

Tectonic and structural controls on mineralization and energy resources in Ethiopia: A comprehensive review

Abstract

Ethiopia hosts a diverse suite of mineral and energy resources that are intrinsically linked to its dynamic tectonic framework. Long lived processes such as continental rifting, faulting, magmatism, and basement deformation have created structurally controlled environments conducive to the concentration of economically significant resources. This review evaluates how structural features—including rift zones, major faults, shear zones, and inherited basement fabrics—govern the occurrence, distribution, and genesis of key geological resources in Ethiopia. Particular emphasis is placed on the Main Ethiopian Rift, Afar depression, and Precambrian terranes as primary structural domains influencing the localization of mineral deposits, geothermal systems, industrial minerals, and potential hydrocarbon accumulations. By synthesizing geological, structural, and resource studies, this review highlights the importance of integrating structural geology into resource exploration strategies. A comprehensive understanding of structural controls not only enhances resource discovery but also underpins sustainable development and informed decision making. The structural evolution of Ethiopia thus provides critical insights into the relationships between tectonics and economic geology in rifted continental settings.

Keywords: structural control, tectonics, economic geology, faults, mineralization

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Introduction

The relationship between tectonic processes and the formation, distribution, and accessibility of natural resources has been a central theme in Earth sciences for decades. Structural features such as faults, fractures, shear zones, and rift-related deformation play a critical role in controlling fluid pathways, creating traps, and focusing mineralizing processes.^{1,2} Ethiopia provides an exceptional geological setting to investigate these relationships due to its position at the heart of active tectonic and magmatic processes within the East African Rift System (EARS) and the presence of extensive Precambrian basement terranes.

The EARS, one of the most prominent continental rift systems globally, is actively dissecting the Ethiopian lithosphere, generating conditions favorable for geothermal energy development, mineralization, and the formation of sedimentary basins with hydrocarbon potential.^{3,4} Superimposed on this is the ancient Arabian–Nubian Shield (ANS), part of the East African Orogen, which hosts major shear zones, suture belts, and deformation corridors that strongly influence the localization of gold, base metals, and industrial mineral deposits.⁵ Ethiopia’s complex interplay of active rifting, magmatism, and inherited basement structures has produced diverse geological environments that support gold-bearing shear zones, volcanic-hosted geothermal fields, salt accumulations, and sedimentary basins with hydrocarbon prospects. Despite this wealth of resources, understanding the structural controls governing their distribution remains a key challenge for exploration and sustainable resource development.

This review provides a comprehensive synthesis of how tectonic structures influence Ethiopia’s economic geology. By integrating geological, structural, and resource data, the study highlights critical relationships that enhance resource discovery, inform exploration strategies, and contribute to responsible resource management.

Tectonic framework of Ethiopia

Ethiopia’s geological and resource distribution patterns are strongly influenced by its position within the East African Rift System (EARS), a major zone of active continental extension and lithospheric deformation (Figure 1). The EARS stretch from the Afar Depression in the northeast to Mozambique in the south, making it a natural laboratory for studying rift evolution and its control on geological resources.^{5,6}

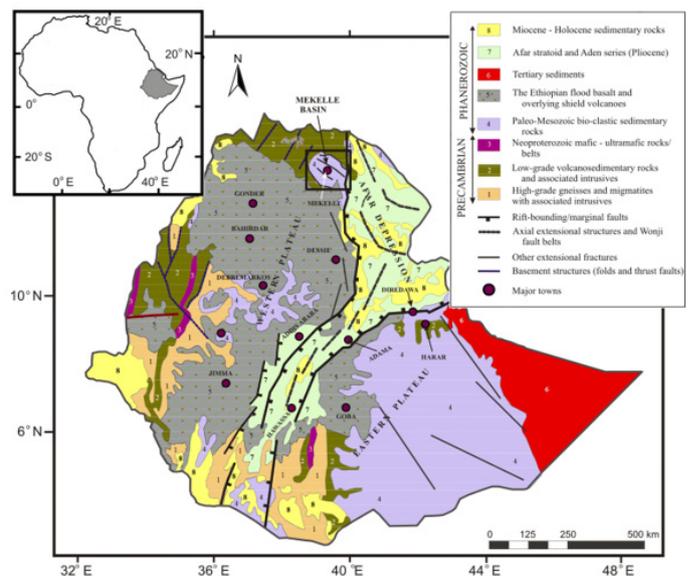


Figure 1 Geologic and Tectonic Map of Ethiopia showing major rift zones, fault systems and Precambrian terranes.¹³

