INTEGRATED GEOLOGICAL, GEOCHEMICAL AND GEOPHYSICAL INVESTIGATION OF COPPER SULPHIDE MINERALIZATION FOR SUSTAINABLE MINERAL RESOURCE DEVELOPMENT

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ABSTRACT

The increasing global demand for copper driven by renewable energy systems, electric vehicles, power transmission infrastructure, and industrial development has intensified the need for sustainable exploration and utilization of copper resources. Conventional mineral exploration methods often rely on isolated geological, geochemical, or geophysical datasets, which may lead to incomplete understanding of ore-forming systems and inefficient resource development. The present study proposes an integrated exploration framework combining geological mapping, geochemical sampling, and geophysical investigations for the identification and characterization of copper sulphide mineralization. Field investigations were carried out over a representative metamorphic terrain hosting sulphide-bearing quartz veins and disseminated copper mineralization. Geological observations revealed structurally controlled sulphide zones associated with shear zones, quartz-carbonate veins, and hydrothermal alteration. Geochemical analysis of rock and soil samples showed significant enrichment of copper along with associated pathfinder elements such as zinc, lead, cobalt, and molybdenum. Geophysical investigations including electrical resistivity and induced polarization (IP) surveys delineated chargeable zones corresponding to subsurface sulphide concentrations. The integration of these datasets enabled the identification of priority exploration targets and improved the understanding of ore controls. A conceptual model for sustainable mineral resource development is proposed, emphasizing data integration, reduced drilling requirements, environmental monitoring, and optimized resource extraction. The study demonstrates that integrated exploration significantly enhances exploration efficiency, reduces uncertainty, minimizes environmental disturbance, and supports responsible mineral resource development. The proposed methodology can be applied to similar copper-bearing terrains in India and other emerging mineral provinces.

Keywords: Copper sulphide mineralization, integrated exploration, geological mapping, geochemical investigation, induced polarization, sustainable mining, mineral resource development.

Broad Area **:** Applied Geology

Sub Area : Mining Geology

1. INTRODUCTION

Copper is one of the most important strategic metals for modern civilization. The transition toward low-carbon technologies has resulted in unprecedented demand for copper used in electric vehicles, renewable energy systems, battery storage, and electrical infrastructure. According to international mineral forecasts, global copper demand is expected to increase substantially over the next two decades. Therefore, the discovery of new copper resources and the efficient utilization of existing deposits have become critical challenges for the mining industry.

Traditional exploration approaches commonly depend on individual datasets such as geological observations, geochemical anomalies, or geophysical signatures. However, copper sulphide deposits are often controlled by complex structural, lithological, and hydrothermal processes that cannot be adequately interpreted from a single type of investigation. Integrated exploration methods provide a more reliable understanding of ore-forming systems by combining complementary datasets.

Sustainable mineral resource development requires not only the identification of economically viable ore bodies but also the minimization of environmental impacts during exploration and mining. Integrated exploration can reduce unnecessary drilling, optimize resource delineation, and improve decision-making, thereby contributing to sustainable mining practices.

The objectives of the present study are:

- To investigate the geological controls of copper sulphide mineralization.
- To evaluate geochemical characteristics of mineralized zones.
- To delineate subsurface sulphide concentrations using geophysical methods.
- To integrate geological, geochemical, and geophysical datasets for target generation.
- To develop a framework for sustainable mineral resource development.

2. STUDY AREA AND GEOLOGICAL SETTING

The study area is located within a Precambrian metamorphic belt characterized by schists, gneisses, quartzites, and intrusive granitic bodies. Regional tectonics indicate multiple phases of deformation resulting in shear zones and fracture systems favorable for hydrothermal mineralization.

The major lithological units observed during field mapping are summarized below.

