GALA: A Multi-Agent GeoAI Framework for Mineral Exploration through SAM3-Augmented Knowledge Graphs and Human-in-the-Loop Validation

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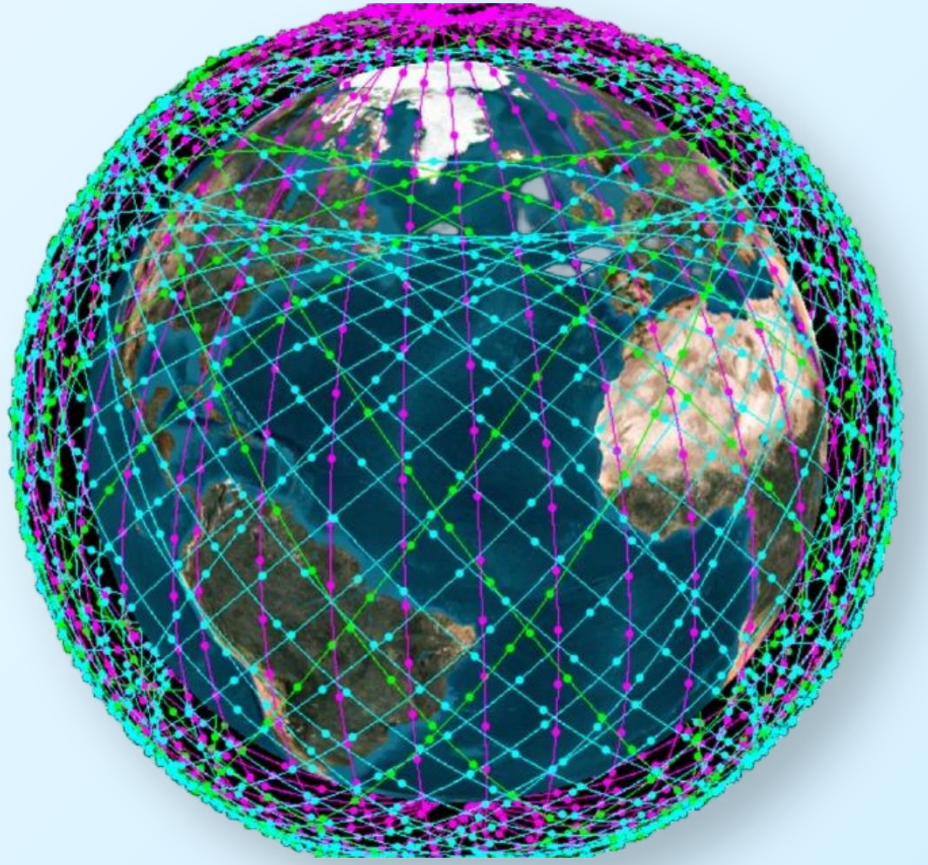
The First International Conference on Geospatial Artificial Intelligence

Introduction: Context and Core Challenges

The Data Deluge and Knowledge Bottleneck in the Aerospace Information Era

We are entering an era of rapidly expanding aerospace information. Massive Earth-observation data provide valuable evidence for understanding the Earth system, but their growth also creates two core challenges:



Computational Gap

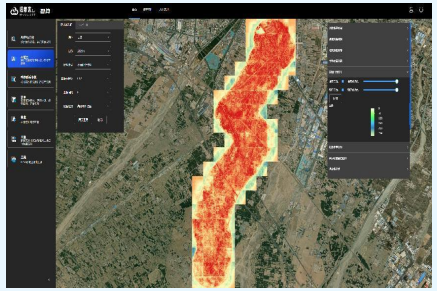
Manual interpretation and standalone processing cannot scale to PB-level multi-source heterogeneous data.

Cognitive Gap

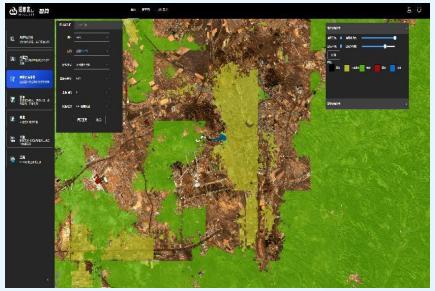
Data alone is not knowledge. The key challenge is to extract decision-oriented information from dynamic geospatial data.

Introduction: Context and Core Challenges

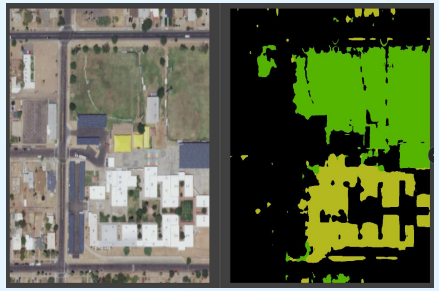
Remote Sensing Interpretation with Visual Foundation Models



