based on the use of copper sulfide ores particularly chalcopyrite, chalcocite, and covellite under reducing conditions. Despite differences in copper grade among these ores (chalcopyrite having a moderate grade, and chalcocite and covellite higher grades), field, petrographic, and geochemical evidence points to their prominent role in supplying raw material to these furnaces. Given the geological evidence from the region, the ore available to feed these furnaces was predominantly sulfidic in nature, consistent with the ancient mining evidence identified within a radius of several kilometers of these smelting sites.

Regarding the second research question, concerning the provenance and type of ores used in the smelting process, it can be stated that the primary ore material used at the Chah Jamal smelting sites was sourced locally, in proximity to the furnaces. Evidence of ancient mining activity, including pits and tunnels within a radius of approximately two kilometers of these sites, has been identified. Field surveys in these areas indicate the presence of copper sulfide ores, particularly chalcopyrite and chalcocite, within these ancient mines consistent with the results of petrographic studies and geochemical analyses of the slags recovered from the smelting sites. Moreover, the presence of anomalies in associated elements such as lead, zinc, silver, and other metals in the analytical results obtained from the slag samples supports the conclusion that the ore material used originated from polymetallic deposits. This finding aligns with the mining evidence within a radius of several kilometers of the smelting sites and reinforces the likelihood that such deposits were exploited in the past.

Conclusion

The aim of the present study was to investigate the metal smelting technology and the provenance of the ores used at the ancient Chah Jamal Khoshomang sites in Yazd Province through field, petrographic, and geochemical studies of slag samples. The results showed that the slags from both sites exhibit considerable mineralogical and geochemical overlap. The principal minerals identified were pyroxene and fayalite within a glassy matrix, with associated metallic phases comprising native copper, copper sulfide minerals (chalcocite and covellite), and the iron-bearing mineral wüstite. On this basis, the furnace operating temperature was estimated at approximately 11001200 °C, with reducing conditions prevailing within the furnace. The results of the chemical analyses likewise indicated elevated levels of silica, calcium oxide, and magnesium oxide, which served as siliceous and carbonate fluxes during the smelting process.

In response to the first research question, the smelting technology employed at the Chah Jamal Khoshomang sites was based on the extraction of copper from sulfide ores particularly chalcopyrite, chalcocite, and covellite under reducing conditions. In response to the second research question, field and geochemical evidence indicates that the raw material feeding these furnaces was sourced locally, notably from ancient mines identified within a radius of several kilometers of the sites, including old tunnels and pits. Furthermore, anomalies of lead, zinc, and silver in the slag samples point to the use of raw material derived from a polymetallic deposit.

The findings of this study demonstrate that the Chah Jamal Khoshomang sites represent an example of copper-smelting and extraction workshops in the central Iranian plateau, expanding our understanding of ancient metallurgical knowledge and technology in this part of the plateau. Nevertheless, the absence of clear structural evidence of furnaces and the lack of precise or relative dating for these sites constitute the main limitations of this study. Targeted archaeological excavations and complementary studies, such as absolute dating, are therefore recommended in future research to more precisely determine the age, chronological sequence, and regional significance of these sites.

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Authors' Contribution

First Author (Amin Allah Kamali): Responsible for sampling and data analysis.
Second Author (Mehdi Razani): In charge of data analysis and manuscript drafting.
Third Author (Seyed Iraj Beheshti): Conducted petrographic studies.
Fourth Author (Hamid Fadaei): Responsible for reviewing and editing the manuscript.
Fifth Author (Vahid Ebrahimzadeh): In charge of sampling and field studies.

Conflict of Interest

The authors declare that there is no conflict of interest in this study and research.

Today, modern scientific analysis of metallic remains and production processes from mining and ore extraction to smelting, alloying, and artifact crafting offers a unique window into the technological capabilities, trade networks, and social structures of ancient communities (Giardino, 2022; Oudbashi et al., 2012). The Iranian Plateau, with its rich mineral resources and long history of metallurgical innovation, stands as a key region in the study of ancient metallurgy (Pigott, 2004a; Thornton, 2009). This region pioneered not only the early use of native copper during the Neolithic period but also the development of sophisticated processes, such as copper smelting from ores during the Chalcolithic and the emergence of alloys like arsenical bronze and tin bronze (Pigott, 2004a; Thornton & Lamberg-Karlovsky, 2004). Effectively, the Iranian Plateau functioned as an ancient laboratory for pyrotechnology, encompassing processes from flint heat treatment and pottery firing to the production of plaster, lime, and metals (Pigott, 2004a). The study of early metal production sites, particularly smelting furnaces and their associated raw materials, is crucial for understanding ancient metallurgical practices (Giardino, 2022; Hashemi et al., 2024). These sites provide direct evidence of the technologies employed, the scale of production, and the types of raw materials used. Geochemical and mineralogical analyses of ores, slags, crucibles, and furnace remains enable the reconstruction of smelting processes, identification of ore types (oxide or sulfide), determination of furnace temperatures, and tracing of raw material origins through stable isotope or trace element analyses (Bérard et al., 2020; Eskandari & Emami, 2022). Advanced analytical techniques, such as ICP-MS, SEM-EDS, and synchrotron radiation, allow precise examination of chemical compositions and material structures, identifying specific minerals in metallic phases or corrosion products (Emami et al., 2022; Oudbashi et al., 2016). Against this backdrop, the Chah Jamal Khoshomang smelting sites in Yazd Province present a significant opportunity to advance our understanding of ancient metallurgy in southeastern Iran.This study aims to characterize the smelting technologies and raw material origins at these sites through geochemical and mineralogical analyses, shedding light on their role in regional and trans-regional metal production networks.

