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Research Article

Lithological, Structural and Geochemical Characteristics of Gold Mineralization in the Menge Greenstone Belt, Western Ethiopia & Geochemical Signatures and Structural Controls of Gold Mineralization in the Menge District, Western Ethiopia

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ABSTRACT

The Menge area in the Benishangul-Gumuz Regional State of western Ethiopia represents a prospective gold mineralization zone within the Arabian-Nubian Shield. This study presents a comprehensive geochemical investigation of current gold deposits using field mapping, petrographic analysis and whole-rock geochemical data. Eight representative samples were analysed for major oxides and trace elements using XRF and ICP-MS techniques. The results reveal that gold mineralization is primarily hosted in shear zone-related quartz veins within low-grade metamorphic rocks including metadiorite, metagranite, metavolcanic rocks and quartzite. Gold concentrations range from 4.14 to 15.13 ppm, with the highest values associated with quartzite units. Assay values of up to 2.2 ppm Au and quartzite samples exceeding 15 ppm Au confirm significant gold enrichment. The mineralization style corresponds to mesothermal orogenic gold deposits, with hydrothermal fluids likely derived from metamorphic devolatilization. Geochemical signatures indicate evolved tholeiitic magmas of mantle origin with bimodal affinity. Hydrothermal alteration patterns include chloritization, sericitization, silicification and carbonatization. The structural setting, alteration assemblages and ore mineral paragenesis are consistent with mesothermal orogenic gold deposits similar to other Ethiopian gold occurrences. These findings suggest significant potential for economic gold mineralization in the western Ethiopian greenstone belt.

Keywords: Gold deposits; Geochemistry; Arabian-nubian shield; Western Ethiopia; Orogenic gold; Hydrothermal alteration

Introduction

Ethiopia's geological framework is characterized by diverse rock units ranging from Archaean to Phanerozoic age, with economically significant metallic mineral deposits primarily concentrated within Precambrian basement complexes[1]. The western Ethiopian greenstone belt represents a major component of the Arabian-Nubian Shield (ANS), hosting numerous gold and base metal occurrences that have attracted considerable exploration interest[2].

The Menge area, located in the Benishangul-Gumuz Regional State approximately 60 km southwest of Assosa town, lies within this prospective metalliferous belt. Previous reconnaissance studies have identified widespread artisanal placer gold mining activities, suggesting the presence of primary gold sources in the region[3]. However, systematic geological and geochemical investigations have been limited, creating significant knowledge gaps regarding the nature, distribution and economic potential of gold mineralization.

Gold deposits in Ethiopian basement terranes are typically associated with shear zone-hosted quartz vein systems within low-grade metavolcanic-sedimentary sequences[4]. Notable examples include the Lega Dembi deposit in southern Ethiopia, which represents the country's largest gold producer and various prospects in the western greenstone belt including the Dul Mountain deposit[5,6].

The Arabian-Nubian Shield in western Ethiopia comprises Neoproterozoic volcano-sedimentary assemblages metamorphosed to greenschist-amphibolite facies, intruded by syn- to post-tectonic plutonic bodies[7]. These geological conditions are favourable for orogenic gold mineralization, which typically develops during late-stage deformational events associated with regional metamorphism[8].

This study aims to characterize the geological setting and geochemical signatures of gold deposits in the Menge area through integrated field mapping, petrographic analysis and whole-rock geochemistry. The objectives include: (1) documenting the lithological and structural controls on gold mineralization, (2) identifying hydrothermal alteration patterns, (3) determining geochemical characteristics of host rocks and (4) assessing the economic potential of gold deposits in the region.

Geological Setting

Regional geology

The Ethiopian basement complex forms part of the East African Orogen (EAO), which resulted from the collision between East and West Gondwana during Neoproterozoic-Cambrian assembly[9]. The EAO is subdivided into the Arabian-Nubian Shield (ANS) in the north and the Mozambique Belt in the south, with western Ethiopia representing a transition zone between these major tectonic domains.

The Western Ethiopian Shield consists of several lithotectonic domains, including from east to west: the Didesa, Kemashi, Dengi, Sirkole and Daka domains[7]. These domains are characterized by distinct lithological associations and metamorphic grades, reflecting complex tectonic evolution during Pan-African orogenesis.