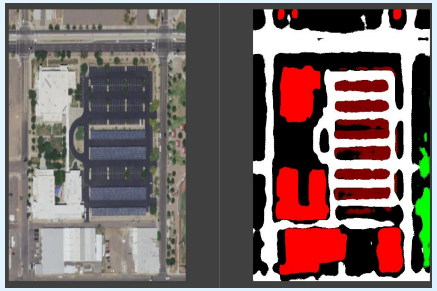
Relative Elevation Estimation



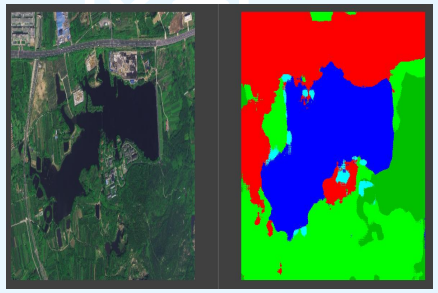
Settlement Recognition



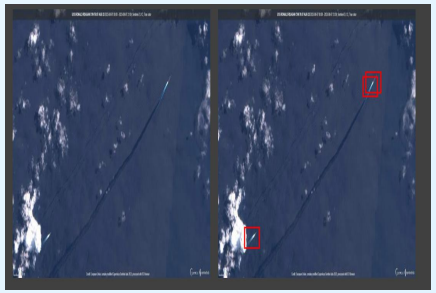
Building Segmentation



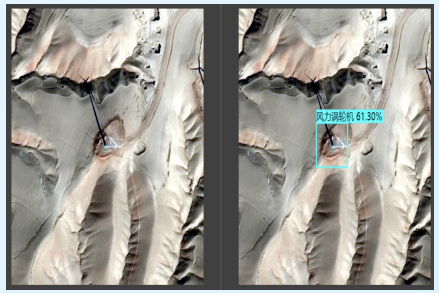
Object Segmentation



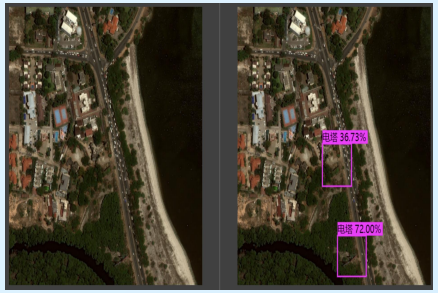
Land-cover Classification



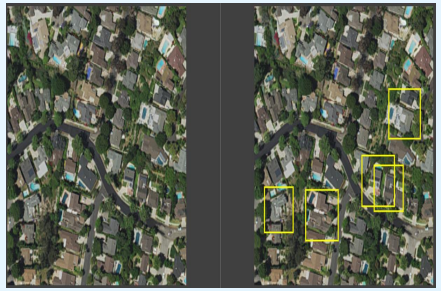
Ship Detection



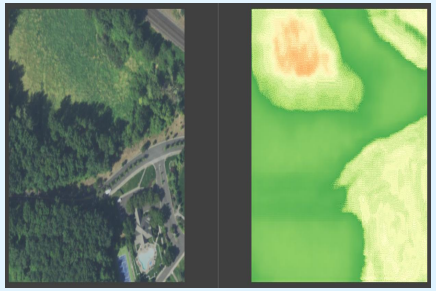
Wind Turbine Detection



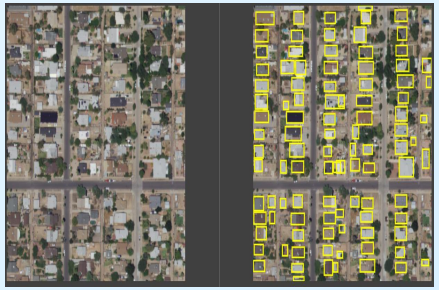
Power Tower Detection



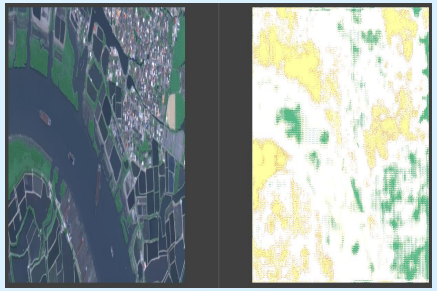
Solar Panel Detection



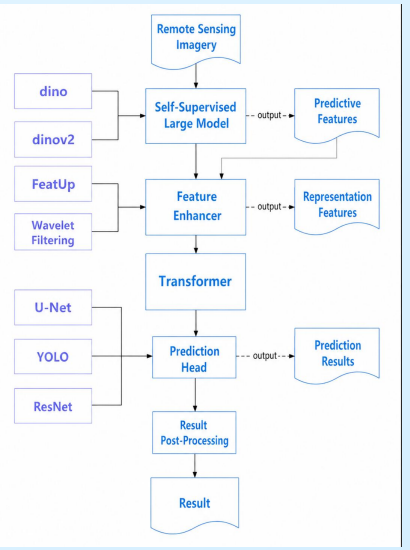
Tree Canopy Mapping

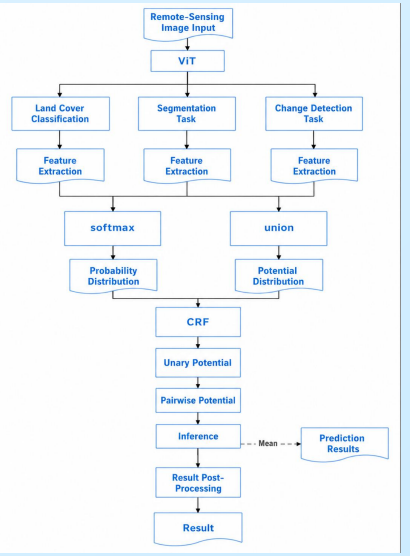


Building Recognition



Elevation Regression





Introduction: Context and Core Challenges

Limitations of Conventional Methods

Passive Execution, Limited Autonomy

Conventional models are usually static: they wait for data and instructions, execute a single task, and lack active perception, understanding, and planning.

