The Importance of Structural Geology in Controlling Mineral Deposit Formation

Mike Robertson
The MSA Group
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The Geological Society of Zimbabwe

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Overview

- **Aim of the talk:** Demonstrate structural controls across mineral deposit types.
- Why is structural geology important in mineral systems?
- Structural controls on different mineral deposit types (at different scales).
- Examples:
  - Orogenic gold deposits: Sheba Mine, Barberton Greenstone Belt.
  - Sediment-hosted copper deposits: Chu Sarysu Basin, Kazakhstan & Kamoa-Kakula, DRC.

Why is structural geology important?

- Most mineral deposit types are controlled by structural geology.
- Structural geology plays a fundamental role in the formation, localization, and preservation of mineral deposits across a wide range of tectonic settings.
- Structure can *influence* mineral deposit formation or exert a *direct control*.
- Structural control:
  - Faults, shear zones, fracture networks, folds, rheological contrasts and contacts:
    - → Act as primary pathways for mineralizing fluids
    - → Create traps or openings where minerals precipitate
    - → Influence rock permeability
- Structural processes operate at multiple scales - from regional tectonic architecture to microscale fracture networks



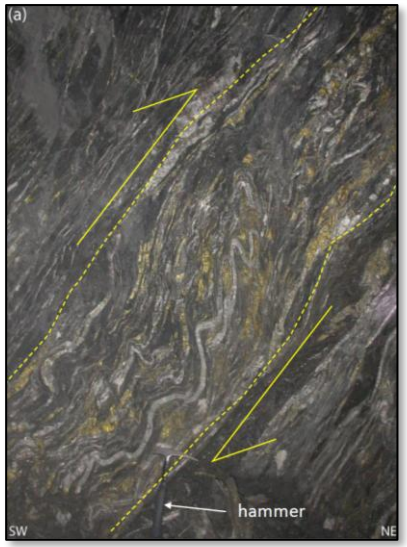
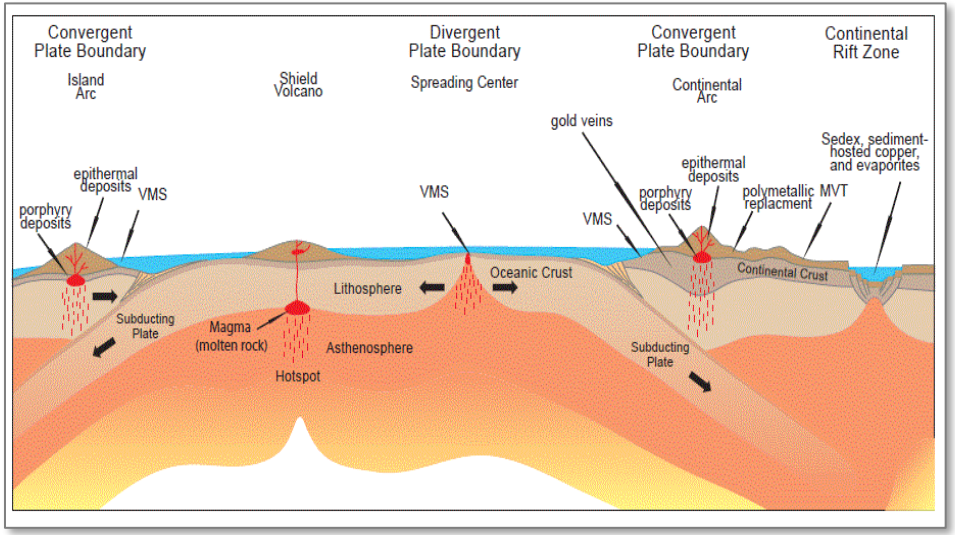


Plate Tectonics – the Big Picture

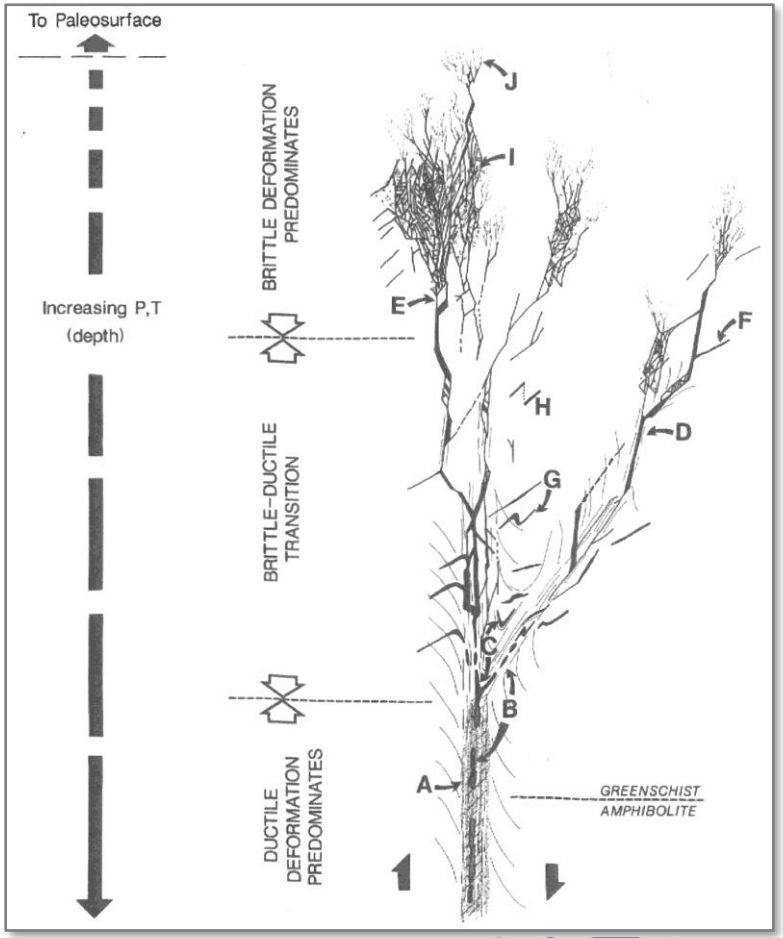
- Mineral deposit types are strongly related to tectonic setting.
- Tectonic setting: a first order control on the structural framework which is a key component of a mineral system.
- Convergent plate margins
  - Subduction zones → accretionary complex → magmatic arcs
  - Porphyry copper; epithermal gold; orogenic gold
- Divergent plate margins
  - Mid-oceanic rifts (VMS deposits); intracontinental rifts (sed-hosted Cu; SEDEX)
- Dynamic 4D space-time interplay between deformation, fluid flow pathways and depositional sites.



earthresources.sakura.ne.jp

Structures as Pathways and Traps

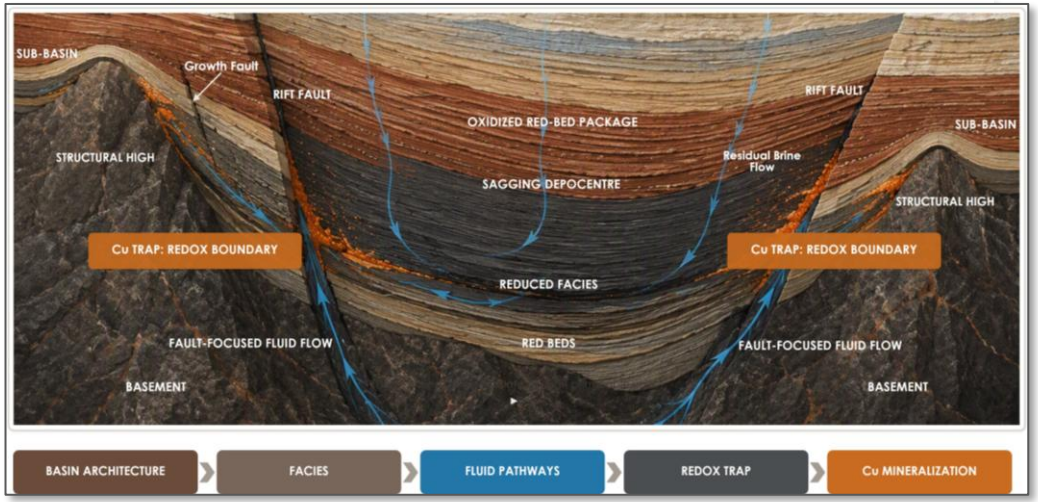
- Structurally-controlled gold deposits
  - Associated with major brittle-ductile fault systems and shear zones (10-12km depth).
  - Vertically extensive hydrothermal systems driven by an inter-connected network of faults, shear zones and veins.
  - Episodic faulting pumps gold-bearing fluids through evolving fracture networks.
  - Spatial and temporal association with large (crustal scale) shear zones. On a deposit-scale, gold mineralization is commonly hosted in 2nd and 3rd order structures.
  - Association with major lithological contacts and terrane boundaries with strong rheological (competency) contrasts.
  - A common spatial association with intrusives.
  - Fractal.

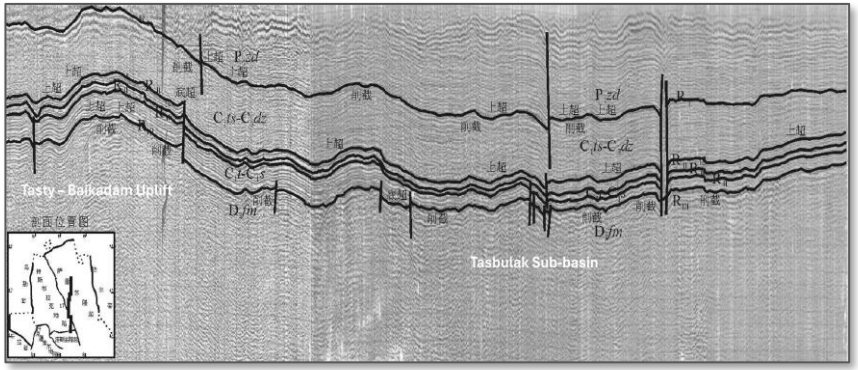


Colvine et al. (1984)

Regional Scale – SH Copper

- Structure is important throughout sedimentary basin history.
- Basin architecture defined by fault-bounded rift basins and sub-basins (half grabens) and local depocenters.
- Faults influence subsidence rates, stratigraphic thickness.
- Faults acts as permeability pathways facilitating basin-wide and local fluid flow.
- Basement topography and folding also influence and control basinal brine fluid movement both as pathways and traps.

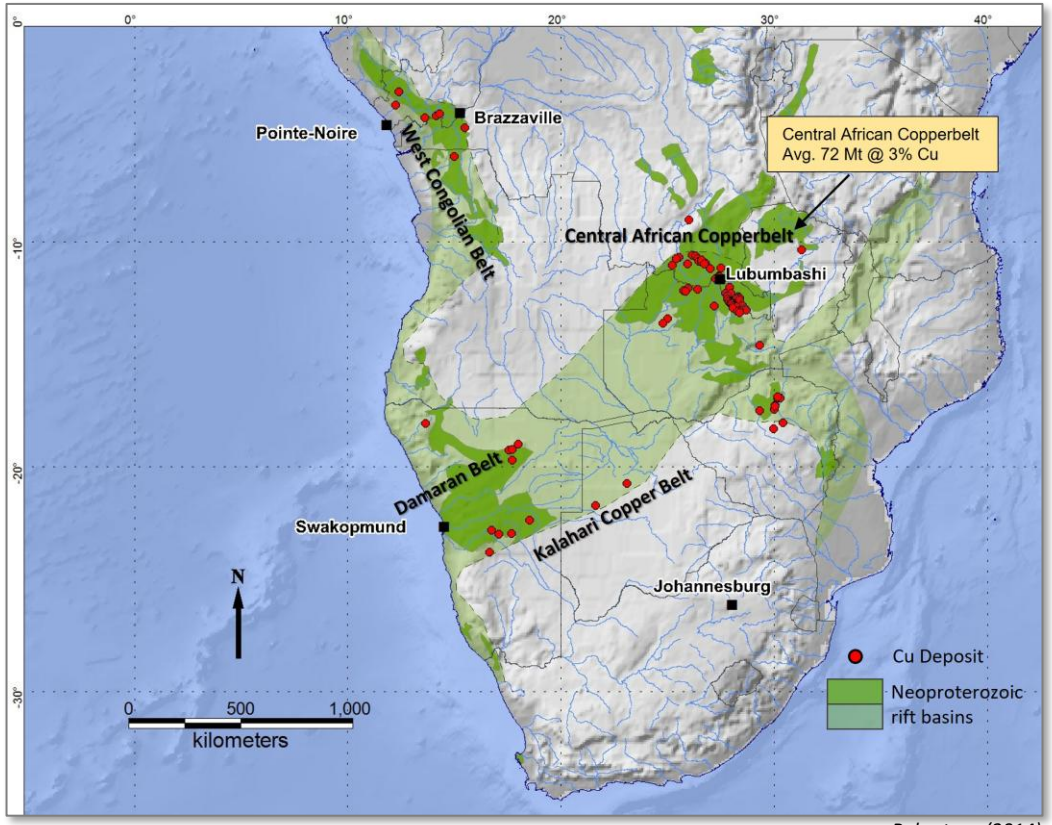




Haiping and Heng (2008)