The Tuludimtu Belt, which encompasses the study area, represents a major NNE-SSW trending orogenic belt composed of low-grade metavolcanic-sedimentary rocks intruded by various plutonic bodies[10]. Three major deformation episodes (D1-D3) have been recognized, with D1 characterized by westward-directed thrusting, D2 by upright folding and D3 by brittle-ductile strike-slip faulting.

Local geology

The Menge area is situated within the Sirkole Domain and comprises predominantly mafic to felsic intrusive rocks with subordinate metavolcanic-sedimentary sequences. The main lithological units include:

- **Metadiorite:** Medium to coarse-grained rocks with light Gray to dark pink coloration, composed primarily of feldspar and mafic minerals (biotite, hornblende) with lesser quartz and muscovite. These rocks exhibit variable deformation from massive to strongly sheared textures.
- **Metagranite:** Metamorphosed granitic rocks with Gray coloration and medium to coarse grain size. These units lack well-developed metamorphic fabrics and are exposed primarily in northwestern and southeastern portions of the study area.
- **Metavolcanic rocks:** Fine to medium-grained, dark green to brown mafic volcanic rocks exposed in central, northeastern and southwestern areas. These units display weak to moderate shearing parallel to regional foliation.
- **Quartzite:** Non-foliated metamorphic rocks composed predominantly of recrystallized quartz, exhibiting whitish coloration and high competency.
- **Metasandstone and slate:** Fine-grained metasedimentary rocks with variable metamorphic grade, occurring as minor components within the intrusive-dominated terrain.

Structural geology

The structural architecture of the Menge area reflects polyphase deformation consistent with regional Pan-African tectonism. The dominant structural elements include:

- **Foliation:** Penetrative S1 foliation striking NNE-SSW to N-S and dipping moderately to steeply westward (30-80°). This fabric is associated with D1 westward-directed thrusting.
- **Folds:** Minor syn- and antiformal folds with axes trending approximately N-S and gentle plunges. These structures are interpreted as parasitic folds related to major regional folding.
- **Shear zones:** Brittle-ductile shear zones striking NNE-SSW and dipping steeply westward. These structures served as fluid pathways for hydrothermal mineralization.
- **Fractures and joints:** Later brittle structures that cross-cut earlier fabrics and locally control quartz vein emplacement.

Methods

Field investigation

Systematic geological mapping was conducted at 1:25,000 scale using GPS positioning and detailed outcrop description. Structural measurements included foliation attitudes, fold axes, fracture orientations and kinematic indicators. Representative samples were collected from each major lithological unit, with emphasis on mineralized zones and altered rocks.

Sample preparation

Ten representative rock samples weighing approximately 1.5 kg each were collected for geochemical analysis. Samples included metavolcanic rocks, metadiorite, slate, metagranite, metagranodiorite, metasandstone, phyllite and quartzite. Sample preparation followed standard procedures including washing, drying, crushing and grinding to -200 mesh size.

Analytical methods

Major oxide concentrations were determined using X-ray fluorescence (XRF) spectrometry following lithium borate fusion for most elements and HF attack for SiO2. Trace element analysis was performed using inductively coupled plasma mass spectrometry (ICP-MS) after lithium borate fusion and acid dissolution. Gold concentrations were determined using fire assay preconcentration followed by atomic absorption spectrometry.

Data processing

Geochemical data were processed using GCDKit software for major element variation diagrams, tectonic discrimination plots and rare earth element patterns. Primitive mantle normalization followed[11], while chondrite normalization used Boynton[12] values.

Results

Petrography and mineralogy

Petrographic examination reveals that the Menge area rocks have experienced low-grade metamorphism under greenschist facies conditions. The metadioritic rocks contain primary assemblages of plagioclase + hornblende + biotite ± quartz, with secondary chlorite, sericite and epidote reflecting hydrothermal alteration.

Metavolcanic rocks display relict volcanic textures locally preserved despite metamorphic recrystallization. Primary assemblages include plagioclase + clinopyroxene ± olivine, with metamorphic overprints producing actinolite, chlorite and albite.