Single-Task Capability, Weak Collaboration

A single model is often specialized for one task and struggles with complex geoscience workflows that require multi-step collaboration.

Black-Box Decisions, Limited Explainability

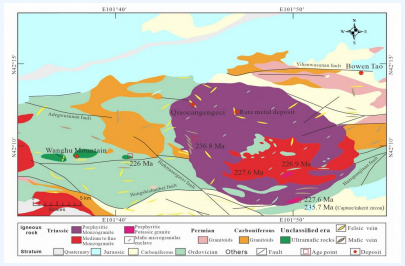
Many deep learning models remain black boxes. In high-stakes domains such as mineral exploration and emergency response, this lack of explainability is a major risk.

Introduction: Context and Core Challenges

A Way Forward: Multi-Agent Collaborative GeoAI

To overcome these bottlenecks, GeoAI should evolve from a single perceptual tool into a collaborative cognitive system. Multi-agent GeoAI simulates an expert team: complex geoscience tasks are decomposed and assigned to specialized agents, which communicate, debate, and integrate evidence to support decision-making.

Multi-Agent Collaborative GeoAI Framework (GALA)



User

Analyze the mineralization conditions of this area

Report Answer

Regional Geological Map Description (English Translation)

This is a regional geological map of the Middle-Lower Yangtze River Metallogenic Belt, focusing on the geological characteristics of southern Anhui Province (centered on Anqing and Qingyang), with a scale of 10 km. From a geologist's perspective, I will systematically analyze its content from three core dimensions: tectonic framework, magmatic activity, and mineral distribution, and interpret its geological significance. The map clearly shows the spatial coupling relationship between Yanshanian intrusive rocks, fault systems and polymetallic deposits, revealing the evolutionary mechanism of this area as an important metallogenic belt in China.

1. Tectonic Framework: Fault Systems Controlling Regional Evolution

Major Fault Zones

A series of NE-SW striking faults (labeled F_1–F_7) developed in the map form the regional tectonic framework.

- **Western fault group (F_1–F_3)**: Running through the area from Anqing to Qingyang, it cuts through Early Yanshanian rock masses and controls magmatic emplacement and ore-fluid migration.
- **Eastern fault group (F_4–F_7)**: Distributed in parallel to the east of Qingyang; for example, F_7 (Qingyang Fault) is closely associated with tungsten and molybdenum deposits.

Tectonic Significance

These faults belong to the southern extension of the Tan-Lu Fault Zone, reflecting an extensional-strike-slip tectonic setting triggered by the subduction of the Pacific Plate beneath the Eurasian Plate during the Jurassic–Cretaceous period, which provided channels for magmatic emplacement and mineralization.

Geographical References

- **Yangtze River**: As a first-order regional water system, it divides the east and west tectonic units, and its strike is nearly parallel to the fault system, implying that fluvial development is tectonically controlled.
- **City/county boundaries**: Labeled points ... as Anqing, Qingyang and Dongzhi provide surface references for geological surveys.

Supervisor

Data Agent
- Data retrieval
- Multi-source spatiotemporal data alignment

Geological Interpretation Agent
- Lithology Identification
- Structural Analysis

Remote Sensing Agent
- Recognition, Classification and Target Extraction
- Change Detection
- Image Analysis