Discussion

The field, petrographic, and geochemical investigations carried out on samples collected from the metal smelting sites provide the information needed to address the main research questions. This discussion first examines the technological characteristics of the smelting process and furnace operation, and then turns to the provenance and type of the ores exploited. The field, petrographic, and chemical analysis data are subsequently integrated to present a coherent picture of the ancient technology used for metal extraction, particularly copper.

The distribution of slag across the two smelting sites, covering areas of approximately 200 and 72 m², indicates that this area hosted two interrelated metal smelting workshops. Macroscopic examination of the slag samples collected from both sites shows that their color ranges from gray to green, a variation attributable to the presence of copper oxides (green coloration resulting from the oxidation of metallic copper). These slags exhibit irregular surfaces and considerable porosity, associated with gas escape during the smelting process. Microscopic studies indicate that the dominant minerals constituting these slags are fayalite and pyroxene. The exploited ore phases identified within the slags include copper minerals such as covellite, native copper, and chalcocite, along with the iron-bearing mineral wüstite, whose presence is indicative of reducing conditions within the furnace.

The results of the chemical analyses reveal a high concentration of silica, followed by iron oxides. In addition to silica, calcium and magnesium are present in significant amounts, having served primarily as siliceous and carbonate fluxes to reduce viscosity and regulate furnace temperature conditions. The estimated operating temperature of these furnaces was approximately 11001200 °C, and the presence of fayalite, together with the iron-bearing mineral wüstite in the slags, points to relatively controlled reducing conditions within the furnace. The silicate minerals pyroxene and fayalite within a glassy matrix likewise corroborate this temperature range and the relatively rapid cooling of the slags. The high (estimated) silica content and carbonate compounds in the slags contributed to reducing viscosity, lowering the melting temperature, and facilitating the separation of impurities features consistent with the structure and function of the furnaces identified at the site. Given the outcrops of carbonate rocks and siliceous veins in the vicinity of the site, sourcing of such materials from local supplies is entirely plausible.

The chemical analysis data indicate that copper is retained in these slags at levels of up to approximately three percent, a value that falls within the typical range for ancient metallurgical slags and is better explained by the conventional efficiency of ancient smelting technology than by any particular inefficiency of these furnaces. In addition to copper, relatively weak anomalies of lead and zinc, as well as a silver anomaly, are observed in these slags, suggesting that the raw ore feeding these furnaces was likely derived from a polymetallic deposit.

In response to the first research question, concerning the technology employed for copper extraction at the Chah Jamal Khoshomang smelting sites, this technology was

Investigation of the Ancient Chah Jamal Khoshomang Metal Smelting Site in Yazd Province Based on Geochemical and Mineralogical Studies

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The Chah Jamal Khoshomang metal smelting sites are located in Yazd Province, in the Kharanaq district east of Ardakan County, approximately 25 km south of Saghand village and 120 km from the city of Yazd. This study aims to identify the smelting technology and the provenance of the ores used at these sites through field investigations, petrographic analysis, and chemical analysis by inductively (ICP-OES) of slag samples collected from two smelting sites. Petrographic results reveal the presence of the silicate minerals pyroxene and fayalite within a glassy matrix, together with metallic phases comprising native copper, copper sulfide minerals (chalcocite and covellite), and the iron-bearing mineral wüstite. The high proportions of silica and iron oxides in the chemical analysis results, together with the presence of CaO and MgO, indicate the use of siliceous and carbonate fluxes to reduce slag viscosity; combined with the observed mineralogical assemblage, this evidence suggests a smelting temperature of approximately 11001200 °C and a reducing, relatively controlled furnace atmosphere. These smelting sites, which were established for copper extraction, also contain lead, zinc, and silver, indicating that the raw ore feeding these furnaces was derived from a polymetallic deposit. Regarding the provenance of this raw material, ancient exploratory tunnels and pits located approximately two kilometers from the sites can be identified as the local source of feedstock for these furnaces. The findings of this study advance our understanding of ancient metal extraction technology in the central Iranian plateau.

Keywords: Archaeometallurgy, Iranian Plateau, Ancient Metal Smelting, Chah Jamal Khoshomang, Geochemical Studies, Smelting Furnace.

Introduction

Archaeometallurgy, as an interdisciplinary field, plays a pivotal role in reconstructing past societies, their technological advancements, and complex socio-economic dynamics. The centrality of metals to the development of ancient civilizations is well established.