ACADEMIA International Journal for Social Sciences
Volume 4, Issue 2, 2025 ISSN-L (Online): 3006-6638

Developing Strategic Business Models for Pakistan's E&P Sector in a Net-Zero Carbon Future: Case Studies on the Beneficiation of Copper (Cu) and Antimony (Sb) Deposits in Lower Chitral

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Received: 09-03-2025 **Revised:** 10-04-2025 **Accepted:** 04-05-2025 **Published:** 19-05-2025

ABSTRACT

The International Energy Agency (IEA) has identified several critical minerals—such as copper (Cu), cobalt (Co), nickel (Ni), and rare earth elements (REEs)—as essential for the production of electric vehicles (EVs), renewable energy infrastructure, power grids, and other clean energy technologies. The production and processing of these minerals are key components of strategic economic growth and are fundamental to developing sustainable business models during the global transition to net-zero emissions between 2024 and 2050. Pakistan possesses substantial and diverse mineral resource potential, including large-scale reserves of critical minerals like copper (Cu) and antimony (Sb). These deposits present a unique opportunity to develop world-class mining operations along with beneficiation and upgrading facilities. Such advancements could form the foundation of a dynamic metallurgical and manufacturing industry, positioning Pakistan as a competitive player in the global clean energy supply chain. This study evaluates the feasibility of value addition through beneficiation of low-grade mineral deposits in Pakistan, with a focus on Fe-Cu and Sb deposits in Lower Chitral. The Fe-Cu occurrences are hosted in metavolcanic and metasedimentary rocks of the Gawuch Formation (Cretaceous) within the Kohistan Arc in southern Chitral. Beneficiation techniques applied to these hydrothermal Fe-Cu ores have shown encouraging results. A combination of gravity and magnetic separation yielded an Fe_2O_3 concentrate with a grade of 90.7 wt.% and a 65% recovery rate, making it suitable for steel production. Furthermore, froth flotation has produced copper concentrates averaging 5.55 wt.% Cu, starting from ores with initial Cu contents below 0.1 wt.%, demonstrating significant recovery potential. In addition, a low-grade Sb deposit located within the Karakoram Plate in the Krinj-Shughor area of Lower Chitral district exhibits promising beneficiation results. With a head grade of 19.05% Sb, the ore—primarily containing stibnite (Sb_2S_3)—was processed via froth flotation to produce a final concentrate of 62.0% Sb at a 95% recovery rate. These results underscore the economic viability of antimony extraction and its potential use in *antimony-based chemical industries. With global oil and gas companies increasingly diversifying into mineral resource development in response to rising demand, there is a strategic opportunity for Pakistan's national enterprises to follow suit. To align with global objectives for clean energy transition, Pakistan should proactively invest in the mining, beneficiation, and refining of critical minerals—particularly copper (Cu), zinc (Zn), lithium (Li), and antimony (Sb). Such investment would not only strengthen the country's energy transition strategy but also position it as a regional hub for green industrial development.*

Key Words: *mineral resources, beneficiation, antimony, copper, iron, investment*

INTRODUCTION

The global transition from fossil fuels to green energy technologies is accelerating in response to the urgent need to mitigate climate change (Mathivathanan et al., 2018). At the 2021 United Nations Climate Change Conference (COP26), a global commitment was made to shift the automotive industry toward zero-emission technologies by 2040. In line with this, the United States aims to ensure that 50% of all new vehicles sold by 2030 are electric. Countries such as Norway and the Netherlands have adopted even more ambitious targets, seeking to phase out fossil fuel-powered vehicles entirely by 2025–2030. Achieving global climate neutrality by 2050 will require a significant reduction in dependence on fossil fuels (Hung et al., 2021).

Green energy technologies are heavily reliant on critical and near-critical minerals—including copper (Cu), cobalt (Co), antimony (Sb), nickel (Ni), manganese (Mn), chromium (Cr), and rare earth elements (REEs) (USGS, 2023). These minerals must be sourced and processed at an unprecedented scale and pace in the coming decades to meet global net-zero emissions targets.

Since 2019, policy trends have increasingly emphasized the importance of responsible mining and production of critical minerals—not only to minimize supply chain disruptions but also to diversify sources of raw materials through enhanced exploration, production, and technological innovation.

Pakistan is endowed with a diverse range of mineral resources, including significant deposits of critical minerals such as Cu, Sb, Cr, and Mn. However, despite their strategic importance, there has been limited policy focus or research on large-scale exploration, production, beneficiation, and value addition of these minerals within the country.