Deposit Analysis Agent
- Deposit Identification
- Metallogenic Analysis

Vote

Review

Update Prompt

QA Agent
- Logical Review
- Voting Selection
- Low-confidence Marking

Correct

Human Export

Writer Agent
- Reference
- Opinion synthesis
- Report generation

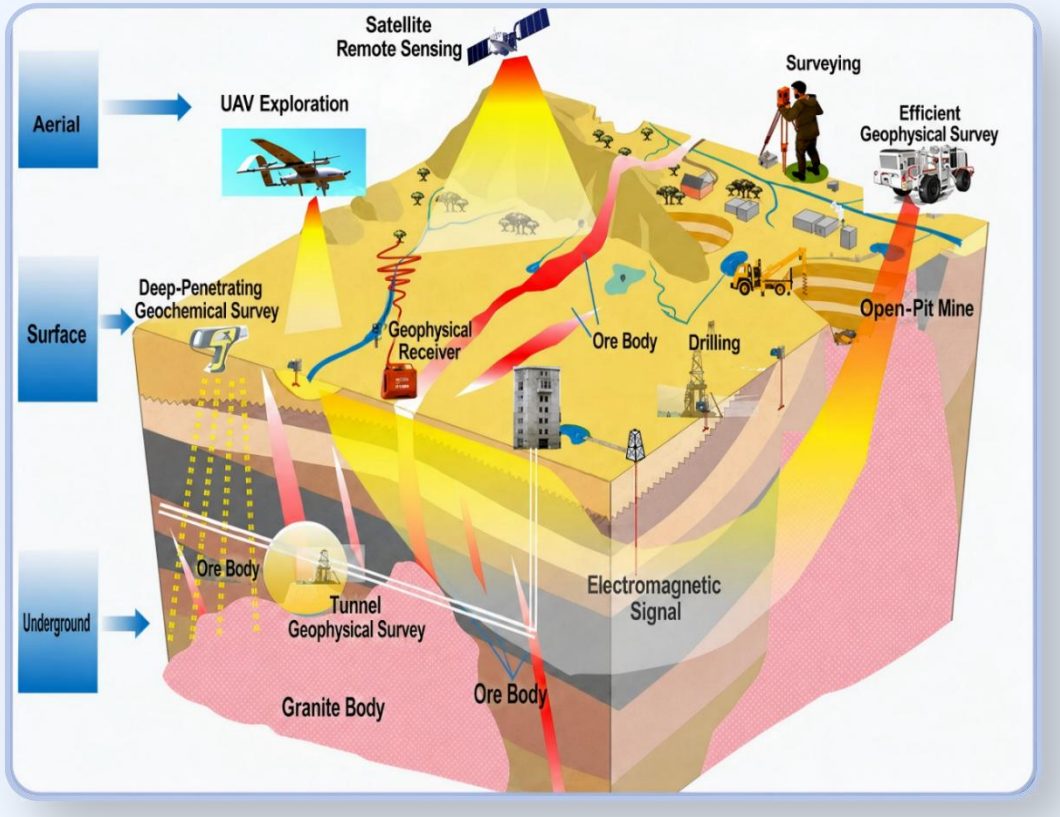
Update

Memory

GeoGraphRAG

Multi-Agent Collaborative GeoAI Framework (GALA)

GALA-Based Intelligent Mineral Exploration Workflow



01 Task Input

Experts issue a natural-language request, e.g., “Find porphyry copper targets related to Yanshanian magmatism and typical alteration zoning.”

02 Task Decomposition

The supervisor decomposes the task into executable subtasks such as remote-sensing extraction, geochemical anomaly analysis, structural interpretation, and 3D modeling.

03 Collaborative Execution

Remote-sensing, geochemical, GIS, and geological agents process their own data streams and subtasks in parallel.

04 Fusion and Reasoning

The QA Agent aggregates agent outputs, cross-validates them with the metallogenic knowledge graph, and produces multi-evidence prospective targets.

05 Human-AI Decision Making

The system outputs ranked targets with explicit rationale. Geological experts review the evidence and determine priorities for field verification or drilling.

Multi-Agent Geoscience Reasoning

The Supervisor organizes a virtual exploration team to collaborate and debate around evidence.

Virtual Expert Team

GALA uses an LLM-based virtual exploration team with clear roles:

- **Data processing:** cleaning, format conversion, spatiotemporal alignment
- **Geological interpretation:** lithology, structures, chronology
- **Remote sensing and deposits:** feature extraction and prospectivity assessment
- **QA and output:** uncertainty detection and report generation

Efficient Collaboration Mechanisms

Shared Blackboard

A common workspace publishes intermediate outputs and prevents information silos.

Direct Messaging

Point-to-point communication handles urgent or time-sensitive queries.

Structured Debate

When agents disagree, they submit evidence and reasoning until a defensible consensus is reached.

Explainable Knowledge Reasoning

Core reasoning engine:

GeoGraphRAG

Agents query geological knowledge graphs and spatial layers in natural language. This grounds each conclusion in explicit entities, relations, and visual evidence, improving traceability and scientific explainability.

Visual Geo-Feature Extraction with SAM3

Open-vocabulary segmentation plus iterative prompt optimization for new geological concepts

Core Technology: SAM3 and Open-Vocabulary Segmentation

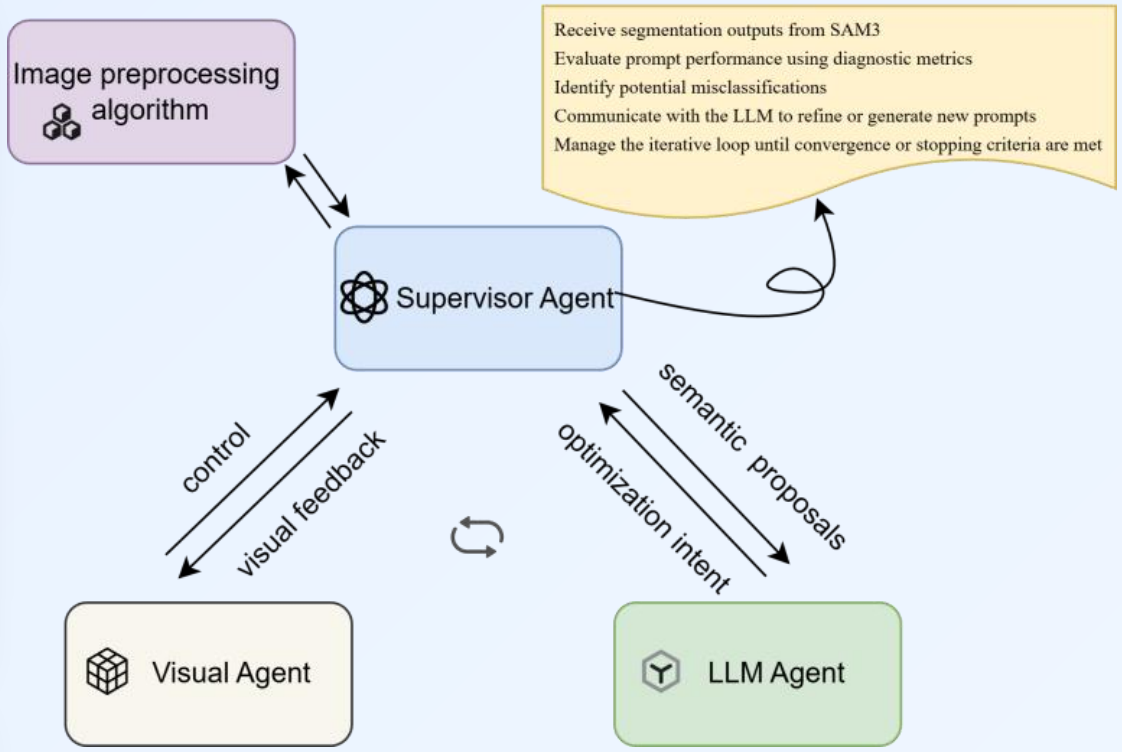
SAM3 supports open-vocabulary instance segmentation. With natural-language prompts such as “extract carbonate rock areas,” it can locate and segment target regions directly from imagery.