Within Ethiopia, the Main Ethiopian Rift (MER) serves as the principal rift segment, trending NE–SW and dissecting the Ethiopian

Plateau. The MER is characterized by pronounced faulting, volcanism, and crustal thinning, all of which significantly shape the structural framework and resource potential of the region.⁷ To the northeast, tectonic complexity increases in the Afar Depression, where the MER intersects the Red Sea and Gulf of Aden rift systems to form the Afar triple junction. This region represents a key zone of lithospheric divergence, volcanic activity, and crustal thinning, providing critical insight into continental breakup processes.^{8–10} Beneath much of Ethiopia lies the Precambrian Arabian–Nubian Shield (ANS), a region of ancient crystalline basement rocks hosting major shear zones, suture belts, and gold-bearing greenstone belts, reflecting the country's long and complex tectonic history.

In addition to the rift and shield domains, the southeastern part of Ethiopia contains the Ogaden Basin, a vast sedimentary basin with significant hydrocarbon potential. Its structural development is controlled by inherited basement fabrics and extensional fault systems related to rifting episodes.¹¹ The structural architecture of Ethiopia includes numerous tectonic elements such as rift-related faults (e.g., the Wonji Fault Belt) and prominent border faults that accommodate active extension.⁴ Basement shear zones, strike-slip faults, and extensional structures further complicate the deformation history. Magmatic lineaments and volcanic centers along the MER and Afar regions illustrate the interaction between tectonic forces and magmatism. Collectively, these structural features strongly influence sedimentary basin geometry and the localization of mineral deposits, geothermal systems, and hydrocarbon accumulations throughout the country.

Structural controls on mineral resources

The formation and distribution of Ethiopia's mineral resources are strongly controlled by the country's complex structural framework, shaped by both ancient tectonic processes and ongoing rift-related deformation. Gold and base metal deposits display a pronounced structural association, with major mineralization zones occurring along shear zones, suture belts, and fault systems.¹²

The Adola Gold Belt in southern Ethiopia exemplifies shear zone-hosted gold mineralization. Significant deposits, including Lega Dembi and Sakaro, are concentrated along NE–SW and N–S trending shear zones, which acted as conduits for mineralizing fluids and localized ore deposition.¹³ Similarly, volcanogenic massive sulfide (VMS) and orogenic gold deposits within Neoproterozoic terranes are structurally confined along suture zones and deformation corridors of the Arabian–Nubian Shield, emphasizing the influence of ancient tectonic boundaries on mineral localization. In addition to Precambrian-hosted deposits, younger epithermal and porphyry-type systems are spatially linked to active magmatism and faulting along the Main Ethiopian Rift (MER) and Afar region. Extensional structures in these rift segments create favorable conditions for hydrothermal fluid circulation and metal enrichment.^{14,15}

Beyond precious and base metals, structural features also influence the distribution of industrial minerals and construction materials. The MER and Afar basins host abundant volcanic products, such as pumice, scoria, and basalt, widely quarried for construction. Industrial minerals, including bentonite and kaolin, occur within volcanic terrains and rift-related hydrothermal alteration zones. Extensive salt deposits of the Afar Depression are structurally confined within subsiding rift basins, where fault-controlled subsidence and high evaporation rates enabled the accumulation of thick evaporite sequences.¹⁵

These examples demonstrate that both ancient basement structures and active rift-related faulting play decisive roles in the localization,

formation, and accessibility of Ethiopia's economically significant mineral resources. Figure 2 illustrates typical structural controls: shear zones facilitate gold mineralization, fault intersections create fluid pathways for copper deposition, and structural traps in anticlines confine hydrocarbon accumulation. These scenarios highlight the central importance of structural interpretation in exploration geology.