Beneficiation refers to the process of improving the quality of mineral ores by removing impurities or enhancing their properties, while value addition involves further processing of raw materials into higher-value products. These practices are widely recognized as key drivers of economic development. For instance, regional initiatives like the Southern African Development Community (SADC) Industrialization Strategy and Roadmap (2015–2063) and Zimbabwe's ZIMASSET Program (2015) have explicitly identified beneficiation and value addition as pillars of sustainable socio-economic transformation.

In Pakistan, the limited economic benefit derived from its mineral wealth can be largely attributed to insufficient investment in large-scale mineral exploration and a lack of structured beneficiation and value addition processes. This study, therefore, seeks to evaluate the potential for beneficiation and value addition of critical minerals in Pakistan, with a particular focus on copper (Cu) and antimony (Sb).

Pakistan's copper deposits are typically hosted in arc systems, ophiolitic thrust belts, and suture zones such as the Kohistan Island Arc (KIA), Chagai Magmatic Arc (CMA), and Waziristan Ophiolites (Kazmi & Jan, 1997; Anjum et al., 2018). Prominent occurrences include Saindak, Reko Diq, Waziristan, and Chitral (Kazmi & Jan, 1997).

Global demand for copper continues to rise as the world advances toward green energy technologies. Despite being resource-rich, Pakistan is not currently ranked among copper-producing countries. This underperformance underscores the urgent need for strategic investment in copper deposits to help Pakistan contribute to global clean energy goals and to establish resilient, responsible supply chains for critical minerals and clean energy technologies.

METHODOLOGY

Four samples of iron (Fe) ore and associated copper (Cu) ore, each weighing 12 kg, were collected from ore bodies at the Gowai Mine in Dammal Nisar (Fig. 2). The samples were initially crushed and then ground in a rod mill for 25-minute intervals to reduce the grain size, achieving over 70% of the material passing below 106 µm. After homogenization using coning and quartering, each sample was subdivided into portions for different beneficiation processes: 1 kg for gravity and magnetic separation, 1 kg for froth flotation, and 500 g retained for head sample analysis. Gravity separation was performed using a Wilfley shaking table, while dry high-intensity magnetic separation was conducted on the gravity concentrates using a magnetic roll separator with a permanent magnetic field intensity of approximately 1.5 Tesla. The pulverized samples were analyzed via wet geochemical analysis using an Atomic Absorption Spectrophotometer (AAS). For details on the beneficiation methodology of antimony (Sb), refer to Bhatti et al. (2008). Thin section preparation and petrographic analysis of the Fe-Cu and Sb ores were carried out at the Department of Geology, University of Peshawar, Pakistan.

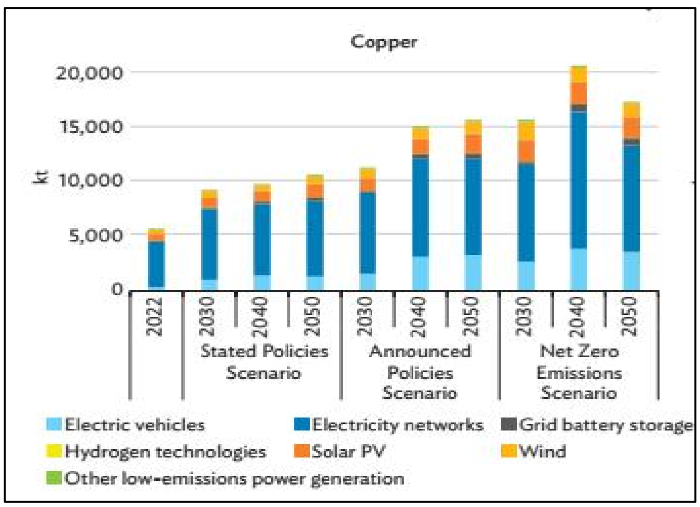


Figure 1. Demand for Cu (kilo-tons) in the clean energy technologies 2022-2050.