Closed-Loop Optimization: Iterative Prompting

1. Initial segmentation ➔ 2. Compute Focus Score ➔
3. Diagnose errors and refine prompts ➔ 4. Iterate until convergence.
This improves segmentation when a single prompt is insufficient.

Output: Vectorization and Attribute Enrichment

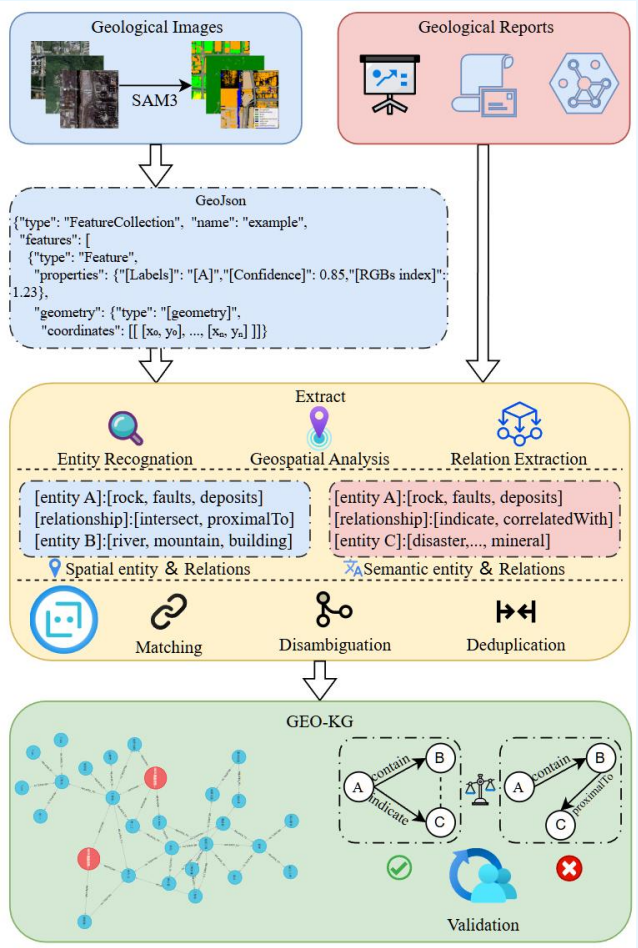
Final masks are converted into GeoJSON features with labels, confidence values, and spatial attributes, enabling direct use in GIS analysis and KG construction.



SAM3 Iterative Optimization
Prompt generation ➔ Segmentation ➔ Evaluation ➔ Prompt refinement

Geological Knowledge Graph Construction and Updating

Encoding remote-sensing features, geological entities, and deposit knowledge as a retrievable relational network



Geo-KG Structure

A heterogeneous geological KG integrates entities such as rock units, faults, deposits, alterations, and remote-sensing indices, with relations such as intersects, indicates, and proximalTo.

Multi-Source Construction Process

SAM3-derived visual features, LLM-extracted report knowledge, image-derived rule mapping, and expert curation are combined to build a reliable graph.

Human-in-the-Loop Updating

The KG is not static. Expert corrections, such as revised fault attitudes or new alteration–deposit links, are written back to support continual knowledge growth.

Human-in-the-Loop Question Resolving and Closed-Loop Learning

Uncertainty triggers expert intervention to continuously correct visual outputs and knowledge relations

Uncertainty Trigger

When SAM3 confidence, prediction uncertainty, or inter-agent disagreement indicates high risk, the system automatically requests expert review instead of making blind decisions.