Regional Scale – SH Copper

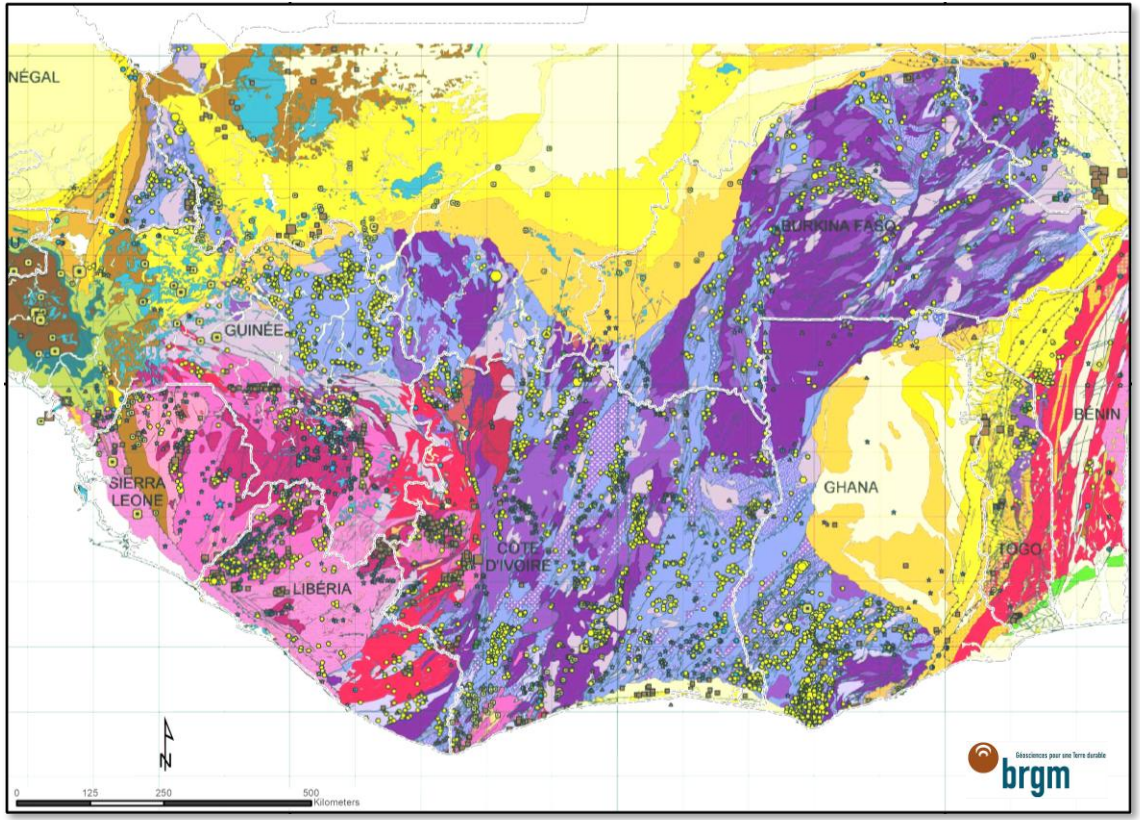
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- **Example – Central African Copperbelt**



Robertson (2014)

Regional Scale – Orogenic Gold

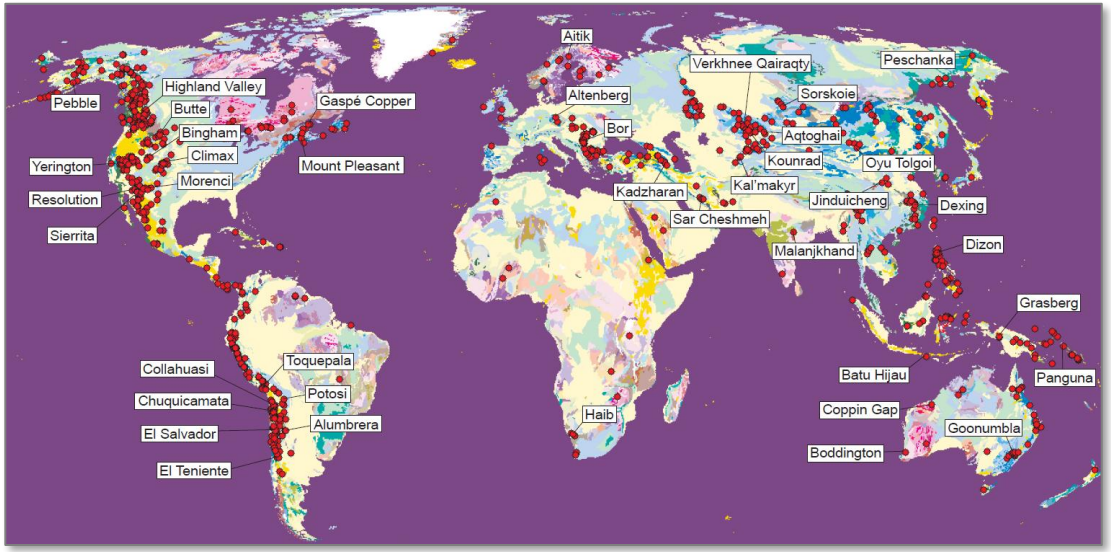
- Compressional, extensional, transpressional tectonic regimes → large-scale structural architecture determines mineral system fertility .
- Terrane boundaries, major shear zones, crustal-penetrating faults act as long-lived conduits:
  - Control hydrothermal fluid flow, heat distribution, magma emplacement
- Structures help localize deposit types
- Reactivation of older inherited structures influences stress distribution and permeability
- **Example – West African goldfields**



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Regional Scale - PCDs

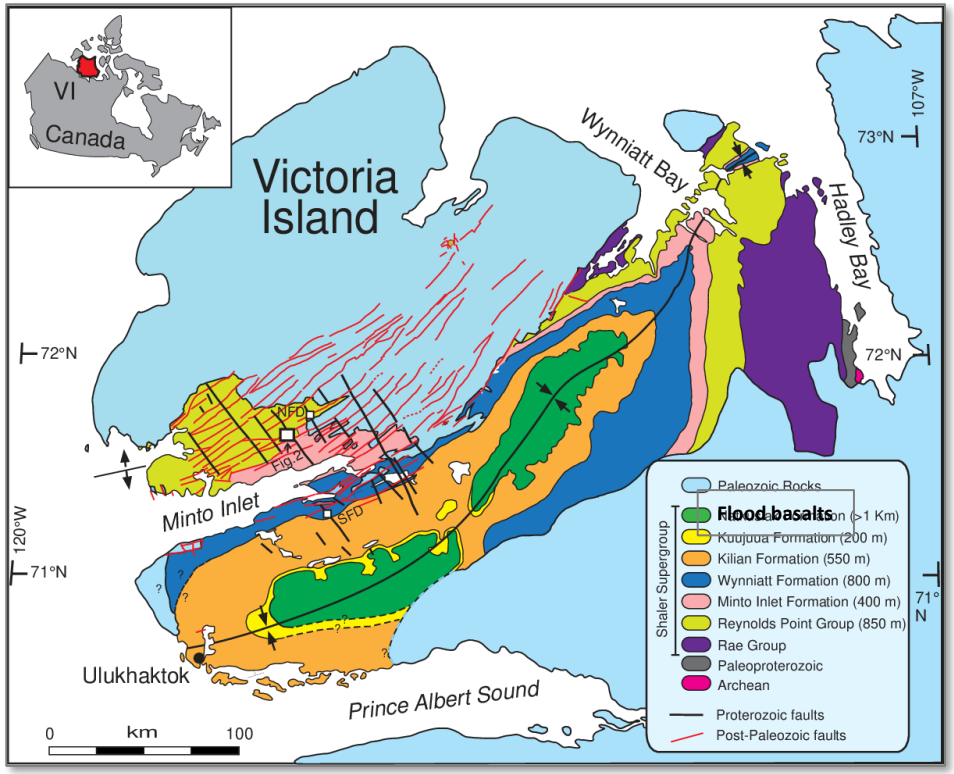
- Linear metallogenic provinces mostly related to convergent plate boundaries in continental and island-arc setting.
- Primarily influenced by (arc-parallel) deep-seated fault systems controlling magma ascent.
- Long-lived, reactivated structures are especially important because they repeatedly channel magma and fluids.
- Dilatational zones such as intersecting faults and strike-slip pull-apart structures are important for focusing magma flow.
- **Example – Porphyry Cu ± Mo ± Au belts**



Sinclair (2007), Kirkham and Dunne (2000)

Regional Scale – Magmatic Ni-Cu-PGEs

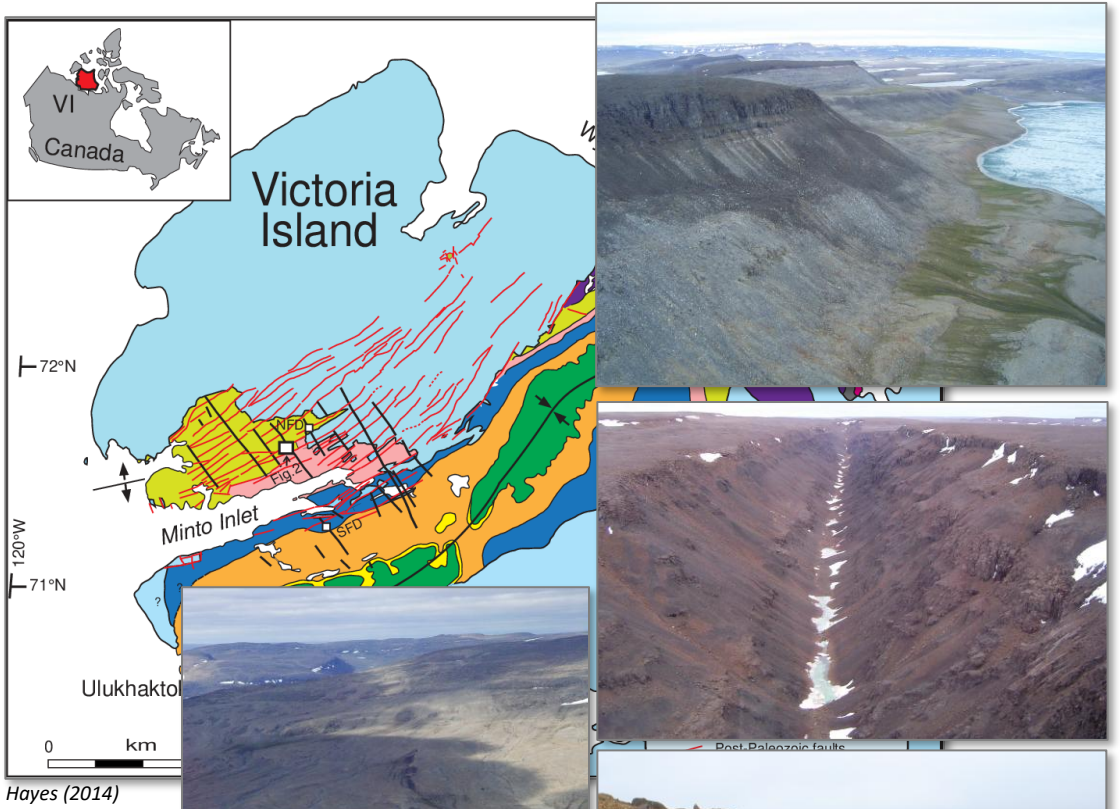
- Main structural controls on magmatic Ni-Cu-PGE deposits operate at several scales, from lithospheric-scale fault corridors to individual magma conduits.
- Deep-seated crustal and lithospheric faults provide pathways for mantle-derived mafic-ultramafic magmas.
- Largest deposits are commonly associated with major crustal-scale fault systems that focus mantle-derived magma into the upper crust.
- Reactivation of older inherited structures influences stress distribution and permeability.
- **Example – Franklin magmatic event**



Hayes (2014)

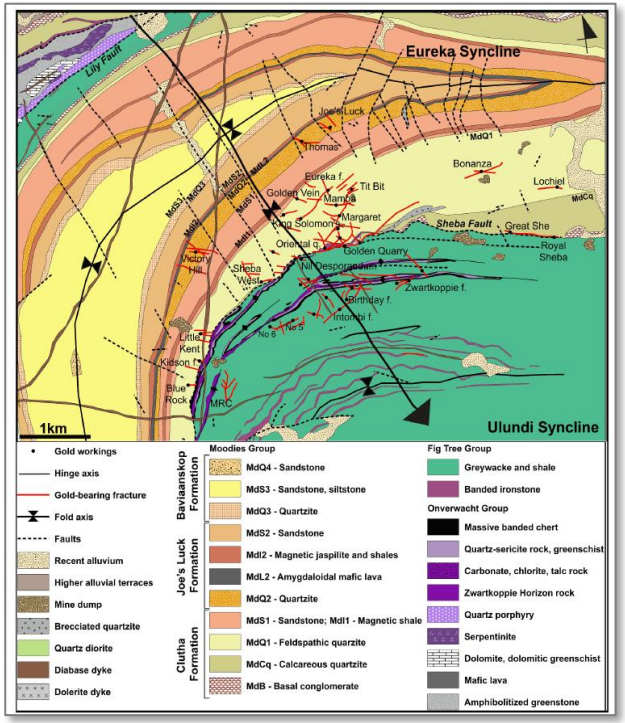
Regional Scale

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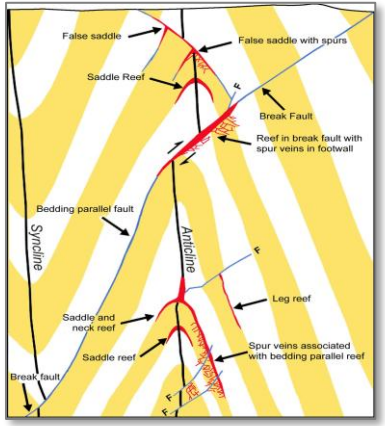