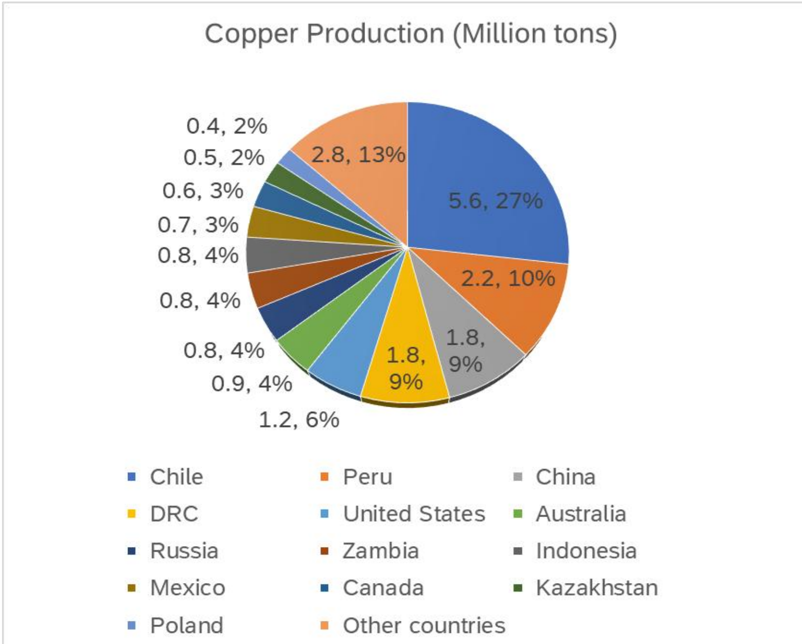


Figure-2: Pie diagram Demonstrating the copper worldwide production in 2021 (Reference: World Economic Forum)

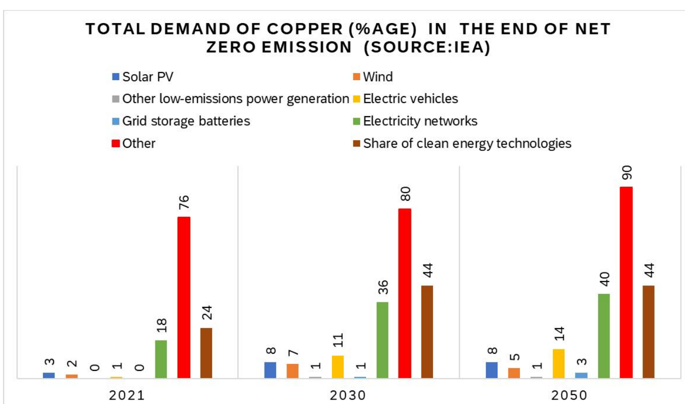


Figure-3: - exhibits the capital expenditure (USD) on non-metal production by 20 big mining companies, 2011 to 2022 (Source: IEA).

Table 1. The parameters for Floatation used for both Cu and Sb

Description	Type	amount used
Sodium Hydroxide (Cu, Sb)	PH Stabilizer	0.5-1gram
Sodium Tri-Ethyl Zinthate (Cu); Potassium Amyl Zenthate (Sb)	Oxide collector	0.2 gram
Cynamide 3302 (Cu) Lead Acetate (Sb)	Promoter	3 drops
Sodium Silicate	Silica Depressor	0.2 gram
Frother-88 (Cu) Polypropylene glycol (Sb)		3 drops

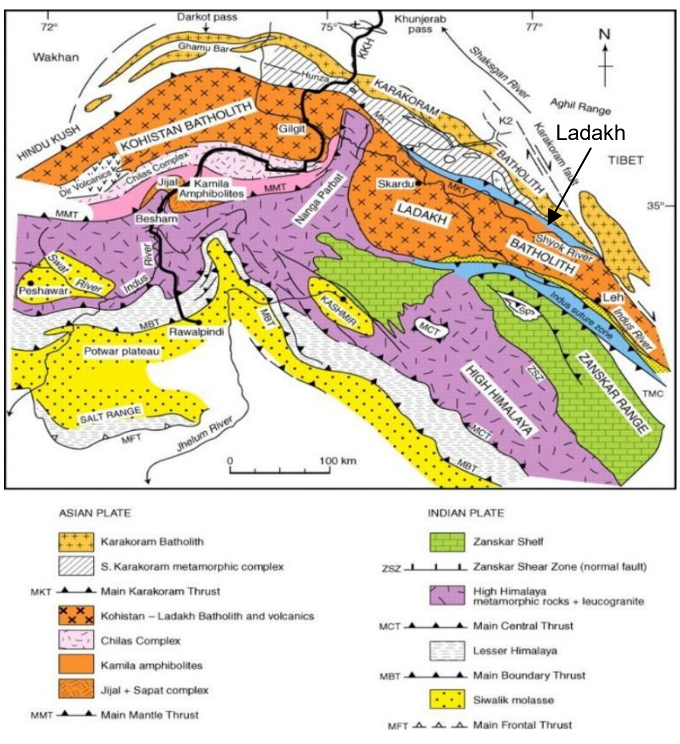


Fig. 4. Geological map showing various litho-tectonic units of north Pakistan (after Searle et al., 1999).