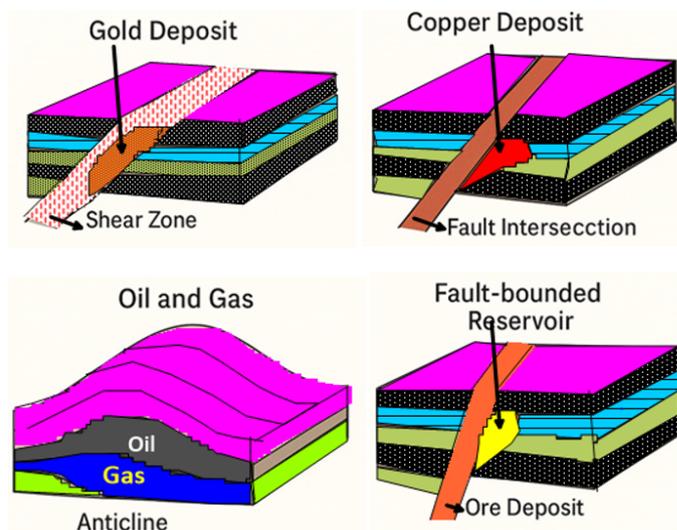


Figure 2 Conceptual model illustrating structural influences on mineral resources, including shear zone-controlled gold, fault intersection copper deposition, and hydrocarbon traps in anticlines.

Structural influences on energy resources

Structural controls are fundamental to the distribution and accessibility of Ethiopia's energy resources, particularly geothermal and hydrocarbon systems. Geothermal potential is closely linked to the EARS tectonic framework, especially along the MER and Afar Depression. Active rifting, magmatic intrusions, and associated structures such as fault intersections, caldera structures, and volcanic complexes facilitate the circulation of heat and hydrothermal fluids. These structures serve as conduits for geothermal fluids, defining prime exploration targets. Major geothermal fields, including Aluto-Langano, Tendaho, Corbetti, and Dofan, are situated within these structurally controlled zones, where fault networks enhance permeability and allow upward migration of heat from magmatic sources.¹⁶

Ethiopia's sedimentary basins, particularly the Ogaden and Abay (Blue Nile) basins, exhibit hydrocarbon potential governed by structural controls. Rift-related fault traps, tilted fault blocks, anticlines, fault-bounded basins, and basement highs provide critical trapping mechanisms, while syn-rift and post-rift sedimentary sequences create favorable conditions for source rock maturation, migration, and accumulation.^{17–19} Understanding the structural architecture of these basins is therefore essential for efficient energy exploration and development (Figure 3).

Case studies: Structural control and resource localization

Several case studies illustrate the influence of tectonic structures on resource formation and accessibility in Ethiopia. The Adola Gold Belt demonstrates how N–S and NE–SW trending shear zones act as conduits for hydrothermal fluid flow, producing significant gold mineralization. Structural intersections and dilation zones enhance permeability, while lithological contrasts between mafic-ultramafic

rocks and felsic intrusions further localize mineralization.^{20,21} Despite decades of exploration, gaps remain in understanding deep structural frameworks, highlighting the need for integrated geophysical and structural investigations.

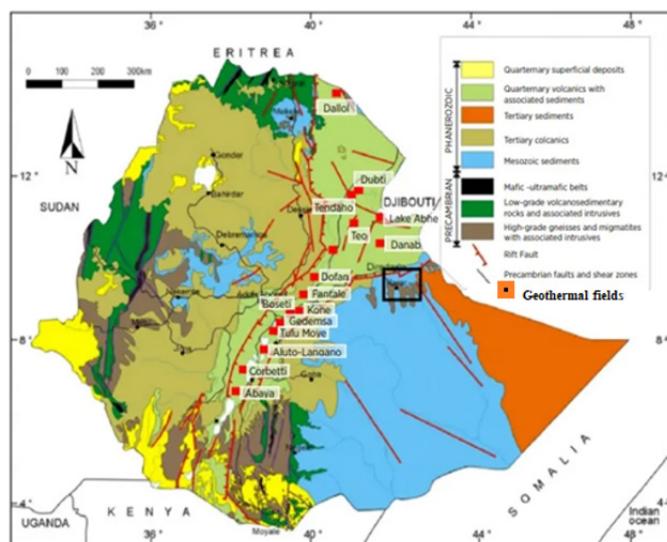


Figure 3 Geothermal fields along the Main Ethiopian Rift and associated fault systems.²⁰