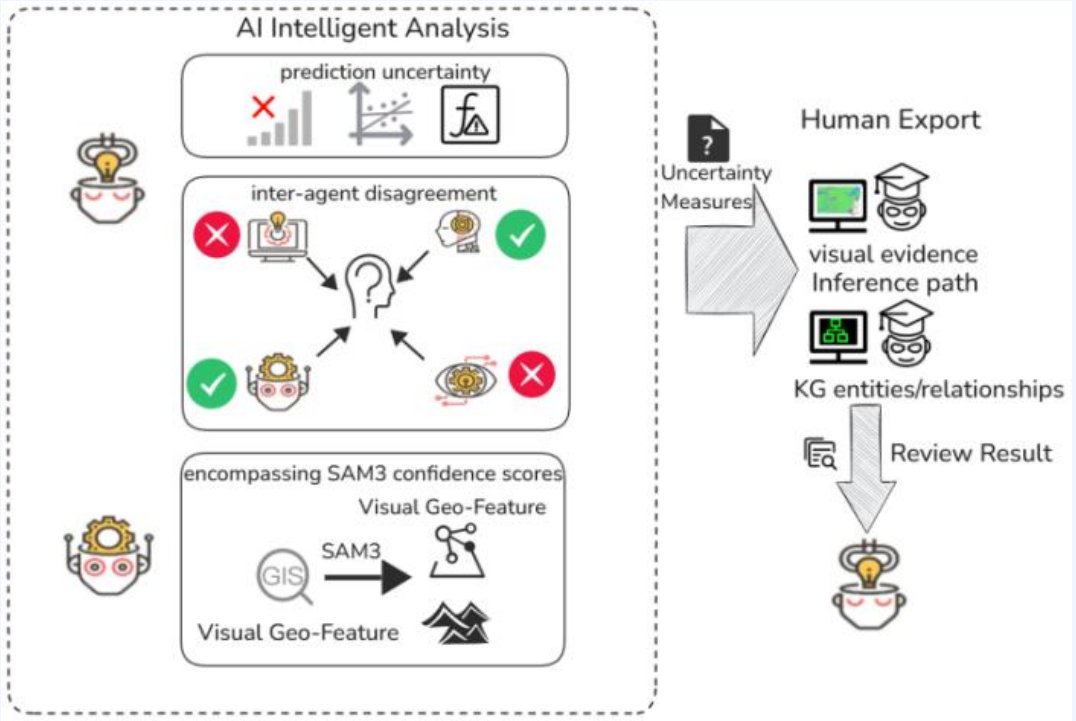
Expert Review and Feedback

Experts review results through an interactive dashboard:

- **Correct SAM3 segmentation boundaries**
- **Add or revise KG triples**
- **Refine prompts to guide future reasoning**

Continual Learning Loop

Expert feedback is captured to optimize prompt strategies, update the KG, and improve agent behavior over time.



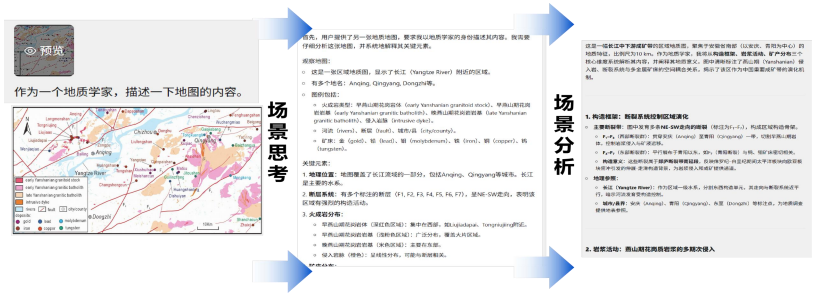
Human-in-the-Loop Process
Uncertainty detection → Expert intervention → Feedback and update → System iteration

Experimental Data, Environment, and Process

Preliminary validation covers aerial imagery, GF-2 imagery, geological maps/reports, and KG retrieval scenarios

Aerial true-color sample

GF-2 / mountainous sample



Geological map and report input

Experimental Platform

CPU	4× Kunpeng 920_5250
RAM	32×32GB
GPU	8× Ascend 910B2-64G
Disk	2×3.84TB NVMe

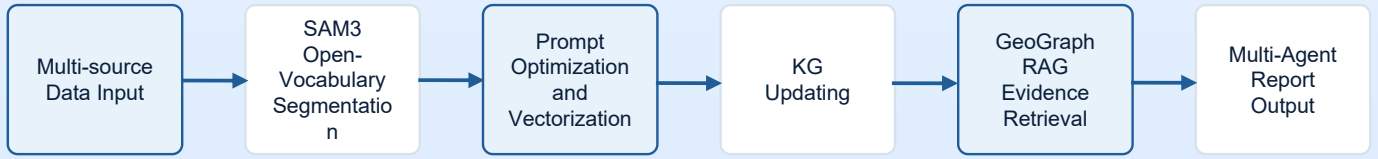
Models and Performance

Qwen3.5-35B-A3B · BF16
Approx. 400 tokens/sec (8 GPUs)

SAM3 · FP16
Approx. 6.8 img/sec (256×256, single GPU)

Experimental Process

The experiment evaluates GALA for visual extraction, knowledge retrieval, collaborative reasoning, and expert feedback.

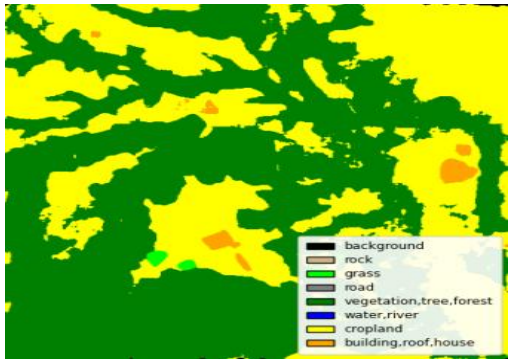


The process emphasizes two evidence chains: visual evidence from imagery to masks to vector features, and knowledge evidence from entities to relations to retrieved context.

