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Structural Evolution and Constraints on Gold Mineralisation in the North-East Section of the Kibi-Winneba Greenstone Belt, Southeastern Ghana

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1 ABSTRACT

Geological structures exert fundamental control on gold mineralisation by governing fluid migration, permeability development, and sites of hydrothermal deposition. The northeast section of the Kibi-Winneba Belt, southeastern Ghana, occupies a structurally intricate yet poorly constrained segment of the Paleoproterozoic Birimian terrane. Despite its proximity to the Ashanti and Sefwi belts, its structural evolution has remained unresolved. This study addresses three questions: which structural features define the northeastern segment of the belt; how structural evolution has controlled the distribution and orientation of gold-bearing zones; and how the deformation history compares with the Ashanti and Sefwi belts. The study investigates structural evolution and controls of gold mineralisation across five deposits — Big Bend, South Ridge, Double 19, Twin Zone, and Boomerang — within a 705 km^2 corridor. Integrated field mapping, drill-core logging, stereonet analysis, and aeromagnetic interpretation were employed. A D_1–D_4 deformational history associated with the Eburnean Orogeny is revealed. Early D_1 deformation produced S_0/S_1 composite foliations (NE-SW trending, dipping 45°–70°) and tight folding, establishing mechanical anisotropies that controlled largely barren quartz-carbonate vein formation. Subsequent D_2–D_3 transpressional deformation generated penetrative S_2 cleavage (generally 046°/60°), regional folds, and brittle-ductile shear zones as primary conduits for auriferous fluids. Gold-bearing quartz veins are concentrated at intersections of S_2 foliations, reactivated shear zones, and fold hinges. The belt represents a transitional structural environment between the Ashanti- and Sefwi-style deformation, providing an exploration framework for underexplored Birimian terranes.

2 INTRODUCTION

Geological Setting

Geological structures play an important role in mineral exploration, acting as pathways for mineralising hydrothermal fluids and facilitating the formation of mineralised systems (Austin & Blenkinsop, 2008). The Kibi-Winneba Belt (~60 km length), partitioned by Cape Coast granitoids into the northern Kibi and southern Winneba sections, exhibits an overall synclinal structure within southeastern Ghana's Paleoproterozoic Birimian terrane. Its western margin is characterised by steeply dipping, highly deformed metasediments with extensive graphite bands adjacent to mafic–intermediate metavolcanic flows.

Eburnean Orogeny

The Eburnean Orogeny is a two-phase event: Phase 1 (ca. 2.2–2.15 Ga) representing early arc accretion producing D_1 S_0/S_1 composite foliations, isoclinal folding, and early TTG intrusions; Phase 2 (ca. 2.15–2.0 Ga) representing the main transpressional event producing the dominant NE-SW structural grain via steep S_2 foliations, regional F_2 folds, and major crustal-scale shear zones, with peak metamorphism and widespread emplacement of Eburnean granitoids. Late D_3 introduced crenulation cleavages critical for auriferous vein formation. D_4–D_6 phases represent post-orogenic brittle overprints.

Research Gap

Although this deformation framework is broadly accepted, it is grounded almost entirely in studies of the Ashanti Belt and remains largely untested in the Kibi-Winneba Belt, which is poorly understood owing to limited mapping and exploration activity (Forson & Amponsah, 2023). The only study focused specifically on the Kibi section (Nkansa et al., 2022) examined mineralising fluid geochemistry only. Gold mineralisation occurs within quartz diorite altered to ankerite, with accompanying sulphidisation, as native gold in quartz-albite-carbonate veins associated with pyrrhotite, arsenopyrite, chalcopyrite, sphalerite, and pyrite.

3 RESEARCH QUESTIONS

1. What are the major structural features (shear zones, quartz veins, foliations, minor cleavages) that define the northeastern segment of the Kibi-Winneba Belt, and how do they control gold mineralisation?
2. How has the structural evolution of the Kibi-Winneba Belt influenced the spatial distribution and orientation of gold-bearing zones within the belt?
3. In what ways does the structural and tectonic framework of the Kibi-Winneba Belt compare with those of the Ashanti and Sefwi Gold Belts in terms of deformation history and mineralisation processes?