RESULTS AND DISCUSSION

The Fe-Cu deposits in Lower Chitral are hosted within metavolcanic and metasedimentary rocks of the Gawuch Formation (Cretaceous), which forms part of the Kohistan Island Arc (Figure 4). These deposits are of hydrothermal origin and occur primarily as fault-controlled and skarn-type mineralizations (TahirKheli et al., 2012; Anjum et al., 2018; Anjum, 2021).

Beneficiation of the Fe-Cu ores was carried out using a combination of gravity separation and magnetic separation techniques. The analyzed ore samples exhibited Fe_2O_3 contents ranging from 72.50 to 76.09 wt.% and Cu contents between 0.29 and 0.55 wt.% (Table 1). The applied beneficiation processes yielded a high-grade Fe_2O_3 concentrate of 90.7 wt.% with a recovery rate of 65% (Table 2), indicating the efficiency of the combined method in producing iron concentrate suitable for use in steel manufacturing.

Furthermore, froth flotation applied to the same ore samples produced an average copper concentrate of 5.55 wt.% Cu, despite initial ore grades being below 0.1 wt.% Cu (Table 1). This highlights the economic potential of recovering copper from low-grade ores through appropriate beneficiation methods (Table 2).

In addition, a low-grade antimony (Sb) deposit from the Krinj-Shughor area in District Chitral, hosted within the metasedimentary units of the Karakoram Plate, was also evaluated. This deposit exhibited a head grade of 19.05% Sb, with stibnite (Sb_2S_3) as the primary ore mineral. The finely ground ore (average particle size ~150 µm) was processed using froth flotation, resulting in a final concentrate grading 62.0% Sb, with a recovery rate of 95% (Bhatti et al., 2008). These results confirm the technical feasibility and economic viability of antimony extraction for use in antimony-based industrial and chemical applications.

Overall, the beneficiation results demonstrate that low-grade Fe-Cu and Sb ores in the Lower Chitral region possess significant potential for commercial exploitation, provided that efficient processing technologies are employed.

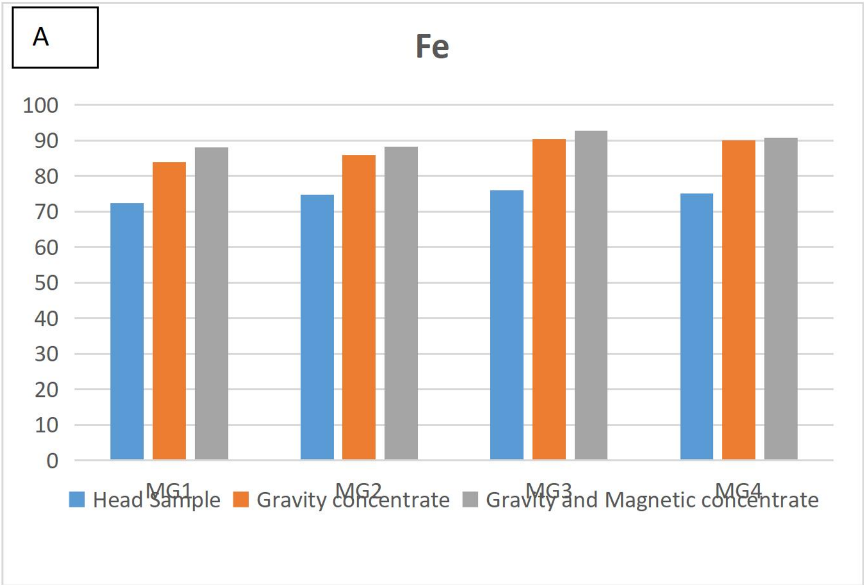
Table 1. Showing geochemical analysis of head samples (wt.%)