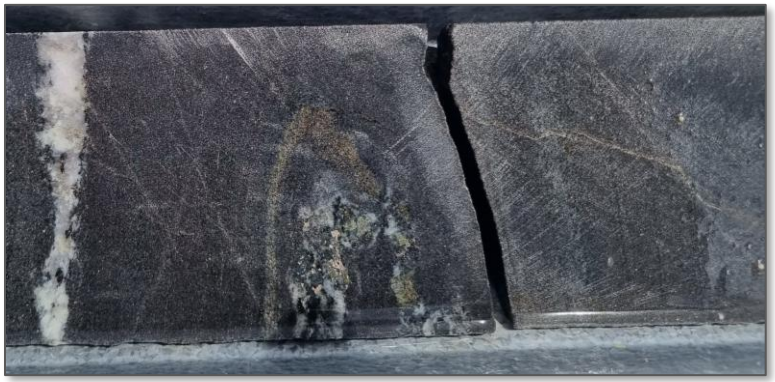
Hayes (2014)

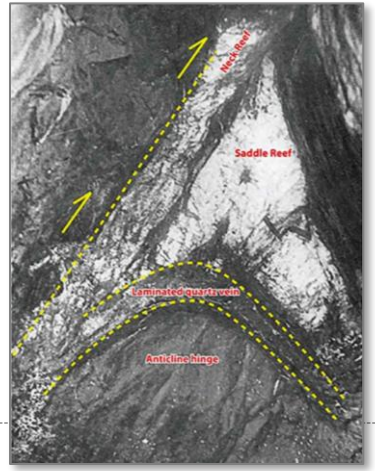
District → Deposit → Ore Shoot → Micro Scale

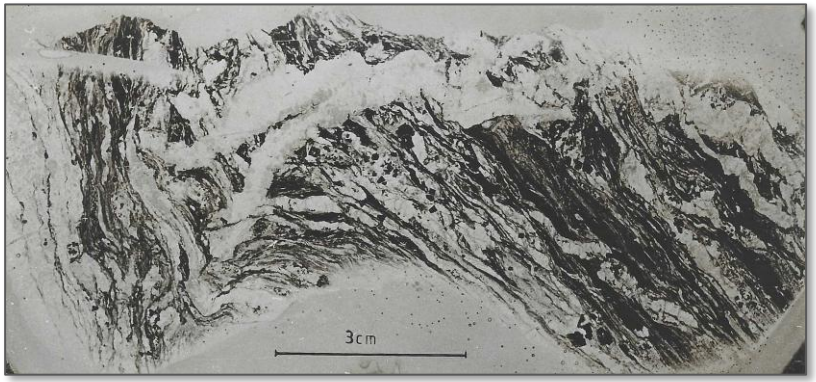


Jones and Kisters (2022)





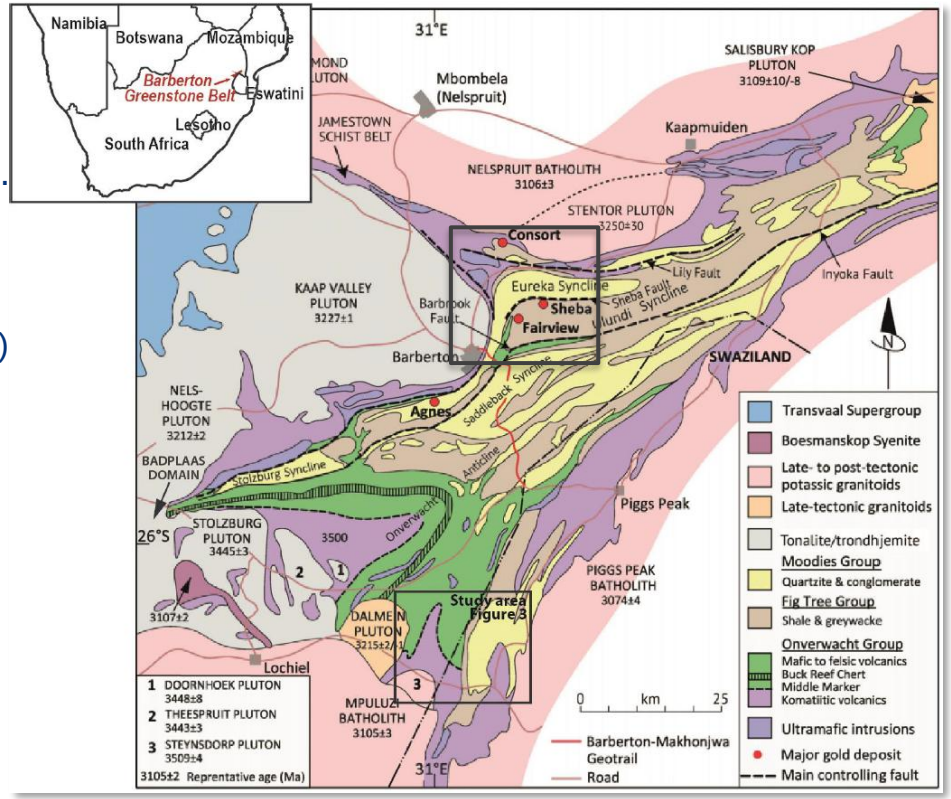




AIS Resources Limited (March 22, 2022)

Sheba Mine - Barberton Greenstone Belt

- One of the best-preserved mid-Archaean (3.55–3.22 Ga) supracrustal sequences.
- Supracrustal sequence (3 lithostratigraphic units).
- Surrounding TTG intrusions.
- Polyphase tectonic evolution.
  - D1: low-angle thrusting and recumbent folding (F1)
  - D2: large-scale upright folding (F2) – NW-SE shortening).
  - D3: refolding of F2 folds (F3).



Travers et al (2023)

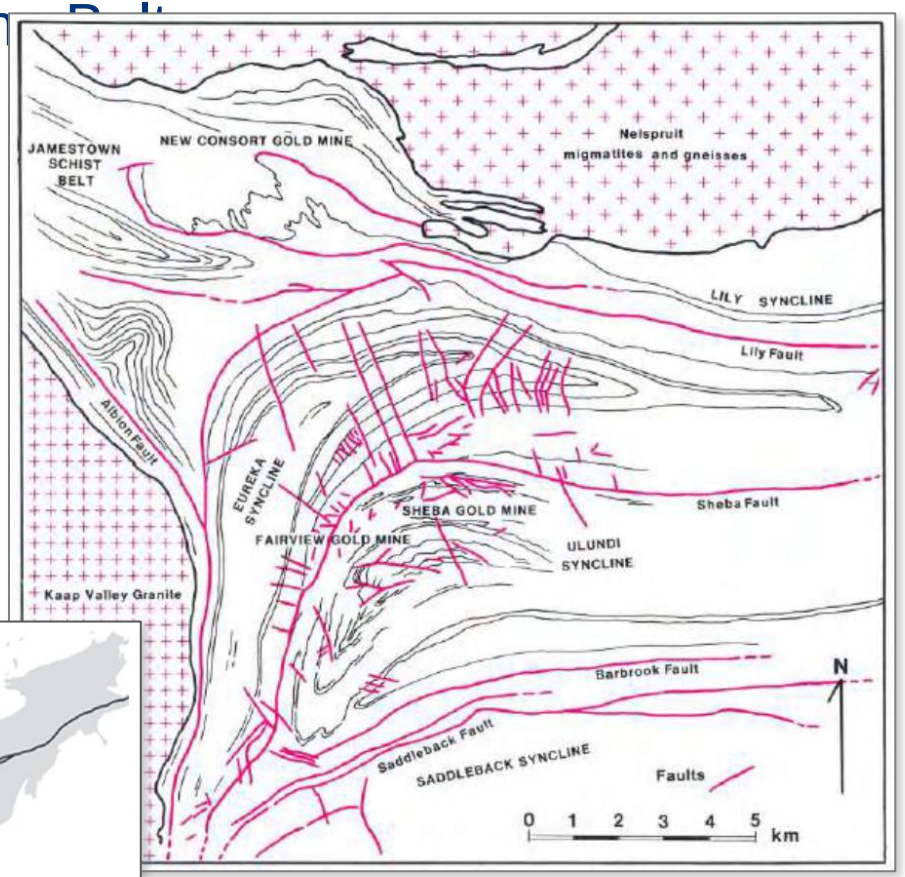
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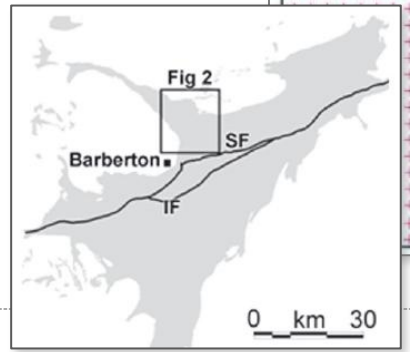
- View looking north from the edge of the greenstone belt over the granite terrain.



Sheba Mine - Barberton Greenston[illegible] Belt

- Major structures in the Sheba Hills area
- Regional scale F2 folds (Eureka and Ulundi Synclines) – refolded during F3
- Tightly infolded anticlines (basal ultramafic Onverwacht Group)
- Separated by belt-scale faults
- Gold mineralization strongly controlled by:
  - Sheba Fault and related 2nd and 3rd order structures
  - Lithological contacts along infolded anticlines
  - Brittle structures related to F3



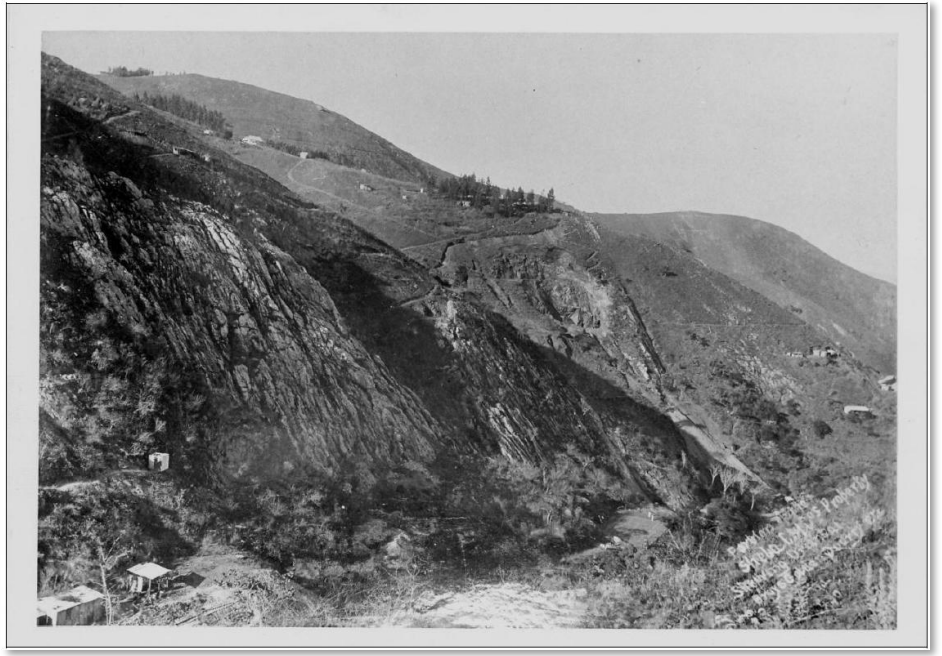


Anhaeusser (2015)

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Source: Anhaeusser (2015)