4 OBJECTIVES

- Map and characterize the structural elements (shear zones, quartz veins, foliations, minor cleavages) of the northeastern section of the Kibi-Winneba belt and assess their controls on gold mineralization.
- Establish the deformation sequence of the Kibi-Winneba belt and its influence on the localization on gold bearing zones
- Compare the structural and mineralisation characteristics of the Kibi-Winneba belt with the Ashanti and Sefwi gold belts to establish regional geological and metallogenic correlations.

5 GEOLOGICAL SETTING

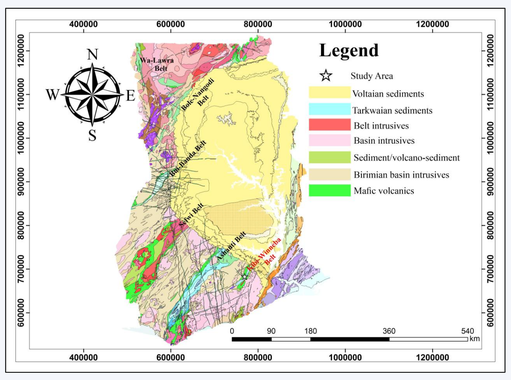

Fig. 1 Regional geology of Ghana illustrating the Birimian belts

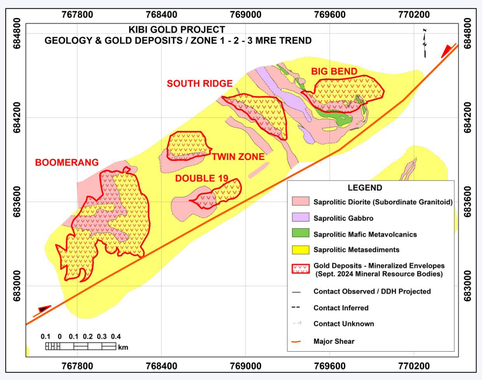

Fig. 2 Geological map of the Kibi Gold Project showing the study deposits

6 MINERAL RESOURCE ESTIMATES

Deposit	Category	Tonnage (Mt)	Grade (g/t Au)	Gold (koz)
Big Bend	*Indicated*	6.47	**1.48**	**307**
	Inferred	1.26	1.03	41
Boomerang	*Indicated*	**13.28**	0.99	**424**
South Ridge	*Indicated*	2.01	1.07	69
	Inferred	0.94	1.02	31
Double 19	*Indicated*	1.58	1.00	70
Twin Zone	*Indicated*	0.36	0.89	10

Source: Lomberg et al. (2024) for Xtra-Gold Mining Limited · Effective date: September 2024

7 METHODS

1. **Field Structural Mapping**
   Systematic measurement of foliations, folds, shear zones, faults, and quartz veins using Brunton compass from 81 trenches across five deposits (Big Bend, South Ridge, Double 19, Twin Zone, Boomerang). Field sketches and photographs documented mesoscopic structures and lithological associations.
   81 trenches
2. **Oriented Drill-Core Logging**
   159 oriented diamond drill holes logged (26 Big Bend, 53 Boomerang, 46 D19, 13 South Ridge, 21 Twin Zone). Alpha/beta angles converted to true orientations in Dips 7.0. Vein generations discriminated by mineralogy, fabric relationships, internal textures, and sulphide assemblage.
   159 drill holes
3. **Stereonet Analysis**
   Equal-angle lower-hemisphere projections in Dips 7.0. Kamb contouring, eigenvector analysis, and great-circle projections used to determine dominant structural sets, fold axes, cleavage geometries, and vein orientations relative to host foliations.
4. **Aeromagnetic Interpretation**
   High-resolution aeromagnetic data covering 705 km^2. First vertical derivative (1VD) maps delineated 465 form lines and 837 interpreted faults classified by relative age (D_1–D_5 inverted extensional, D_2–D_5 transpressional, D_6 brittle). MapInfo and Encom Discover used for azimuth analysis.
5. **Multi-Scale Integration**
   Field, drill-core, and geophysical datasets integrated in GeoArcGIS Pro and Leapfrog Geo for 3D visualisation of fold geometries. Regional correlation with Ashanti (Perrouty et al., 2012) and Sefwi (Grenholm et al., 2019) frameworks.