Result 1: Open-Vocabulary Segmentation on Aerial and GF Imagery

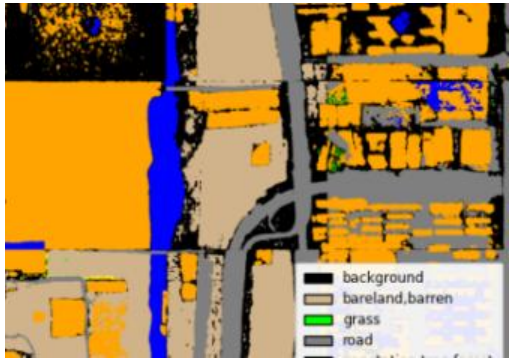
Testing remote-sensing segmentation capability for urban and land-cover features

a) Image Input



b) Segmentation Result

c) Image Input

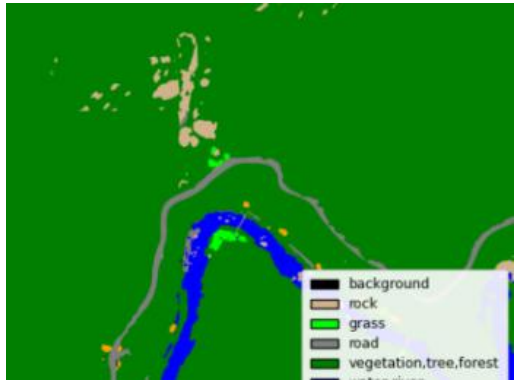


d) Segmentation Result

Under open-vocabulary prompts, SAM3 identifies buildings, roads, vegetation, water, bare land, and other visual elements, providing structured inputs for entity mapping.

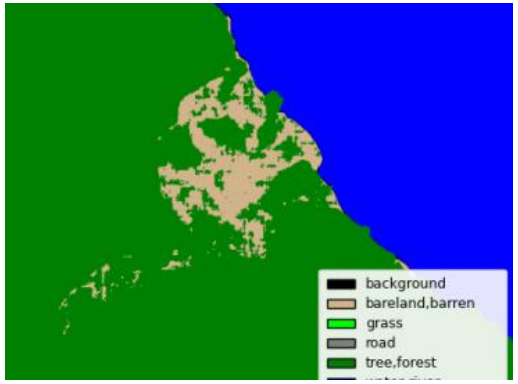
Testing the extraction of geology-related visual cues in mountainous and mining areas

a) Image Input



b) Segmentation Result

c) Image Input



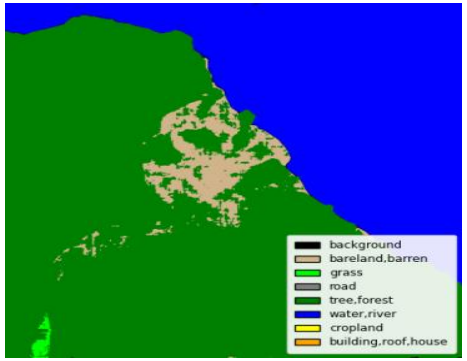
d) Segmentation Result

Significance: segmentation outputs become candidate geo-features for KG relation completion and evidence ranking, rather than isolated pixel-level classes.

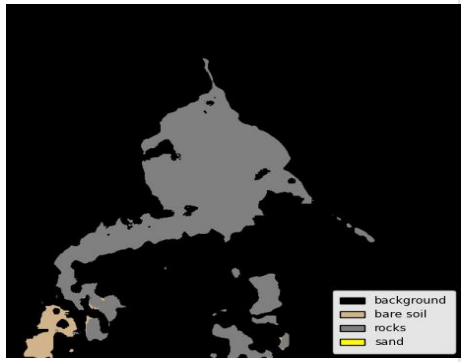
Result 2: Iterative Prompt Optimization Improves Visual Extraction

- LLM-assisted cross-modal verification progressively refines prompts so that segmentation better matches target geological concepts.