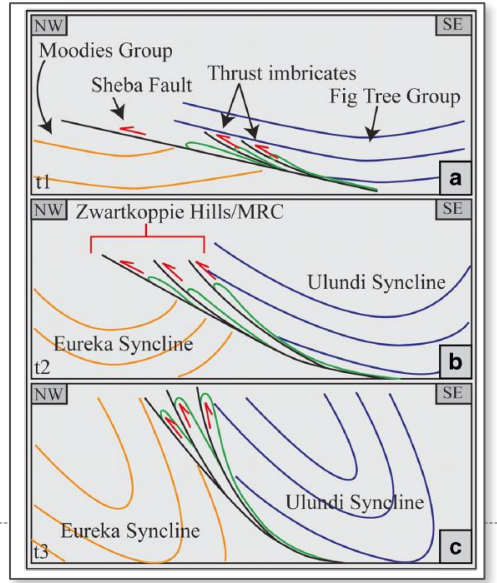


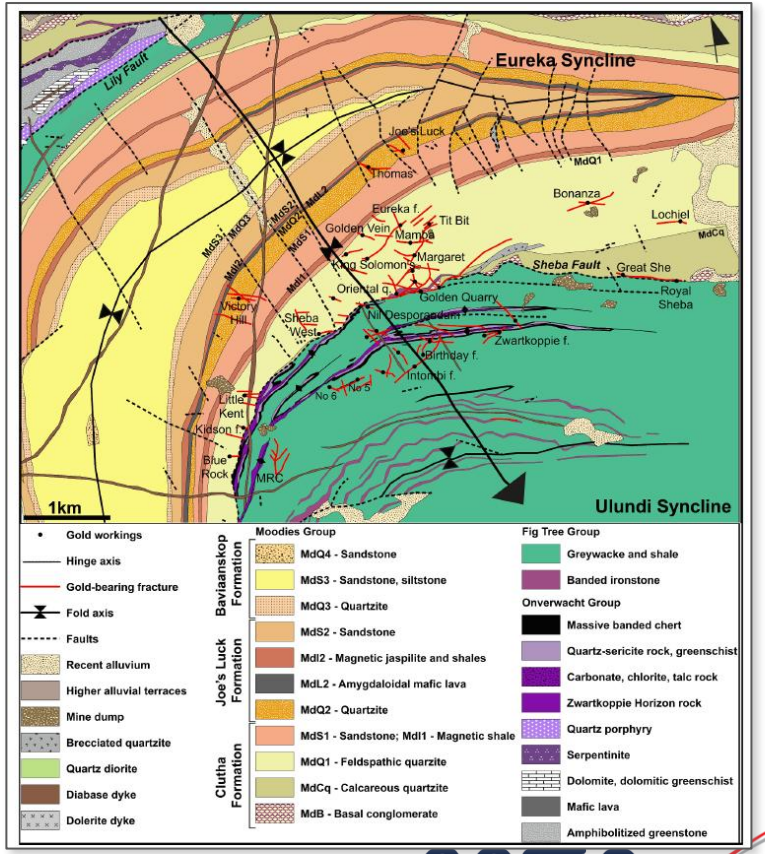
Sheba Mine - Barberton Greenstone Belt



Sheba Mine - Barberton Greenstone Belt

- Gold-bearing reefs and fractures in the Sheba Hills
- Clustered in the hinge zone of the refolded F2 folds
- Two styles of gold mineralization:
  - Quartz-carbonate-sulphide veins and vein networks in brittle lithologies (quartzite and chert)
  - Disseminated sulphide mineralization in metagreywackes and shales

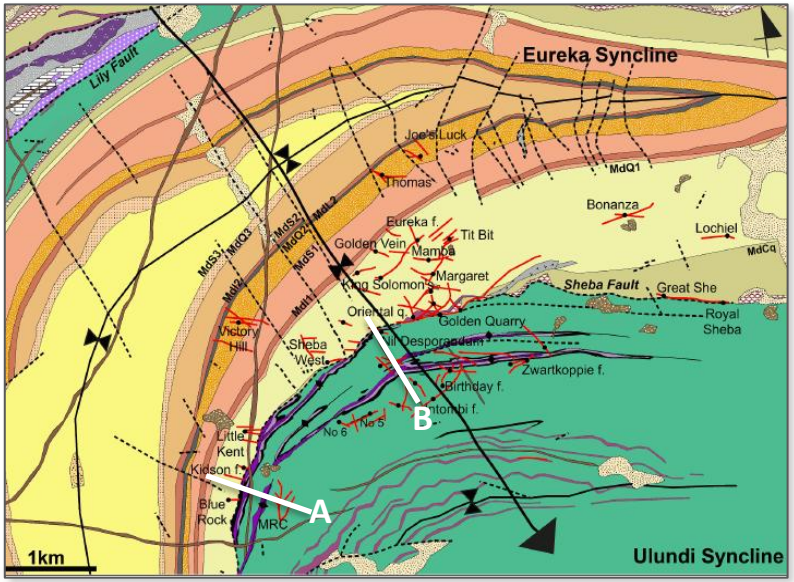


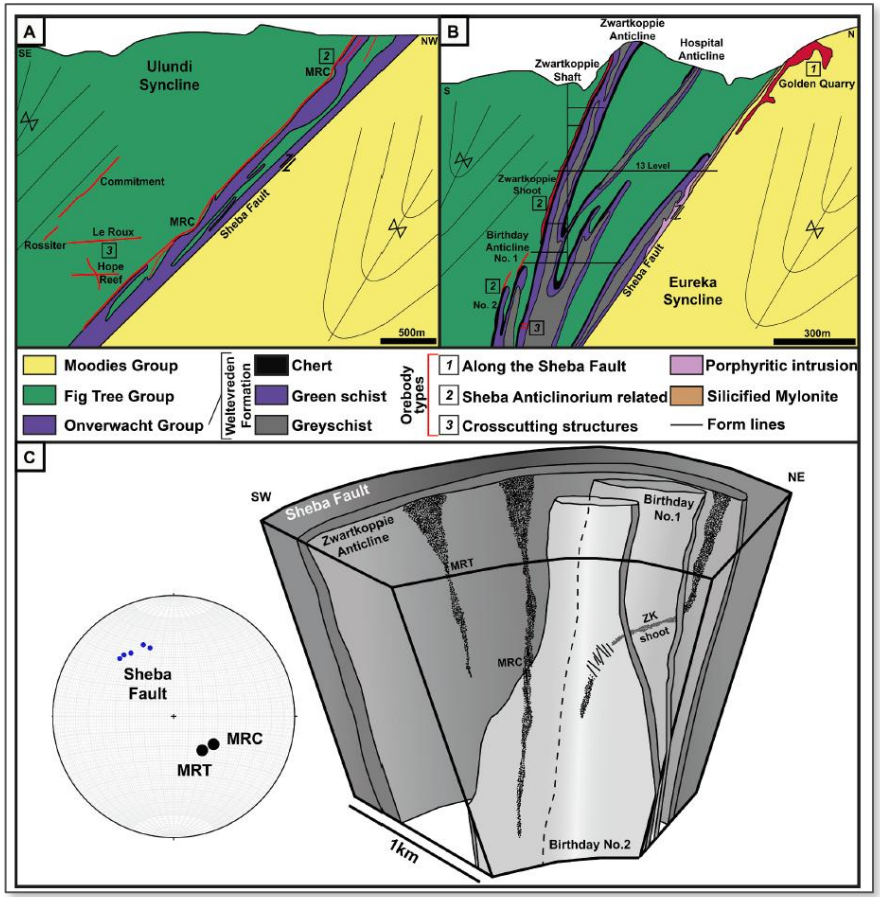


Jones and Kisters (2022)

Sheba, Barberton Greenstone Belt

- Cross-sections through the Sheba Fault.
- Mineralized structures developed in the FW and HW.
- Historical mining focused on high-grade quartz veins.





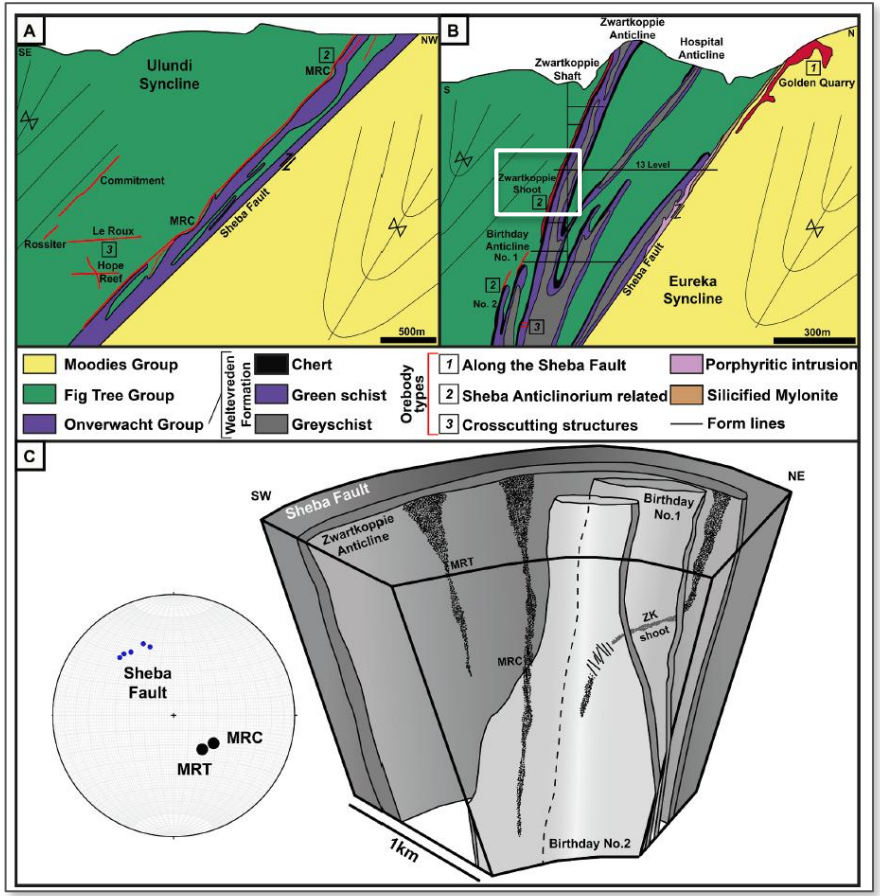
Jones and Kisters (2022)

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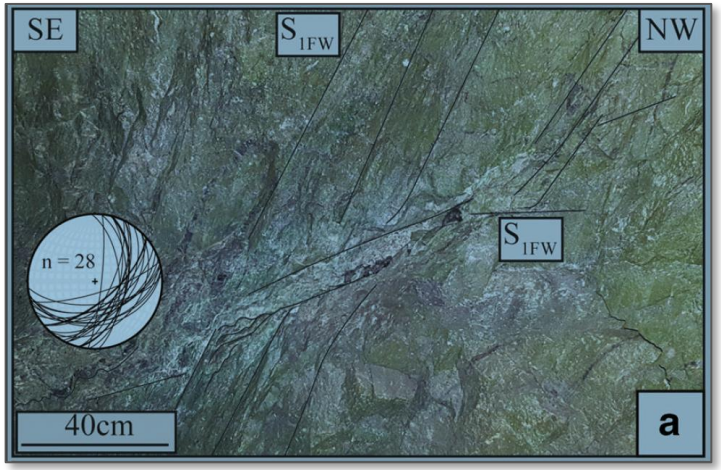


Jones and Kisters (2022)

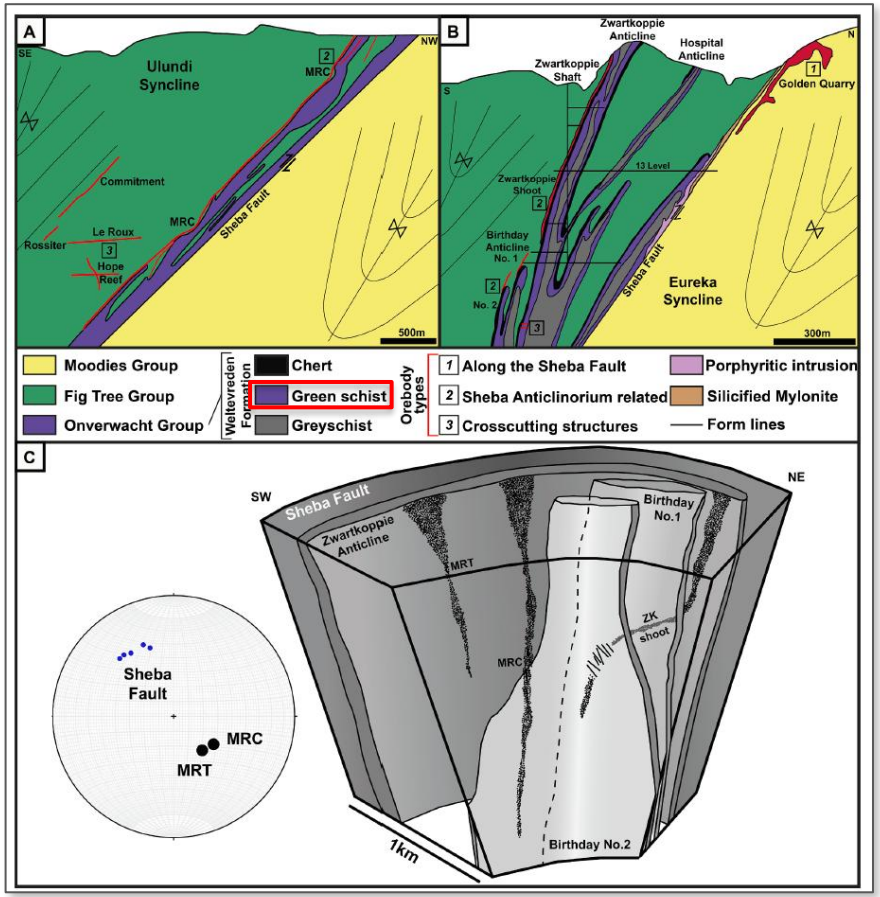
Sheba, Barberton Greenstone Belt

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- **Talc-quartz-carbonate-fuchsite schist**





Gloyn-Jones and Kisters (2019)