8 RESULTS AND DISCUSSIONS

Foliation Architecture: S_0/S_1 and S_2 Patterns; Evolution of Foliations, Cleavage and Fold Geometry

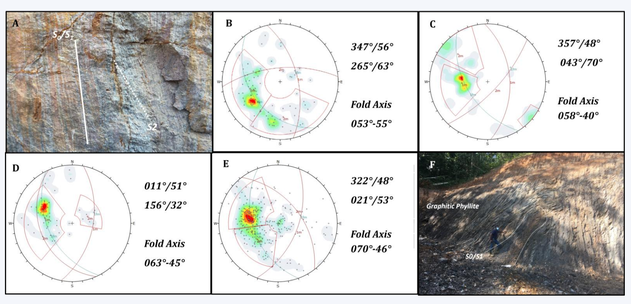

Fig. 3 (A and F) Outcrops Showing S_0/S_1 foliation. Stereographic Projection of S_0/S_1 measurements from (B) Big Bend Deposit, (C) Double 19, (D) Twin Zone and (E) Boomerang Deposit.

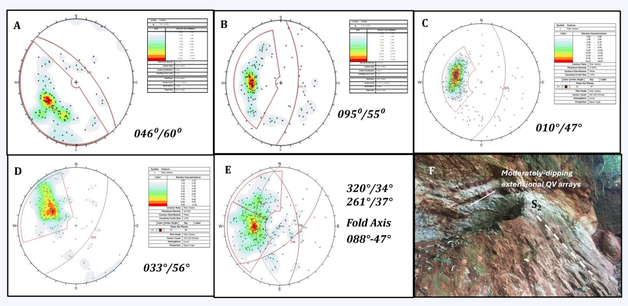

Fig. 4 Stereographic Projections of S_2 Foliation Measurements From (A) Big Bend, (B) South Ridge (C) Double 19 (D) Twin Zone and (E) Boomerang Deposits. (F) Photograph Of Outcrop at Double 19 Showing Penetrative S_2 Foliation Through Diorite Unit and Moderately Dipping Quartz Veins.

Shear-Zone Development and Strain Partitioning

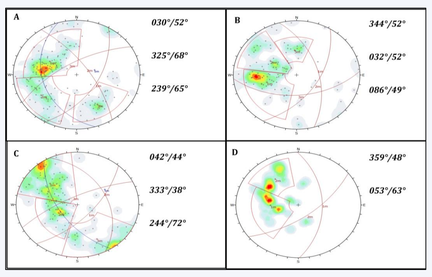

Fig. 5 Stereographic Projections of Shear Measurements From (A) Big Bend Deposit, (B) South Ridge, (C) Double 19 and (D) Boomerang Deposit

Vein Styles, Fluid Emplacement, and Gold Localisation

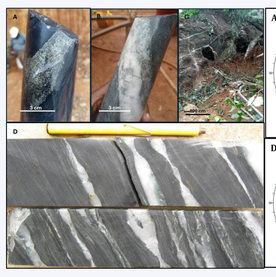

Fig. 6 Field and core photographs showing quartz vein types. (A) Foliation-concordant Quartz-Calcite vein (B) Auriferous Quartz-Albite-Ankerite vein (C) Crosscutting quartz vein sets (D) Foliation-concordant vein.

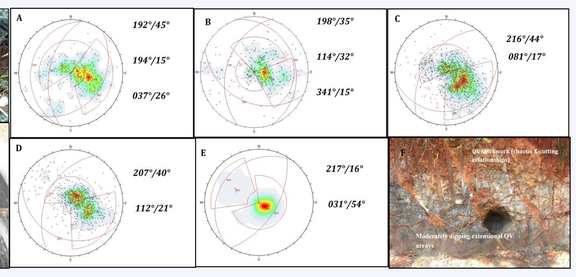

Fig. 7 Stereographic Projections of Quartz Veins Measurements From (A) Big Bend Deposit, (B) South Ridge, (C) Double 19, (D) Twin Zone and (E) Boomerang Deposit. (F) Extension Veins in Weathered Diorite Unit Displaying Chaotic Crosscut Relationships and Moderately Dipping Vein Sets

Integrated Structural Evolution of the Big Bend-Boomerang Corridor in a Regional Context

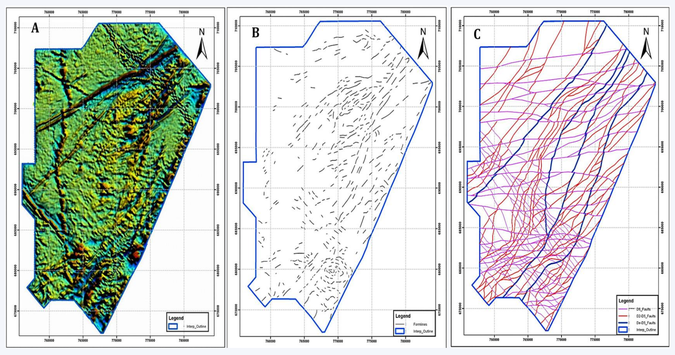

Fig. 8 Structural Interpretation of Magnetic Data. (A) Manipulation of 1VD Data, (B) Form Line Mapping, and (C) Fault Network (structural base layer/age and cross cutting relationships/fault order).