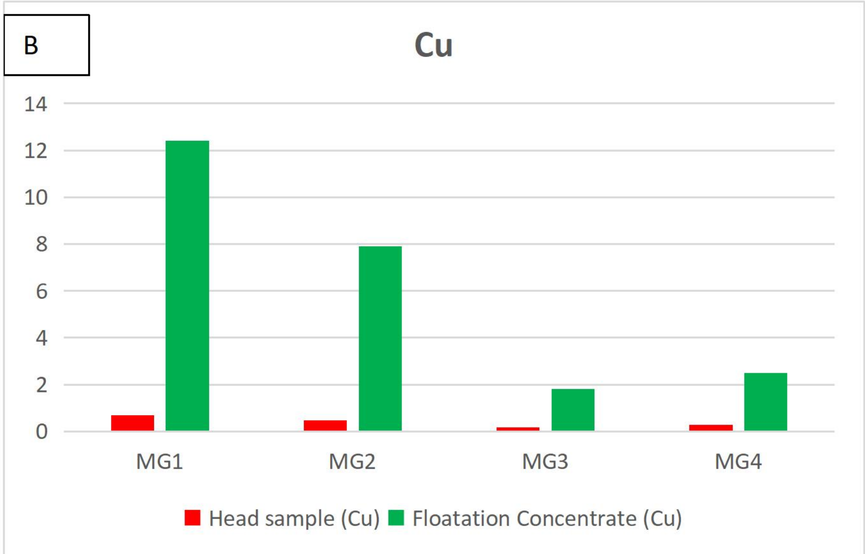
S. N.	GC (Fe_2O_3)	MC (Fe_2O_3)	FC (Cu)
MG1	84	88	12.4
MG2	86	88.2	7.9
MG3	90.4	92.8	1.8
MG4	90	90.8	2.5

ACADEMIA International Journal for Social Sciences
Volume 4, Issue 2, 2025 ISSN-L (Online): 3006-6638

Table 2. Showing geochemical analysis of Fe and Cu concentrates (wt.%)

S. N.	HS (Fe_2O_3)	SiO_2	CaO	Cu
MG1	72.50	14.50	10.60	0.55
MG2	74.80	16.04	6.44	0.48
MG3	76.04	5.8	12.6	0.18
MG4	75.09	10.4	13.4	0.29





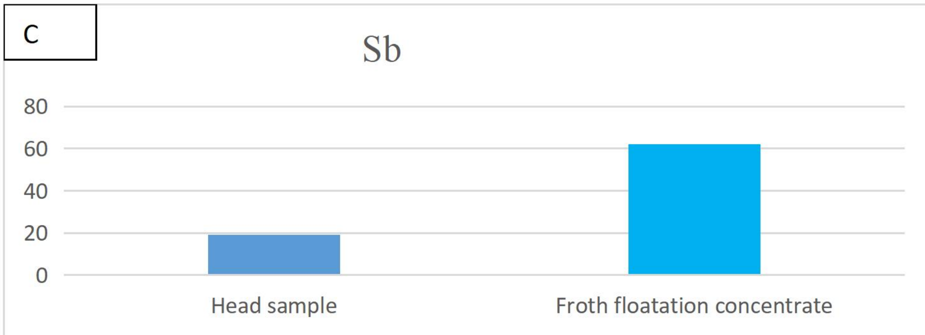


Figure 5. Histograms showing the values of head samples and concentrates (A-C); note the upgradation in values of Fe, Cu and Sb (wt.%).

S. N. = sample name; GC = Gravity concentrate; MC = Magnetic concentrate; FC = Floatation Concentrate

CONCLUSIONS

The metamorphosed volcano-sedimentary lithologies of the Gawuch Formation, within the Kohistan Island Arc (KIA), host economic-scale Fe-oxide and Cu ore bodies, which are classified as world-class Fe-skarn deposits.

Beneficiation studies indicate that these deposits can be upgraded to meet the quality specifications required for steel production, confirming their potential for application in the steel industry.

At a particle size of approximately 106 µm, an average Fe_2O_3 recovery rate of 65% can be achieved, yielding a concentrate grade of approximately 90 wt.%, through a combination of gravity separation and high-intensity magnetic separation techniques.

The study further demonstrates that, using froth flotation, an average copper concentrate of approximately 6 wt.% Cu can be obtained from Fe-Cu head samples with an initial average grade of 0.5 wt.% Cu, achieving a twelve-fold increase in copper concentration, with an overall recovery rate of 64%.

The froth flotation technique applied to antimony-rich deposits demonstrates significant upgradation, enhancing the head sample grade from 19.05% to 62.0% Sb in the concentrate, with a recovery rate of 95%. These results underscore the economic viability of such deposits.

This study concludes that strategic investment in the exploration and production of green energy minerals, coupled with beneficiation and value addition, can serve as a catalyst for transforming Pakistan from an economically unstable nation into a stable and prosperous one within a relatively short timeframe.