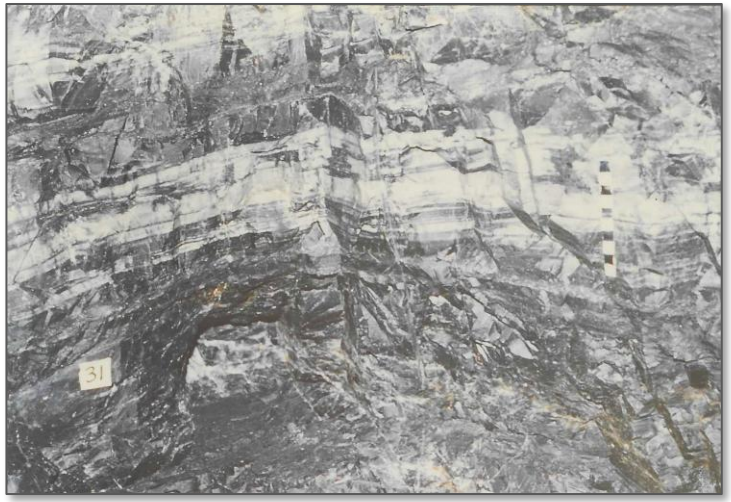
Jones and Kisters (2022)

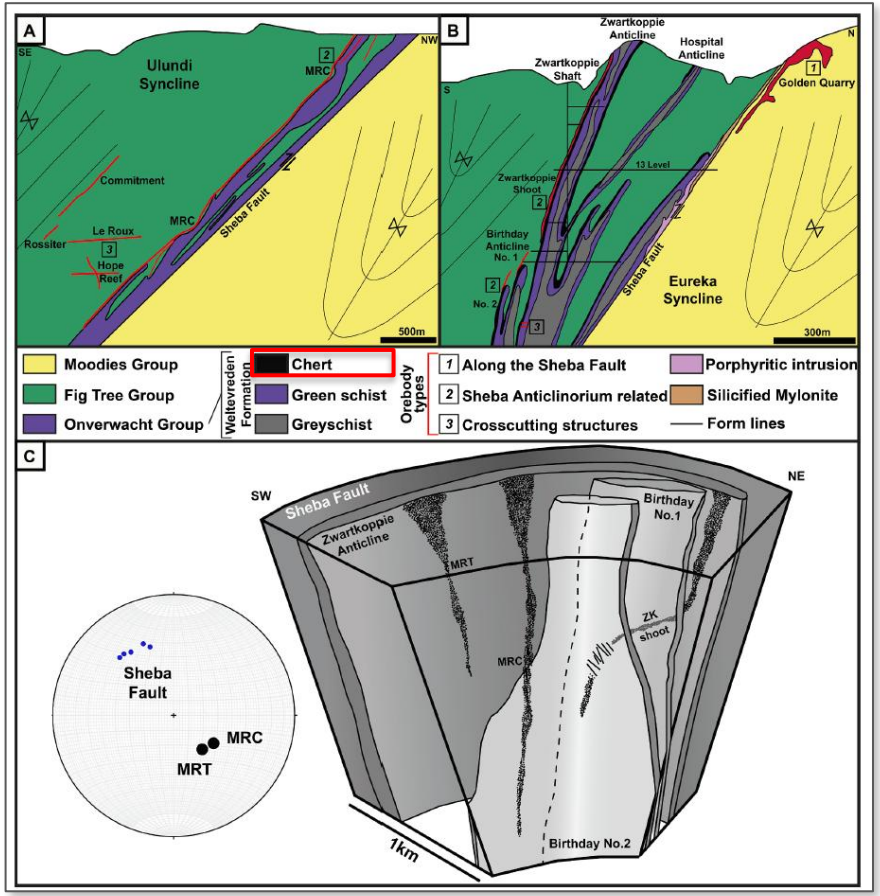
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Sheba, Barberton Greenstone Belt

- Cross-sections through the Sheba Fault.
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- Historical mining focused on high-grade quartz veins.
- **Banded chert**

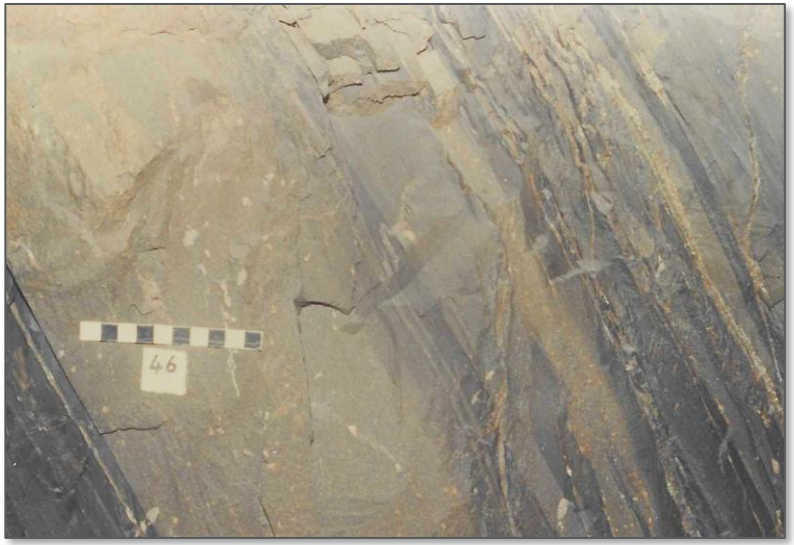


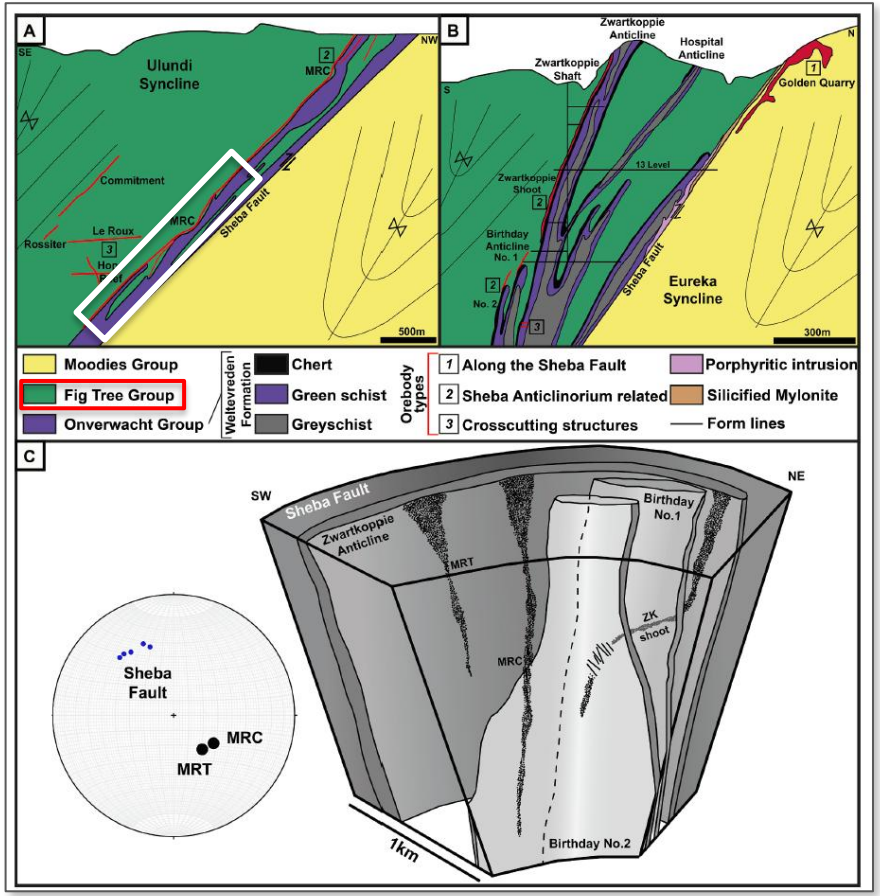


Jones and Kisters (2022)

Sheba, Barberton Greenstone Belt

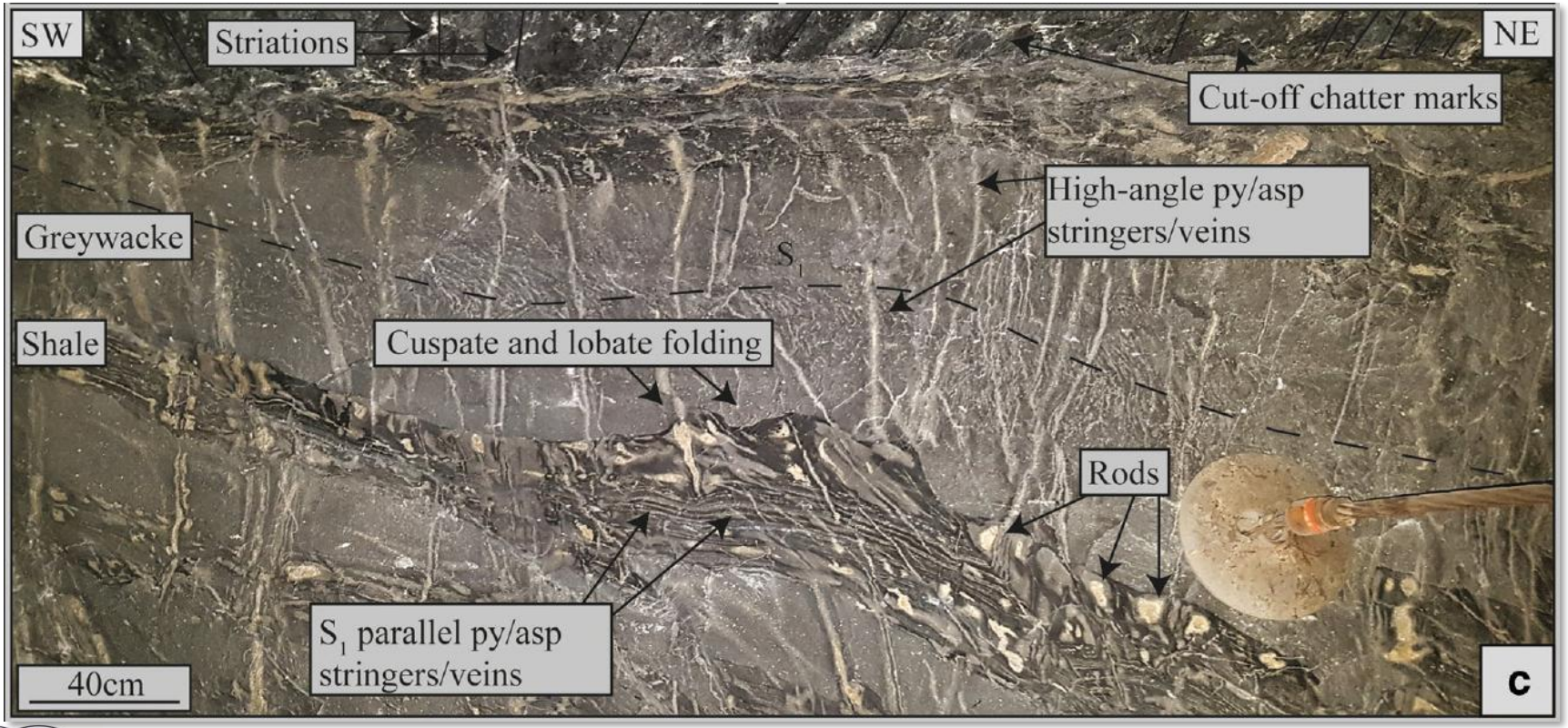
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- **Meta-greywacke and shale**





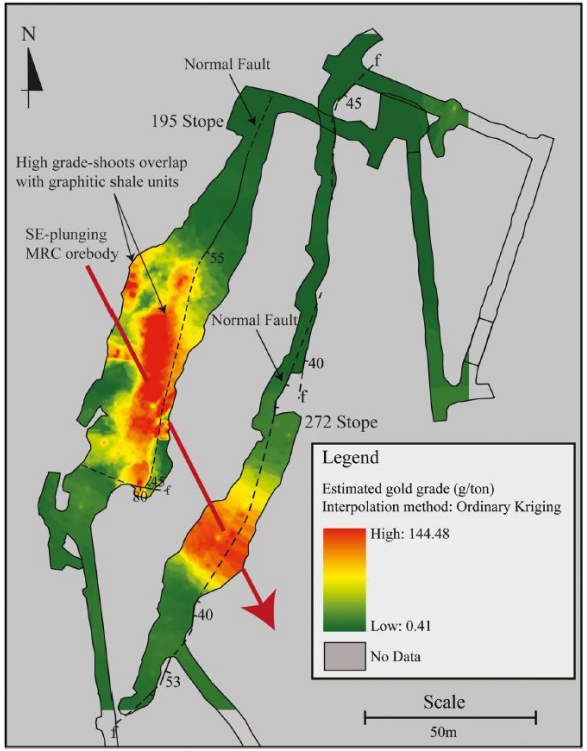
Jones and Kisters (2022)