Evolution of Structures and their Controls on Mineralisation

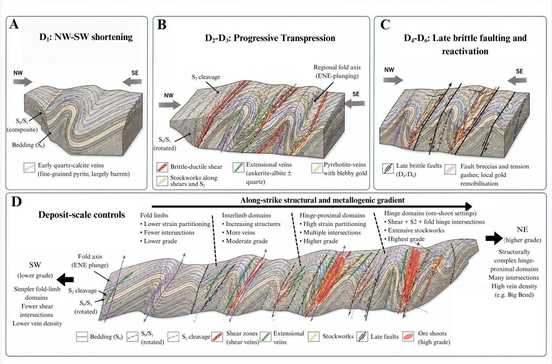

Fig. 9 Conceptual model of the structural evolution of the Big Bend-Boomerang corridor, northeastern Kibi-Winneba Belt, and its control on gold mineralisation (not to scale).

Regional Comparison (Ashanti and Sefwi belts) and Metallogenic Sequence

- The Big Bend-Boomerang corridor shares structural similarities with both the Ashanti and Sefwi belts, but with notable local variations.
- **S_0/S_1 foliation** in the northeast section is strongly transposed with paired maxima, consistent with the intense D_1-D_2 deformation of the Ashanti Belt; the Sefwi Belt shows a less transposed, more locally variable fabric; the Kibi-Winneba Belt mirrors both depending on location.
- **S_2 fabric** varies significantly along strike (steep ENE at Big Bend/South Ridge to NNE at Double 19/Twin Zone to folded at Boomerang), contrasting with the regionally consistent steep S_2 of the Ashanti Belt; the Sefwi Belt is intermediate in consistency.
- **Shear structures** are multiphase and spatially variable (three sets at Big Bend/South Ridge/Double 19; two at Boomerang; absent at Twin Zone), unlike the Ashanti Belt's major continuous transcurrent/reverse shear zones; the segmented, distributed shear of the Sefwi Belt is a closer analogue.
- **Quartz vein patterns** are variable in orientation and dip across the corridor, contrasting with the predictable shear- and fold-controlled vein geometry of the Ashanti Belt; the Sefwi Belt again occupies an intermediate position.
- **Overall**, the Kibi Gold Belt occupies a transitional structural regime; its variable S_2, mixed shear intensity, and diverse vein orientations resemble the Sefwi Belt, while its intense foliation transposition and steep ENE-plunging fold systems align more closely with the Ashanti Belt.

9 CONCLUSIONS

1. The corridor records a polyphase D_1–D_6 structural evolution. Early S_0/S_1 foliations (D_1, ca. 2.2–2.15 Ga) established mechanical anisotropies controlling barren vein emplacement. D_2–D_3 transpression produced S2 cleavage varying from steep ENE-E (Big Bend) to NNE (central) to folded geometry (Boomerang), reflecting hinge-controlled refolding.
2. Shear zones — three dominant sets at Big Bend, South Ridge, and Double 19; two at Boomerang — provided conduits for auriferous fluid flow. Highest grade (1.48 g/t Au, Big Bend) coincides with maximum shear complexity and fold-hinge proximity, consistent with repeated dilation during progressive D_2–D_3 deformation.
3. Auriferous quartz-ankerite(-albite) veins form as shear, extensional, and stockwork types along S_2 foliations. Vein systems simplify southwestward from three-set (Big Bend, South Ridge) to two-set geometries, mirroring decreasing structural complexity and grade.
4. The corridor is transitional between the Ashanti Belt (intense transposition, continuous shears, predictable geometry) and Sefwi Belt (moderate fabric intensity, variable S_2, heterogeneous veins), illustrating along-strike Birimian deformation variation.
5. Exploration targeting should prioritise structural intersections, reactivated shear corridors, fold hinges, and diorite-phyllite competency contrasts. This integrated structural–aeromagnetic workflow is a transferable template for other underexplored Birimian terranes.

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