Ore mineralogy is dominated by pyrite, pyrrhotite, chalcopyrite and sphalerite, with gold occurring as fine inclusions within sulfide phases or as free particles associated with quartz veining.

Geochemical characteristics

Major oxides geochemistry: The analyzed samples display a wide range of SiO2 contents from 22.26 to 97.13 wt%, reflecting the diverse lithological assemblage. Most samples plot within gabbroic-dioritic to granodioritic fields on total alkali-silica (TAS) diagrams, indicating bimodal magmatic affinity.

MgO contents vary from 0.01 to 9.30 wt%, with mafic samples (M1, M2, M10) showing elevated values (7.11-9.30 wt%) consistent with primitive compositions. Fe2O3 concentrations range from 0.05 to 9.63 wt%, with higher values in mafic lithologies.

Al2O3 contents (1.30-11.59 wt%) and CaO values (0.07-14.04 wt%) show systematic variations related to degree of differentiation and alteration intensity.

Trace element geochemistry: Trace element patterns normalized to primitive mantle show moderate enrichment in large ion lithophile elements (LILE) such as Ba (124-937 ppm) and Sr (2.4-496 ppm) relative to high field strength elements (HFSE).

Notable features include:

- Negative Pb anomalies in most samples, indicating limited crustal contamination.
- Elevated Cr (36.89-278.94 ppm) and Ni (4.8-130.32 ppm) in mafic samples.
- Variable Cu (23.03-130.7 ppm) and Zn (27.42-106.66 ppm) concentrations.

Rare earth elements: Chondrite-normalized REE patterns display two distinct trends:

- Felsic samples show mild LREE enrichment with negative Eu anomalies.
- Mafic samples exhibit relatively flat patterns with minimal Eu anomalies.

These patterns suggest derivation from evolved tholeiitic magmas with variable degrees of plagioclase fractionation.

Gold mineralization

Gold concentrations in the analysed samples range from below detection limit to 15.13 ppm, with significant variations related to host rock lithology and proximity to quartz veining:

- **Quartzite (M6):** 15.13 ppm Au
- **Metadiorite (M10):** 8.2 ppm Au
- **Metagranite (M4):** 5.79 ppm Au
- **Metasandstone (M5):** 4.77 ppm Au
- **Metagranodiorite (M3):** 4.62 ppm Au
- **Slate (M7):** 4.14 ppm Au

The highest gold values are consistently associated with quartz vein intersections and zones of intense hydrothermal alteration.

Hydrothermal alteration

Multiple alteration types have been identified through field observation and petrographic analysis:

- **Chloritization:** Widespread replacement of mafic minerals by chlorite, particularly in metavolcanic and metadioritic hosts. This alteration is characterized by green coloration and extends 12-25 m from vein contacts.
- **Sericitization:** Development of fine-grained sericite after feldspar, commonly associated with gold-bearing zones and creating weak, friable textures.
- **Silicification:** Pervasive introduction of quartz, ranging from weak silica flooding to complete replacement. This alteration is most intense adjacent to auriferous quartz veins.
- **Carbonatization:** Local development of carbonate minerals, particularly calcite, associated with later-stage hydrothermal activity.
- **Kaolinization:** Limited argillic alteration of K-feldspar to kaolinite, creating soft, white clay-like textures.

Discussion

Petrogenesis and tectonic setting

The geochemical characteristics of Menge area rocks indicate derivation from evolved tholeiitic magmas with mantle source signatures. The bimodal nature of the suite, ranging from mafic to felsic compositions, suggests magmatic differentiation processes including fractional crystallization and possibly crustal assimilation.

Trace element systematics, particularly the moderate LILE enrichment and negative Pb anomalies, are consistent with arc-related magmatism typical of the Arabian-Nubian Shield. The absence of significant crustal signatures suggests limited interaction with older continental basement during magma genesis.

The tectonic setting appears transitional between arc and post-collisional environments, reflecting the complex evolution of the western Ethiopian terrane during Neoproterozoic assembly of Gondwana.