Sheba, Barberton Greenstone Belt

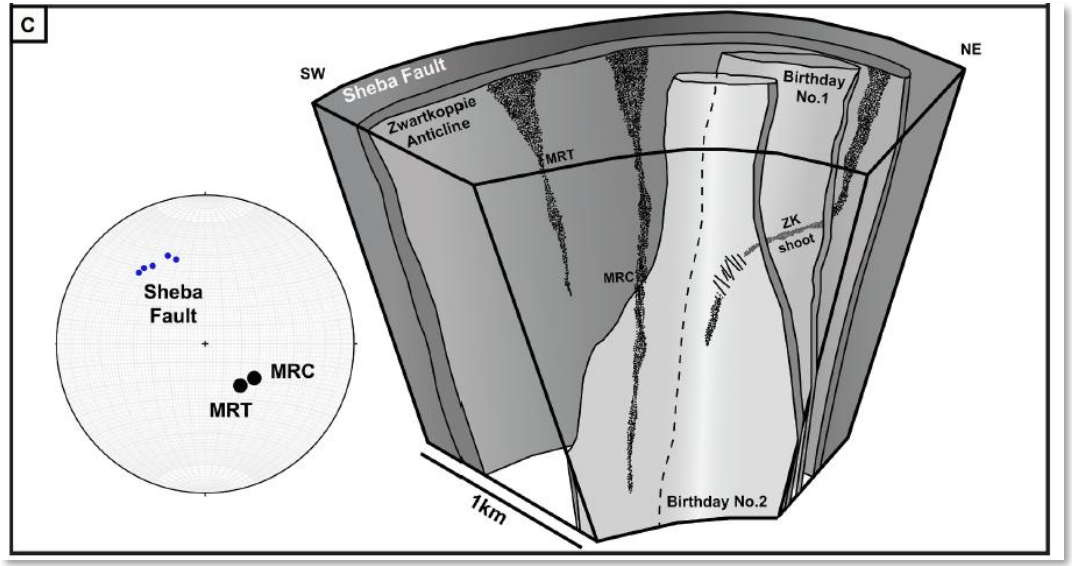


Gloyn-Jones and Kisters (2019)

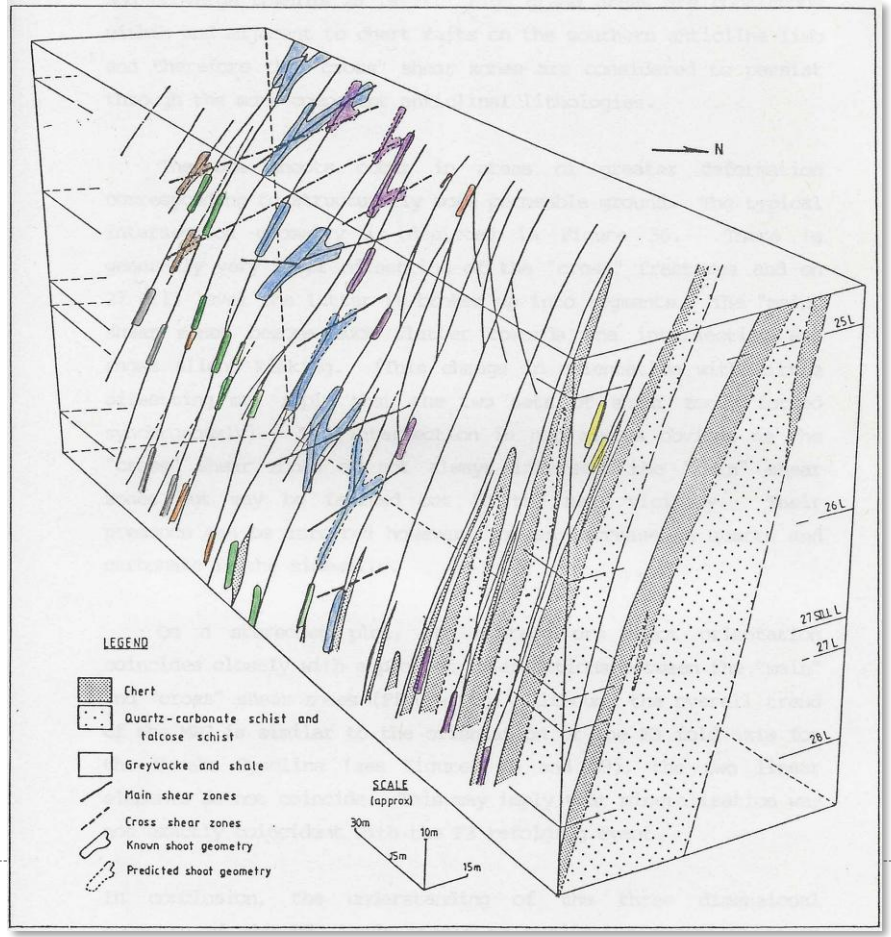
Sheba, Barberton Greenstone Belt



Gloyn-Jones and Kisters (2019)

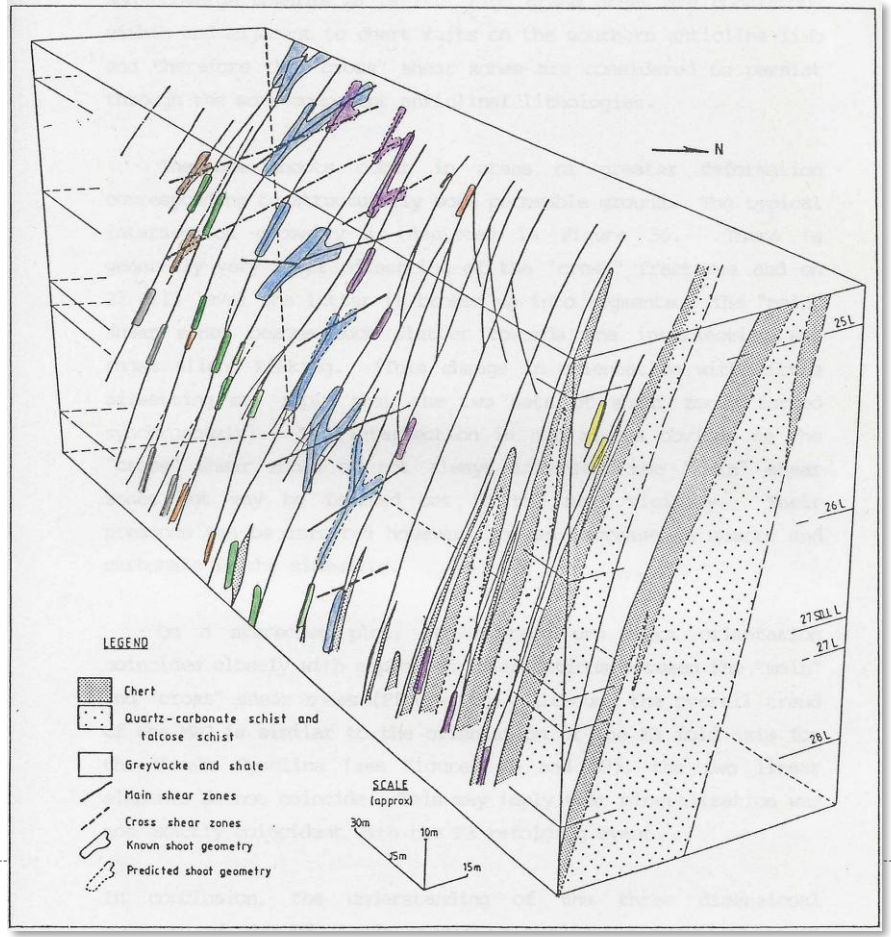


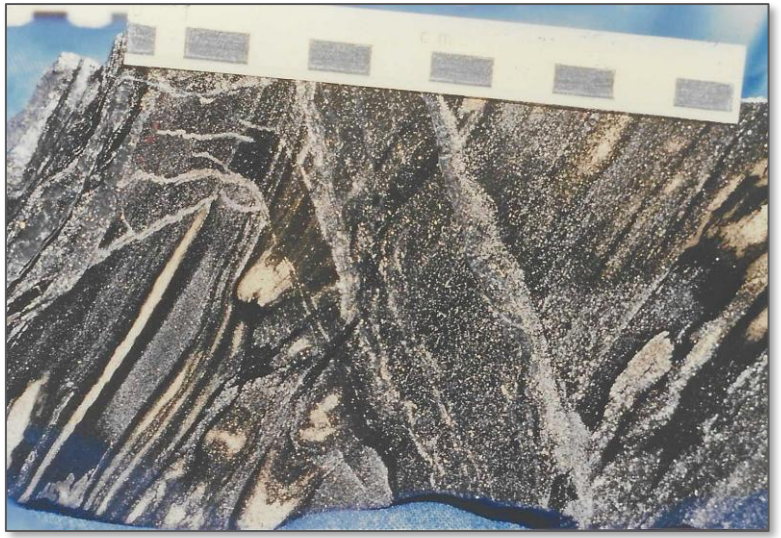
Sheba, Barberton Greenstone Belt

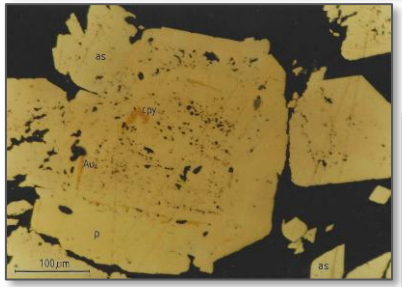


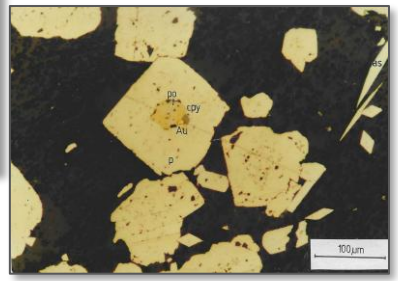
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Sheba, Barberton Greenstone Belt









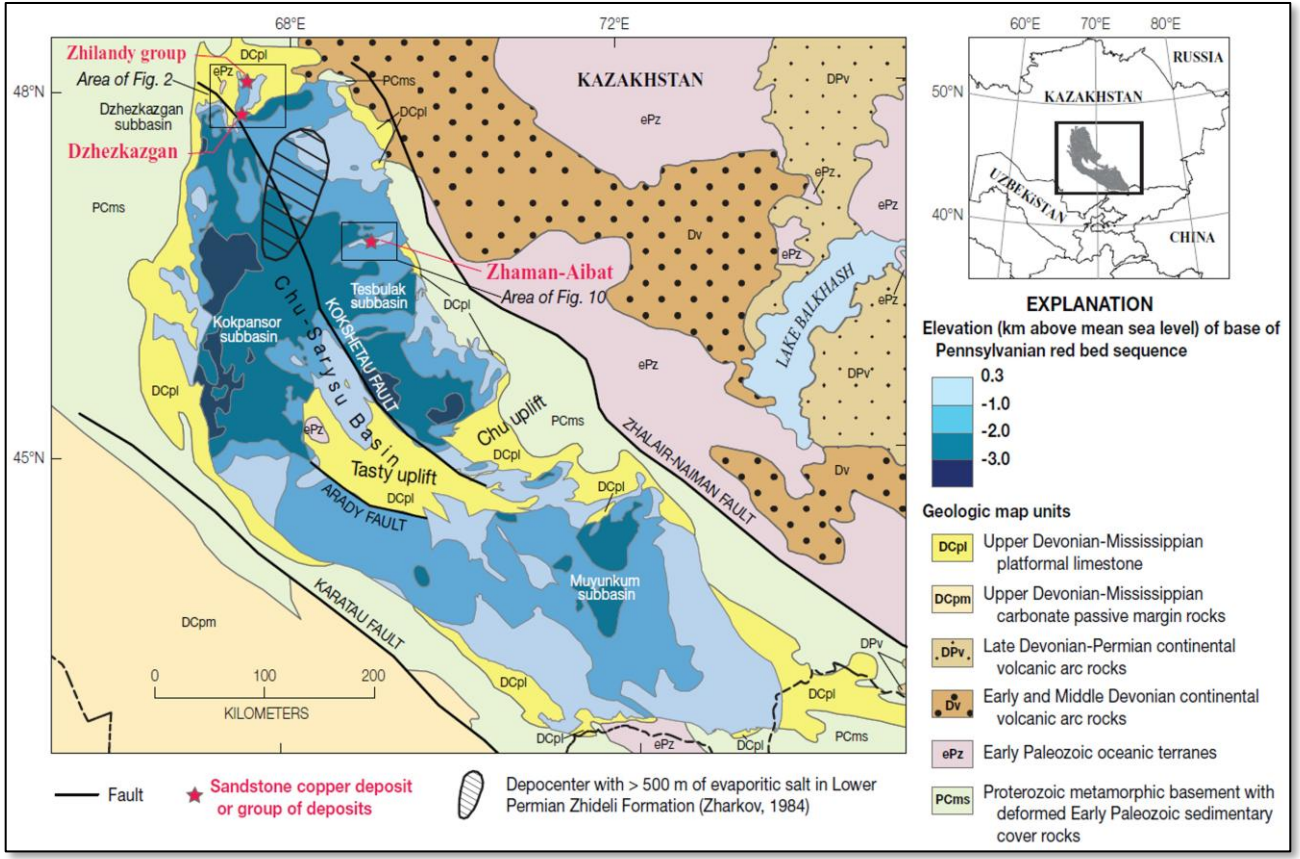
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Chu Sarysu Basin



Chu Sarysu Basin

- South-central Kazakhstan.
- Third largest SHC basin in the world (700 x 250km).
- 2010 USGS study on the sandstone copper potential of the Chu-Sarysu Basin.
- Mining at Dzhezkazgan and Zhaman-Aibat.
- >100 years of mining in the Dzhezkazgan, but the basin is poorly explored for copper.