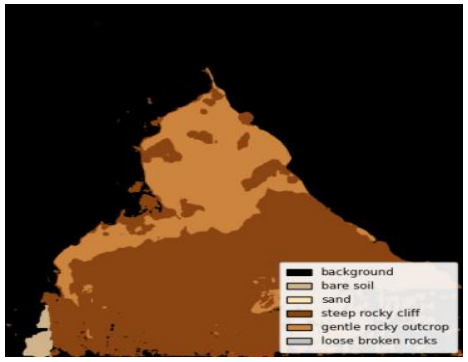
a) True Color Data



b) Segmentation Result

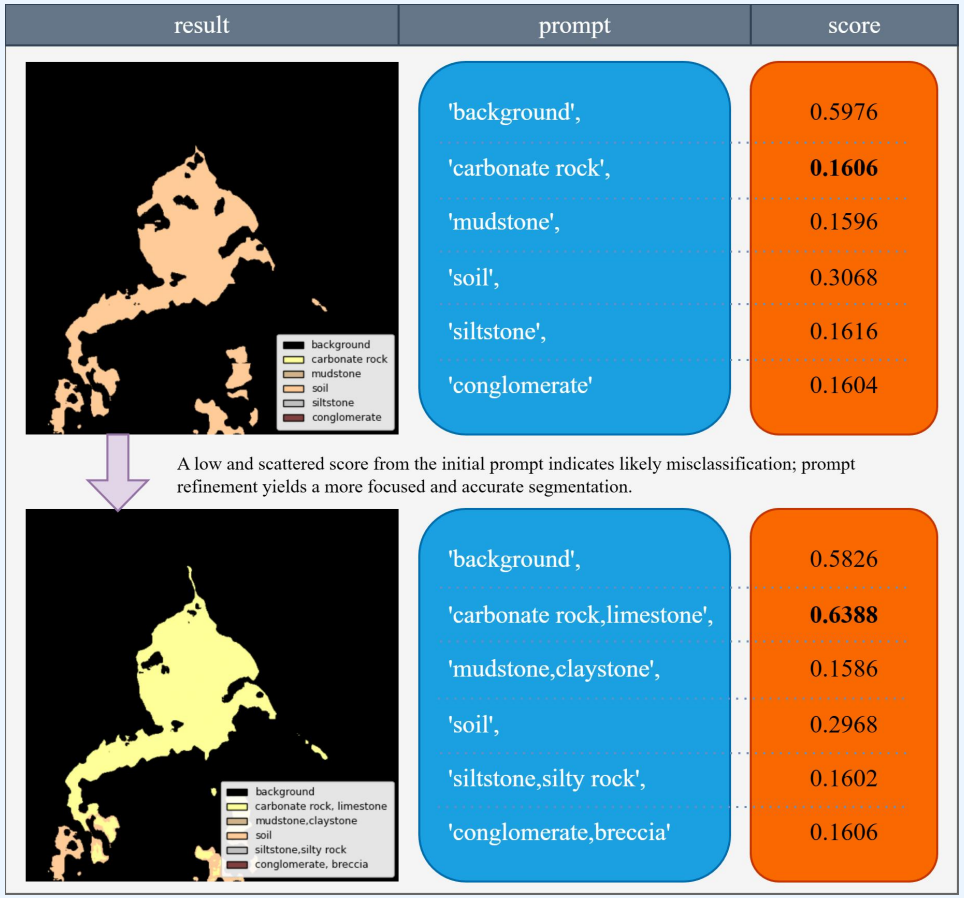


c) Land Usage Input



d) Segmentation Result

- The Focus Score evaluates segmentation quality; low-scoring categories trigger prompt replacement or expansion to improve segmentation accuracy.



Mechanism: each round feeds segmentation results, Focus Score, and semantic descriptions back to the prompt optimizer until a more stable feature representation is reached.

Result 3: GeoGraphRAG and Knowledge Graph Updating

Expert corrections and new relations are written back to the graph to improve subsequent retrieval and reasoning.

Query Scenario	Retrieval Result	KG Update	After Update
Find fault zones trending northwest.	Fault_A is retrieved, but its direction is wrong.	Correct Fault_A attitude: <330°, 60°> → <315°, 68°>	Fault_A is correctly identified as a northwest-trending fault.
What are the indicator alterations for the Chaoyang Gold Mine?	All alteration types are returned, without focusing on key indicators.	Add <Alteration_B, indicates, Ore_Deposit>	Highlight pyritization and silicification while filtering unrelated alteration types.

☑Strong Reuse Effect

Expert feedback successfully updates the KG and is reused in later tasks, forming a feedback–update–reuse loop. The updated KG improves retrieval accuracy and enhances agent decision quality in complex geological scenarios.

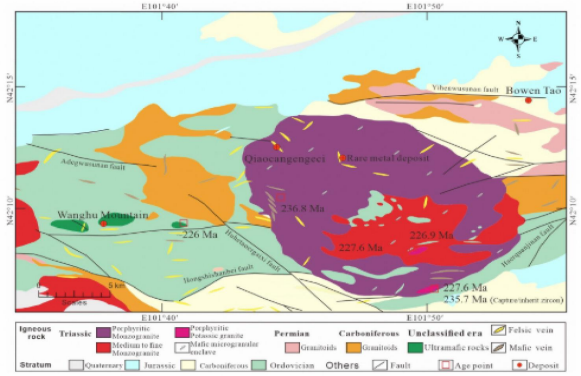
Result 4: Multi-Agent Reasoning

Specialized agents retrieve evidence from KGs through GeoGraphRAG.

用户

01/28 14:14

Describe the contents of the map as a geologist.



Tokens: 14048

Test

01/28 14:16

As a geologist, the map presents a detailed geological overview of an area marked by diverse rock formations and significant tectonic activity. The region is characterized by a variety of igneous rocks, predominantly porphyritic monzogranite and potassic granite from the Triassic period, with notable age points indicating their formation around 236.8 Ma to 226.9 Ma. There are also medium to fine-grained monzogranites and mafic microgranular enclaves present. The Permian era is represented by granitoids, while unclassified eras show ultramafic rocks and felsic veins. Fault lines such as the Adegwusunan fault, Yihenwusuun fault, Huhetaoergaixi fault, Hongshishanbei fault, and Haerquanjin fault crisscross the area, suggesting a history of significant tectonic movements. Notably, there is a rare metal deposit at Qiaocangengeci, which could be of economic interest. The presence of various strata from the Quaternary to the Ordovician periods indicates a rich geological history. This map provides valuable insights into the geological structure and potential mineral resources of the region.

Tokens: 253 ↑253 ↓253

a) Origin round: geological map and initial Q&A

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These faults belong to the southern extension of the Tan-Lu Fault Zone, reflecting an extensional-strike-slip tectonic setting triggered by the subduction of the Pacific Plate beneath the Eurasian Plate during the Jurassic–Cretaceous period, which provided channels for magmatic emplacement and mineralization.

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b) GALA-enhanced result: retrieval report

The output report includes target ranking, spatial evidence, KG relations, reasoning narratives, and auditable evidence for experts.

Conclusions and Outlook

Key Advantages

It provides explainable evidence chains, role-specialized collaboration, and writable expert feedback, making it suitable for complex mineral exploration scenarios.

Current Limitations

The KG still requires expert curation; SAM3-based segmentation perform bad on low-contrast geological features.

Future Work

Expand multi-region samples, improve benchmarks, accumulate domain KGs, and validate the framework in real exploration workflows.

“TanMai” models news

国产大模型DeepSeek-V4在地质领域实现24小时快速适配与落地应用（应用页面截图）

Thank You!

Q & A

Questions and discussion are welcome

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