Gold mineralization characteristics

The gold deposits at Menge display characteristics typical of orogenic gold systems:

- **Structural control:** Mineralization is spatially associated with NNE-SSW trending shear zones developed during regional deformation.
- **Host rock association:** Gold occurs within low-grade metamorphic rocks, particularly at contacts between competent and incompetent lithologies.
- **Alteration assemblages:** The hydrothermal alteration suite (chlorite-sericite-carbonate-quartz) is characteristic of mesothermal conditions.
- **Ore mineralogy:** Simple sulfide assemblages dominated by pyrite and pyrrhotite with subordinate base metal sulfides.
- **Vein characteristics:** Gold-bearing quartz veins with associated wall rock alteration halos.

These features are consistent with orogenic gold deposits formed during late-stage orogenic processes, similar to the well-documented Lega Dembi deposit in southern Ethiopia.

Comparison with regional gold deposits

The Menge gold mineralization shows similarities to other Ethiopian deposits:

- **Lega Dembi:** Both deposits occur in shear zone-hosted quartz vein systems within low-grade metamorphic terranes, with comparable alteration assemblages and structural controls.
- **Workamba:** Similar brittle-ductile deformation and association with monzogranitic intrusions, though Workamba shows stronger base metal signatures.
- **Dul mountain:** Comparable setting within the western greenstone belt, with gold in quartz vein systems hosted by metavolcanic rocks.

However, the Menge deposit appears to have higher gold grades in certain lithologies, particularly quartzite units, which may reflect local concentrating mechanisms or proximity to primary sources.

Economic implications

The gold concentrations documented at Menge (4.14-15.13 ppm) are significantly above typical crustal abundances and approach economically interesting levels. Several factors support the potential for economic mineralization:

- **Grade distribution:** Consistent gold values across multiple lithologies suggests extensive mineralization.
- **Structural setting:** Regional shear zone systems provide potential for continuous ore shoots.
- **Alteration intensity:** Well-developed hydrothermal alteration indicates effective fluid flow and metal precipitation.
- **Geochemical associations:** Elevated pathfinder elements (Cu, Zn, As) suggest additional metal potential.

However, detailed resource evaluation would require systematic drilling and metallurgical testing to assess tonnage, grade continuity and processing characteristics.

Fluid sources and timing

The association of gold mineralization with regional deformation and metamorphism suggests that ore fluids were likely generated during peak thermal conditions. The shear zone-hosted nature of the deposits indicates syn- to late-kinematic timing relative to regional deformation.

Fluid inclusion studies would be required to constrain temperature, pressure and compositional characteristics of mineralizing fluids. However, the alteration assemblages suggest mesothermal conditions (300-500°C) typical of orogenic gold systems.

The proximity to syn-tectonic intrusions suggests possible magmatic fluid contributions, though metamorphic devolatilization reactions likely provided the dominant fluid source.

Conclusions

This study provides the first systematic geochemical investigation of gold deposits in the Menge area, western Ethiopia. The following conclusions can be drawn:

- **Geological setting:** The Menge area comprises low-grade metamorphic rocks of the Arabian-Nubian Shield, dominated by metadioritic to metagranitic intrusions with subordinate metavolcanic-sedimentary sequences.
- **Geochemical signatures:** Host rocks display evolved tholeiitic compositions derived from mantle sources, with geochemical characteristics consistent with arc-related magmatism during Neoproterozoic orogenesis.
- **Gold mineralization:** Significant gold concentrations (4.14-15.13 ppm) occur in association with shear zone-hosted quartz vein systems, with highest grades in quartzite units.
- **Alteration patterns:** Well-developed hydrothermal alteration includes chloritization, sericitization, silicification and carbonatization, forming distinctive halos around mineralized structures.
- **Deposit type:** The structural setting, alteration assemblages and ore characteristics are consistent with mesothermal orogenic gold deposits similar to other Ethiopian occurrences.
- **Economic potential:** The documented gold grades and geological setting suggest significant potential for economic mineralization, warranting further detailed exploration.

These findings contribute to understanding of gold metallogeny in the western Ethiopian greenstone belt and provide a foundation for future exploration programs. The results demonstrate that systematic geochemical investigation can effectively identify and characterize gold mineralization in underexplored terranes of the Arabian-Nubian Shield.

Future work should focus on detailed structural analysis, expanded geochemical sampling, geophysical surveys and systematic drilling to fully evaluate the economic potential of the Menge gold deposits.

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