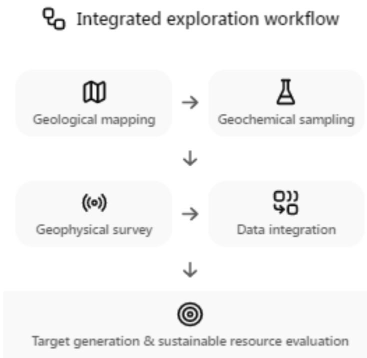
Table 1. Lithological units of the study area

Lithology	**Field characteristics**
Quartz-mica schist	Foliated, highly weathered, hosts sulphide veins
Biotite gneiss	Massive to banded, forms the dominant country rock
Quartzite	Hard, resistant ridges, locally fractured
Granite intrusions	Medium-grained, cross-cuts metamorphic units
Quartz-carbonate veins	Associated with sulphide mineralization

The mineralization occurs mainly within shear zones trending NE-SW and dipping steeply to the southeast. Chalcopyrite, pyrite, and minor bornite occur as disseminations, veinlets, and fracture fillings.

3. METHODOLOGY

An integrated exploration program was designed to combine surface and subsurface investigations.



- Integrated exploration workflow
- Geological mapping
- Geochemical sampling
- Geophysical survey
- Data integration
- Target generation & sustainable resource evaluation

3.1 Geological Investigation

- Detailed geological mapping at 1:10,000 scale.
- Structural measurements of foliation, joints, faults, and veins.
- Identification of alteration zones.
- Collection of representative rock samples.

3.2 Geochemical Investigation

- 50 soil samples collected along grid lines.
- 20 rock samples from mineralized and unmineralized zones.

- Samples analyzed for Cu, Zn, Pb, Co, Mo, and Fe using ICP-OES.

3.3 Geophysical Investigation

Electrical resistivity and induced polarization (IP) surveys were conducted along four profiles.

Survey parameters

- Electrode spacing: 25 m
- Profile length: 400 m
- Array type: Dipole-dipole
- Maximum investigation depth: ~120 m

4. GEOLOGICAL OBSERVATIONS

Field mapping identified three principal mineralization styles:

- Disseminated sulphides within schistose host rocks.
- Vein-hosted mineralization along quartz-carbonate veins.
- Breccia-related sulphides within brittle shear zones.

Hydrothermal alteration includes silicification, sericitization, chloritization, and limonitic weathering. The most intense copper mineralization is associated with silicified shear zones.

Table 2. Structural data from mineralized zones

Feature	Orientation
Foliation	N45°E / 70°SE
Shear zone	N40°E / 80°SE
Quartz veins	N35°E / 75°SE
Cross fractures	NW-SE

The parallelism between foliation, shear zones, and quartz veins suggests strong structural control on mineralization.

5. GEOCHEMICAL RESULTS

5.1 Copper Distribution

Copper concentrations in soil samples range from 35 ppm to 1240 ppm, with anomalous values concentrated near mapped shear zones.

Table 3. Selected geochemical results

Sample ID	Cu (ppm)	Zn (ppm)	Pb (ppm)
S-08	145	92	28
S-15	420	165	46
S-21	860	240	72
S-27	1240	310	95
S-33	690	205	61
S-41	215	118	37

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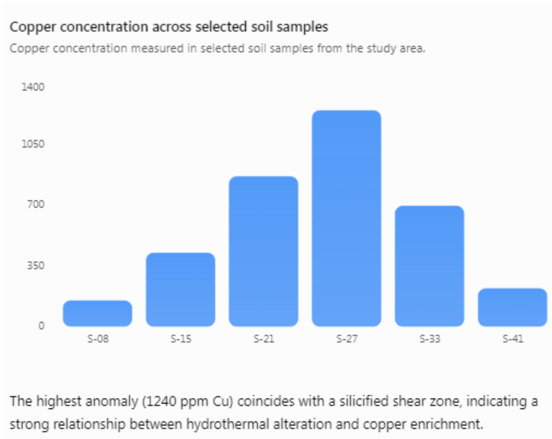
COPPER CONCENTRATION ACROSS SELECTED SOIL SAMPLES



Copper concentration measured in selected soil samples from the study area.