The Aluto-Langano geothermal field, located along the Wonji Fault Belt, exemplifies the role of fault-controlled permeability in geothermal development. Extensional faulting and shallow magmatic intrusions facilitate hydrothermal fluid circulation, while relay zones and fault intersections influence well productivity.^{22–24} Advanced geophysical imaging and 3D structural modeling are essential to resolve subsurface fault architecture and predict reservoir behavior accurately. In the Afar Depression, extensive salt and evaporite deposits are structurally confined within subsiding rift basins. Normal faults and graben structures control accommodation space for evaporite deposition, highlighting the relationship between tectonics, basin evolution, and resource preservation.^{23,24}

Integrated approaches to resource exploration

Effective resource exploration in Ethiopia requires an integrated, multidisciplinary approach due to complex structural controls. Modern exploration combines structural mapping, geophysical surveys, and geochemical analyses to provide holistic understanding.²⁵ High-resolution remote sensing, field-based structural analysis, and InSAR mapping allow detailed delineation of fault networks, shear zones, and deformation patterns. Geophysical methods, including seismic reflection, gravity, and magnetic surveys, further reveal subsurface structures essential for resource accumulation.

Geochemical and mineralogical analyses, such as fluid inclusion studies, isotope geochemistry, and alteration mapping, bridge surface observations and subsurface models, characterizing ore-forming processes and hydrothermal pathways.^{26–28} Integrated 3D geological modeling platforms, supported by GIS and machine learning, can synthesize diverse datasets, improve predictive capabilities, and guide exploration in structurally complex terrains.^{29,30}

Implications for sustainable resource development

Understanding structural controls is critical for sustainable resource development, reducing exploration risks and improving success rates. Accurate characterization of faults, shear zones, and magmatic intrusions enables targeted exploration, minimizing unnecessary drilling.³⁰ Knowledge of structural influences also mitigates geohazards, including earthquakes, ground deformation, and fluid-induced seismicity in geothermal zones. Integrating structural geology into resource management supports Ethiopia's long-term development by promoting responsible exploitation of geothermal, mineral, and hydrocarbon resources. This approach balances economic benefits with environmental protection and social well-being.³¹ Achieving these outcomes requires multidisciplinary collaboration, investment in geoscientific research, and capacity building to apply integrated structural models effectively in policy and industry frameworks.

Conclusion

Ethiopia's tectonic evolution, located at the intersection of the EARS and the Afar Triple Junction, fundamentally influences its economic geology and resource endowment. Ongoing continental rifting, magmatism, and crustal deformation produce diverse structural features from Proterozoic basement shear zones to active rift faults and volcanic complexes that control the localization and accessibility of mineral and energy resources. Shear zones enhance mineralization by serving as fluid pathways, while fault intersections and relay zones in rift settings control geothermal fluid circulation and heat flow. Rift-bounding faults and basin architecture determine hydrocarbon trap geometries in the Ogaden and Abay basins, emphasizing structural frameworks' critical role in resource formation. Despite advances, gaps remain in fully resolving 3D structural complexity at depth, limiting precise targeting and risk assessment. Addressing these gaps requires high-resolution structural mapping, advanced geophysical imaging, and geochemical characterization, integrated via 3D modeling platforms with GIS and machine learning.³² Collaboration between academia, industry, and government agencies, alongside capacity building in advanced exploration technologies, is essential to responsibly unlock Ethiopia's resource potential. Integrating structural geology within a multidisciplinary framework advances scientific understanding and underpins sustainable resource management in this tectonically dynamic region.

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Data availability statement

The data supporting the findings of this study are provided within the manuscript as guidelines of review article.

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