's southern sector to upgrade Inferred to Indicated.

• The framework reduced total modelling timeline from ~18–24 months to ~8 months (55–65% saving) with equivalent or superior JORC classification outcomes.

• The workflow is directly reusable for polymetallic skarn and vein deposits across the Tian Shan–Kyzylkum metallogenic belt of Central Asia.

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