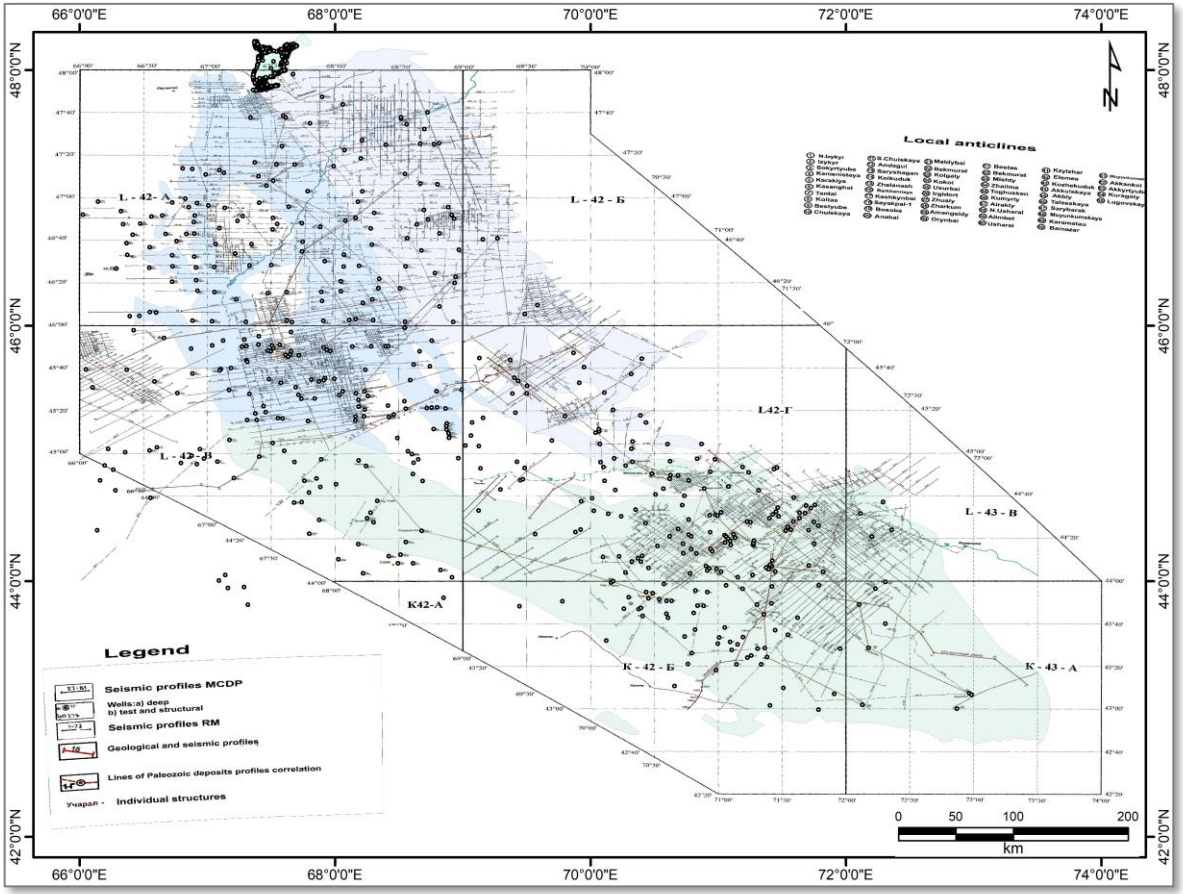


Box et al. (2012)

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Chu Sarysu Basin

- Poorly explored for copper.
- Hydrocarbon exploration since the 1950s with extensive seismic coverage and drilling.

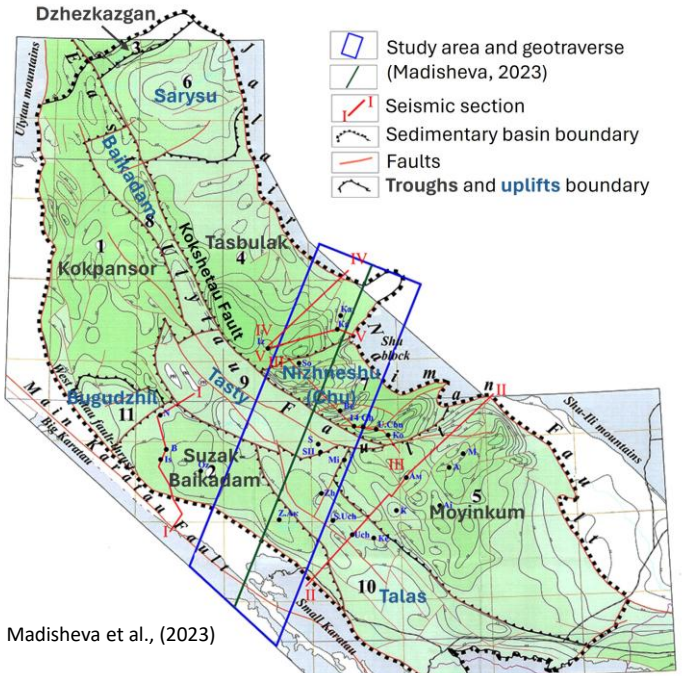


USGS (2010)

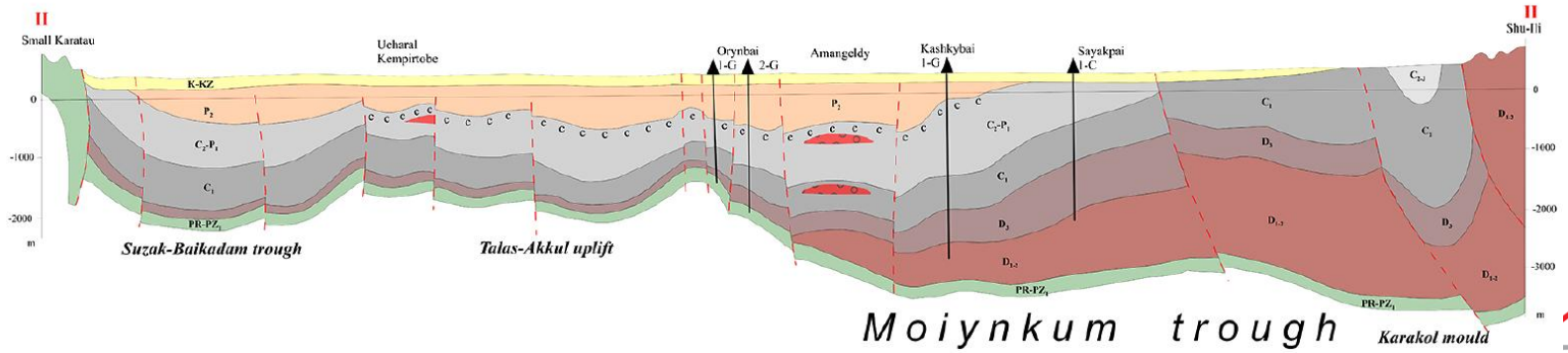
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Chu Sarysu Basin

- Understanding of the structural framework supported by seismics and drilling.
- Paleogeography of the basin studied by Madisheva et al in 2023 and shows the basin defined by a number of troughs or sub-basins and local intra-basinal highs, bounded and intersected by faults.
- This is clear in the seismic section below, which also shows reverse faults and folding associated with basin inversion.



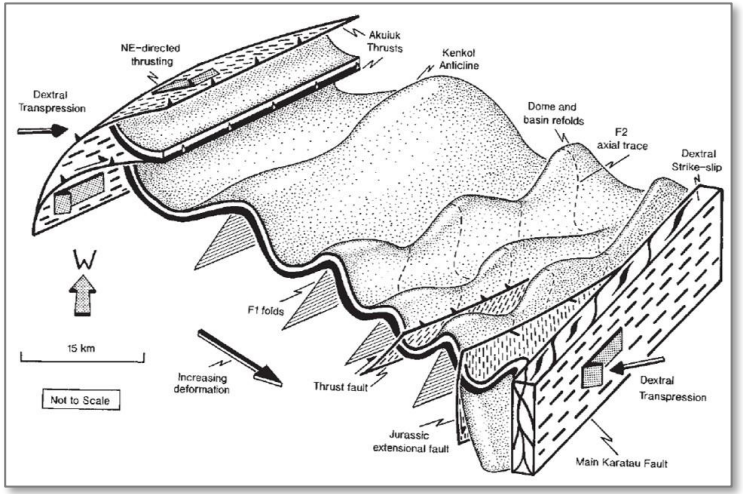
Madisheva et al., (2023)



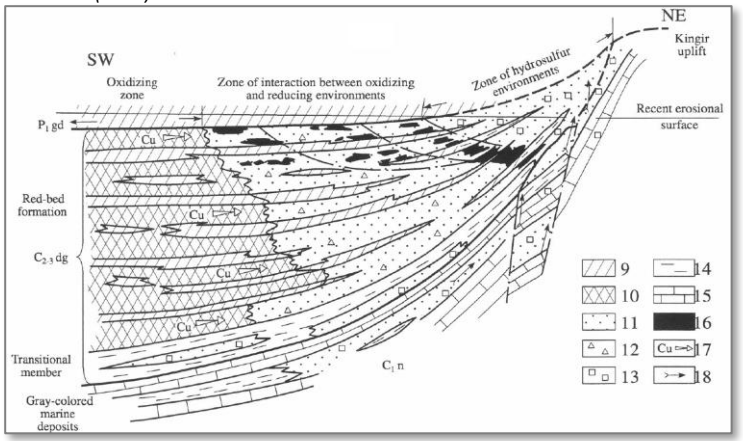
Chu Sarysu Basin

Key controls on SHC mineralization in the Chu-Sarysu Basin:

- Stratigraphy: Red bed sequence + permeable reduced sandstone units with interbedded siltstone-argillite units that acted as aquicludes.
- Interference fold geometry facilitated the migration and entrapment of hydrocarbon gases which resulted in reduced grey sandstone beds and prepared them as redox traps for subsequent migrating metalliferous fluids.
- Particular focus of fluid movement along the crests of anticlinal and monoclinal structures.
- Copper mineralization is localized along basin and sub-basin margins and on the flanks of paleohighs where host sandstone stratigraphy pinches out below an aquiclude.
- Copper mineralization is proportional to fault density.
- Mineralization is zoned, but complicated by overprinting resulting from multiple pulses of metal-bearing brines.



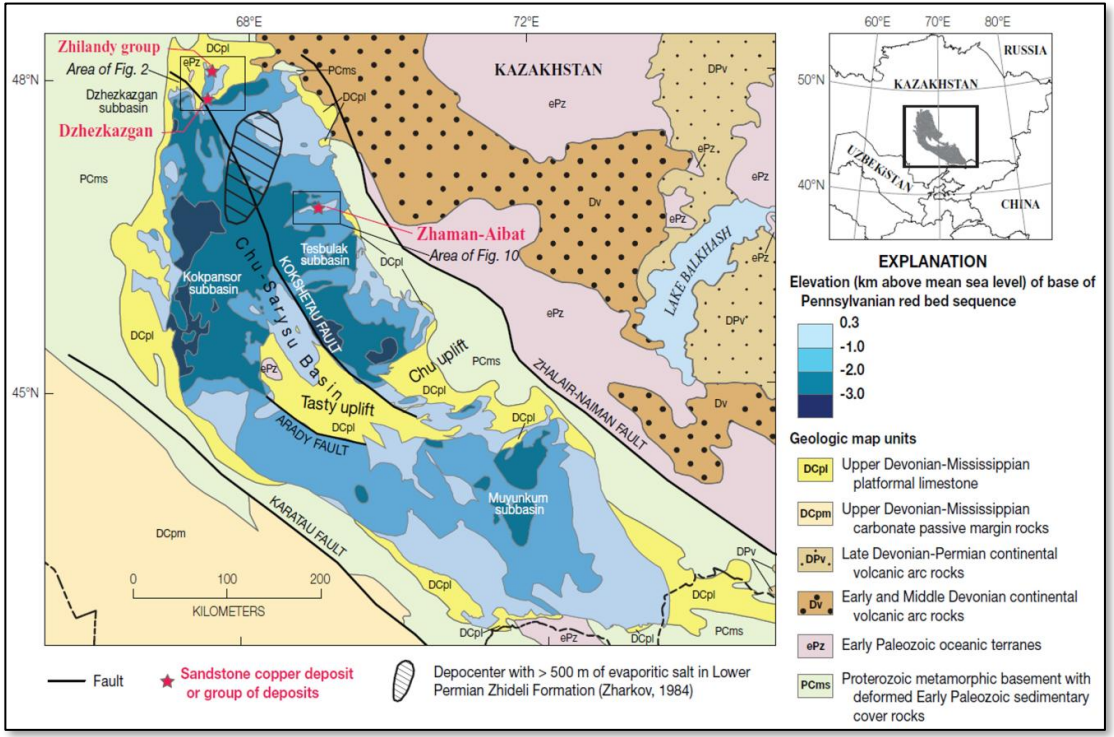
Alan et al (2001)