The highest anomaly (1240 ppm Cu) coincides with a silicified shear zone, indicating a strong relationship between hydrothermal alteration and copper enrichment.

5.2 Element Correlation

Positive correlation between Cu-Zn and Cu-Co suggests a hydrothermal sulphide association.

Element pair	Correlation coefficient (r)
Cu-Zn	0.78
Cu-Co	0.69
Cu-Pb	0.54
Cu-Mo	0.63

These relationships indicate that Zn, Co, and Mo can be used as pathfinder elements during regional exploration.

6. GEOPHYSICAL RESULTS

6.1 Resistivity Survey

Resistivity values range from 20 ohm-m to 1200 ohm-m. Low resistivity zones occur beneath mineralized shear zones.

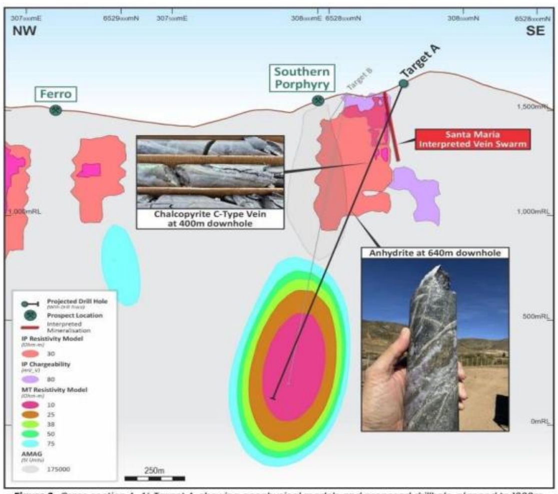


Figure 2. Cross section A-A', Target A, showing geophysical models and proposed drillhole, planned to 1600m downhole depth, testing relatively shallow IP-RES and IP Chargeability features related to the Santa Maria epithermal vein system, and a large MT high amplitude feature at depth (+/- 10m window).*

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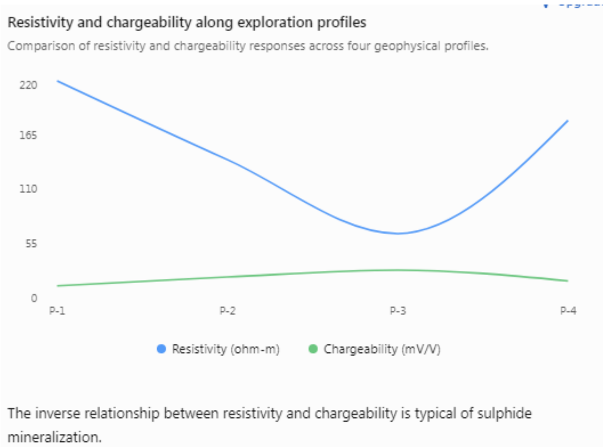
6.2 Induced Polarization Survey

Chargeability values vary from 3 mV/V to 28 mV/V.

Table 4. IP anomaly characteristics

Profile	Peak chargeability (mV/V)	Interpretation
P-1	12	Weak sulphides
P-2	21	Moderate sulphides
P-3	28	Strong sulphide zone
P-4	17	Moderate anomaly

The strongest anomaly occurs along Profile P-3 where high chargeability coincides with low resistivity and surface copper anomalies.



RESISTIVITY AND CHARGEABILITY ALONG EXPLORATION PROFILES

Resistivity and chargeability along exploration profiles

Comparison of resistivity and chargeability responses across four geophysical profiles.

Resistivity (ohm-m)

Chargeability (mV/V)

055110165220P-1P-2P-3P-4

The inverse relationship between resistivity and chargeability is typical of sulphide mineralization.

7. INTEGRATED INTERPRETATION

The integration of geological, geochemical, and geophysical datasets was carried out using GIS-based overlay analysis.