Furthermore, by developing domestic beneficiation and value-added industries, Pakistan can reduce its reliance on imports, fostering the growth of ancillary sectors such as manufacturing, transportation, and logistics—thereby stimulating broader economic development.

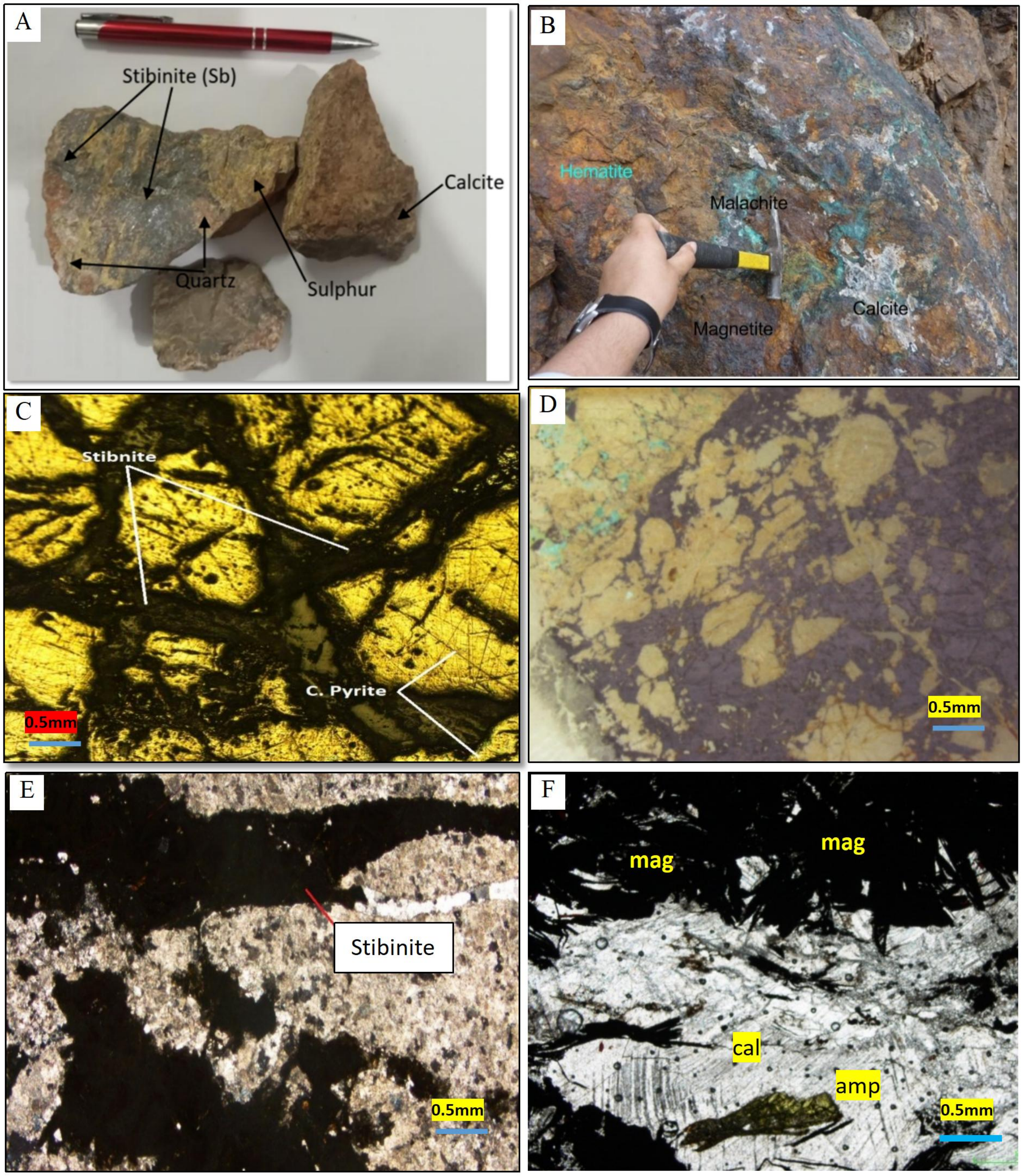


Figure 6. Photographs of field samples from the study area (A, B); Antimony ore comprising of stibinite and associated gangue (A), Fe-Cu ores (B); Reflected light photomicrographs (C, D), Stibinite replacing pyrite (golden), Magnetite and malachite replacing carbonates (E, F); Calcite and quartz (light colour) as gangue with stibinite (E), magnetite replacing calcite (F).

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