Table 5. Integrated target ranking

Target	Geology	Geochemistry	Geophysics	Priority
T-1	Shear zone + veins	Strong Cu anomaly	Strong IP anomaly	Very High
T-2	Fractured schist	Moderate anomaly	Moderate IP	High
T-3	Quartzite contact	Weak anomaly	Weak IP	Low

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The highest-priority target (T-1) is characterized by:

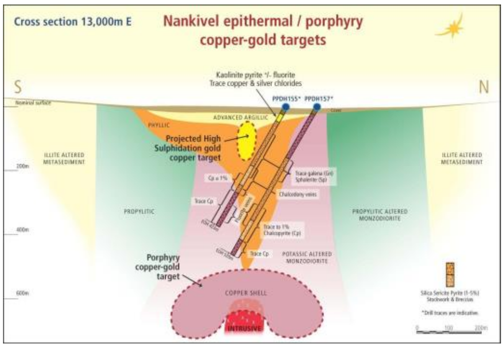
- Silicified shear zone.
- Copper anomaly greater than 1000 ppm.
- Chargeability greater than 25 mV/V.
- Resistivity less than 100 ohm-m.

This integrated approach significantly improves target confidence compared with any single dataset.

8. CONCEPTUAL MODEL OF MINERALIZATION

The proposed mineralization model involves:

- Regional deformation creating NE-SW shear zones.
- Intrusion-related hydrothermal fluid circulation.
- Precipitation of chalcopyrite-pyrite assemblages in fractured zones.
- Supergene enrichment near the surface.



This model explains the observed association between structural zones, alteration, geochemical anomalies, and geophysical responses.

9. SUSTAINABLE MINERAL RESOURCE DEVELOPMENT

Integrated exploration contributes to sustainability in several ways.

Table 6. Sustainability benefits of integrated exploration

Aspect	Conventional exploration	Integrated exploration
Drilling requirement	High	Reduced
Land disturbance	Extensive	Targeted
Exploration uncertainty	High	Lower
Environmental monitoring	Limited	Integrated
Resource estimation	Less reliable	More reliable

PROPOSED SUSTAINABLE DEVELOPMENT FRAMEWORK

- Use remote sensing and GIS before ground disturbance.
- Combine geochemistry and geophysics to optimize drilling.
- Implement baseline environmental monitoring.
- Plan selective mining based on ore controls.

- Utilize mine waste for construction materials where feasible.
- Rehabilitate disturbed areas progressively.

Such an approach aligns with national objectives for responsible mining and resource security.

10. DISCUSSION

The study demonstrates that copper sulphide mineralization is strongly controlled by structural and hydrothermal processes. Surface geological observations alone would not adequately delineate the extent of mineralization, whereas geochemical anomalies provide only indirect evidence of subsurface sulphides. The addition of IP and resistivity data allows the detection of buried sulphide zones, thereby improving exploration efficiency.

The correlation between high copper values, silicification, and chargeability anomalies indicates that the mineralization is likely dominated by disseminated sulphides rather than massive sulphide bodies. This has important implications for drilling strategy and resource evaluation.

The integrated workflow also has economic advantages. By reducing the number of exploratory drill holes, exploration costs can be significantly lowered. Environmentally, targeted exploration minimizes vegetation clearance, road construction, and waste generation.

The methodology is particularly suitable for Indian Precambrian terrains where copper mineralization is commonly associated with shear zones, quartz veins, and metamorphic host rocks.

CONCLUSIONS

The present investigation demonstrates the effectiveness of an integrated geological, geochemical, and geophysical approach for the exploration of copper sulphide mineralization.

Major conclusions

- Copper mineralization is structurally controlled by NE-SW shear zones.
- Silicification and sericitization are important indicators of mineralized zones.
- Soil geochemistry identified strong copper anomalies exceeding 1200 ppm.
- IP surveys successfully delineated subsurface sulphide concentrations.
- Integrated interpretation generated high-confidence exploration targets.
- The approach reduces exploration uncertainty and environmental disturbance.
- Integrated exploration supports sustainable mineral resource development.

The proposed framework can be applied to similar copper-bearing terrains for efficient resource discovery and responsible mining.

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