Gablina (1997)

Chu Sarysu Basin

- Sandstone-type (Revett sub-type) dominant (lower grade than reduced facies-type).
- Global average grade 1.11% Cu.
- Zhaman-Aibat:
  - Cu mineralization along the crest of a monoclinal structure
  - 136Mt at 1.56% Cu and 18.69g/t Ag (U/G Zhomart mine; PorterGeo, 2013)
- Dzhezkazgan:
  - One of the world's largest sandstone-hosted Cu deposits
  - 22Mt contained Cu (2012)
  - Average grade ~1% Cu

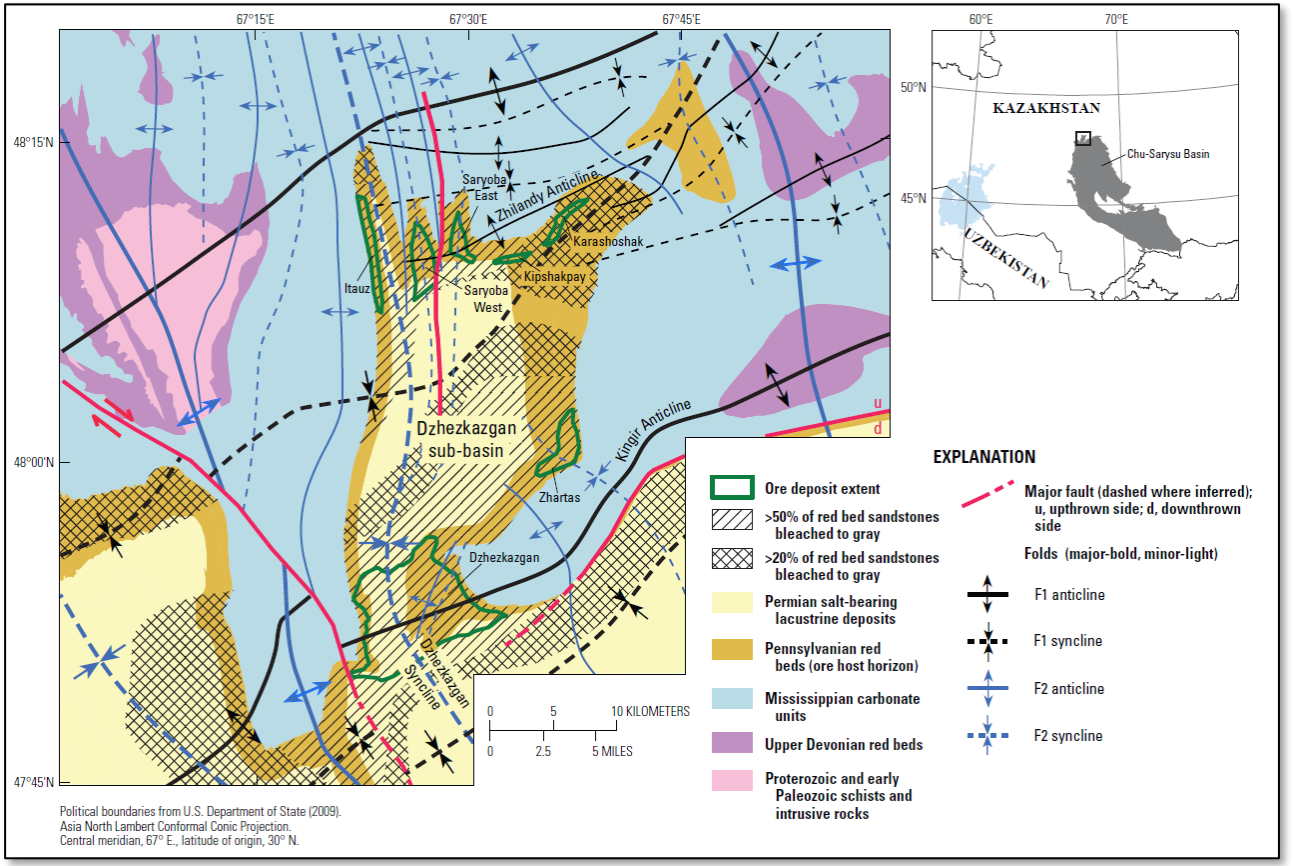


Box et al. (2012)

Chu Sarysu Basin

Dzhezkazgan Sub-basin:

- An embayment on the northern margin of the Basin
- Mineralized system covers 120km^2
- Satpaev and Zhelandy Orefields
- Mined intermittently since 1500 BC, but continuously over the past 100 years.

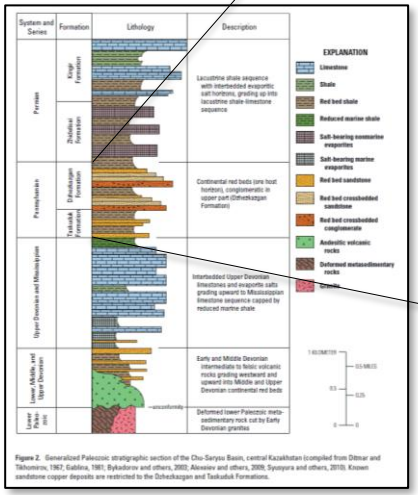


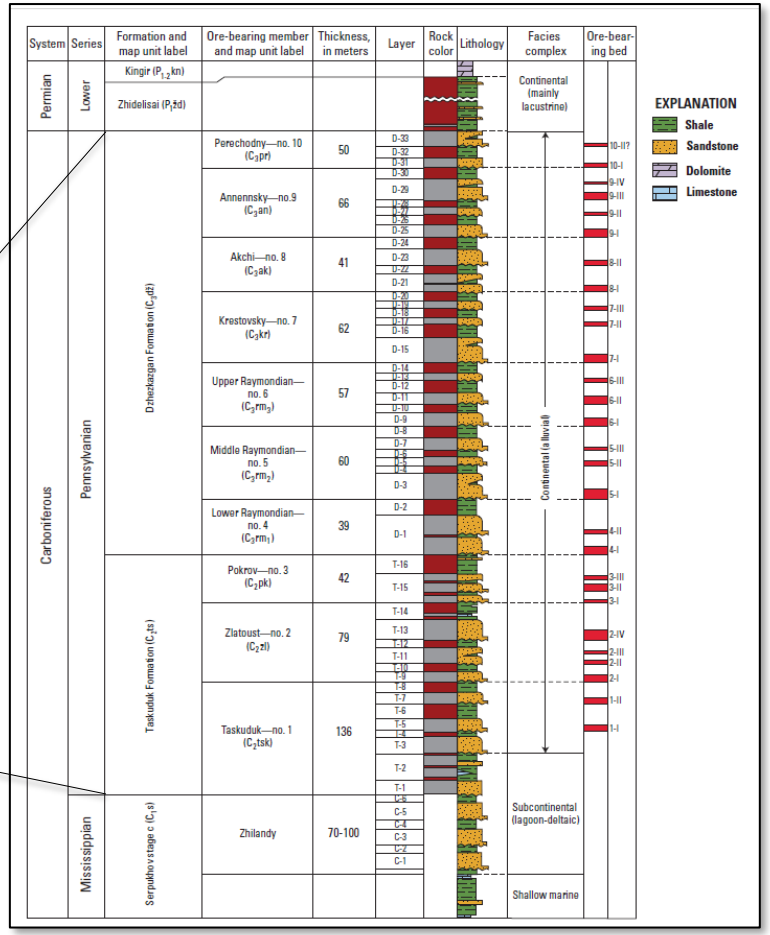
USGS (2010)

Chu Sarysu Basin

Dzhezkazgan Sub-basin:

- Up to 10 mineralized sandstone members are recognised, each containing up to 5 individual mineralized units with average 3-5m thickness.
- Host Carboniferous Dzhezkazgan Fm (630m thick) and Taskuduk Fm, capped by an evaporite sequence.
- Mineralized restricted to reduced grey sandstone strata. The interstratified reddish-brown argillites and siltstones are not mineralised (Gablina, 1981).





USGS (2010)

Chu Sarysu Basin

Dzhezkazgan Sub-basin:

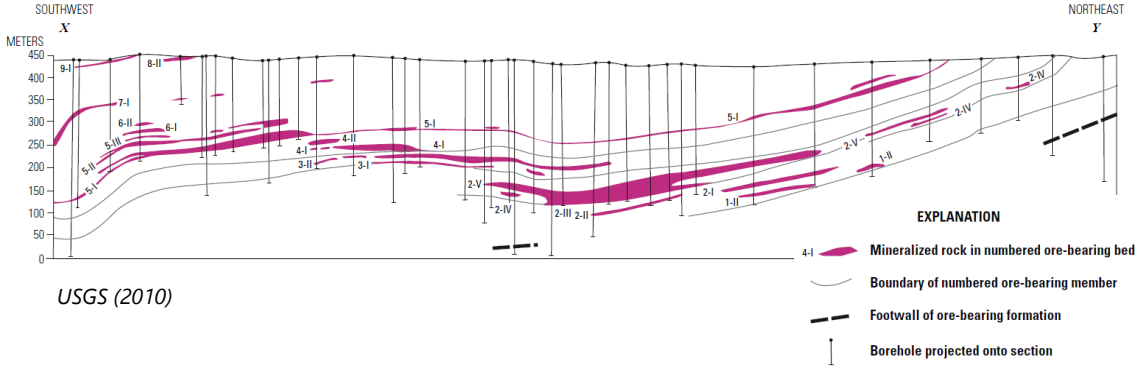
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Chu Sarysu Basin

Dzhezkazgan Sub-basin:

- Copper mineralisation is proportional to the density of faulting.
- Faulting has also induced monoclinal flexures in the host sequence where mineralization is spatially associated with the arches and crests of the flexures.
- Orebody shape reflects structural influence, being typically elongate along the hinge of anticlines and monoclinal flexures and arcuate around the crests.
- The section shows orebodies across ~ 350m of vertical stratigraphy



USGS (2010)

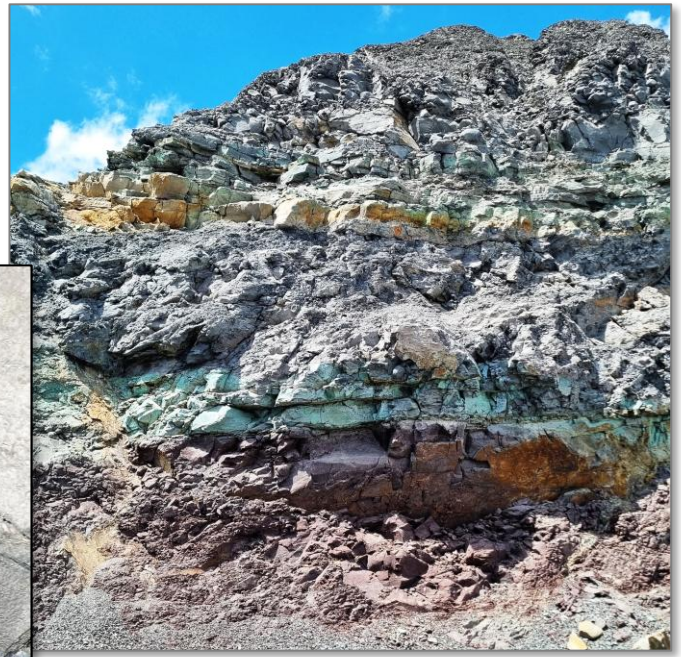


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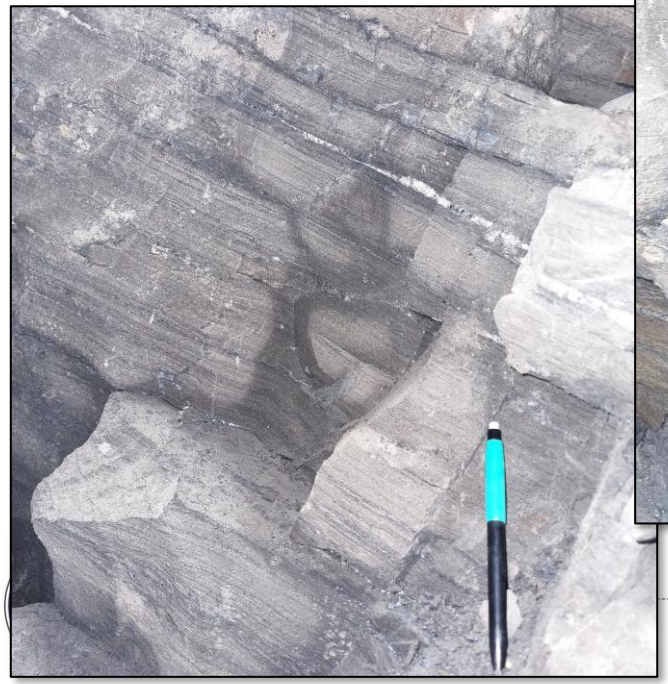
Chu Sarysu Basin

Dzhezkazgan Sub-basin:

- Sandstone-hosted oxide and sulphide mineralization
- Reduction of oxidized red-beds





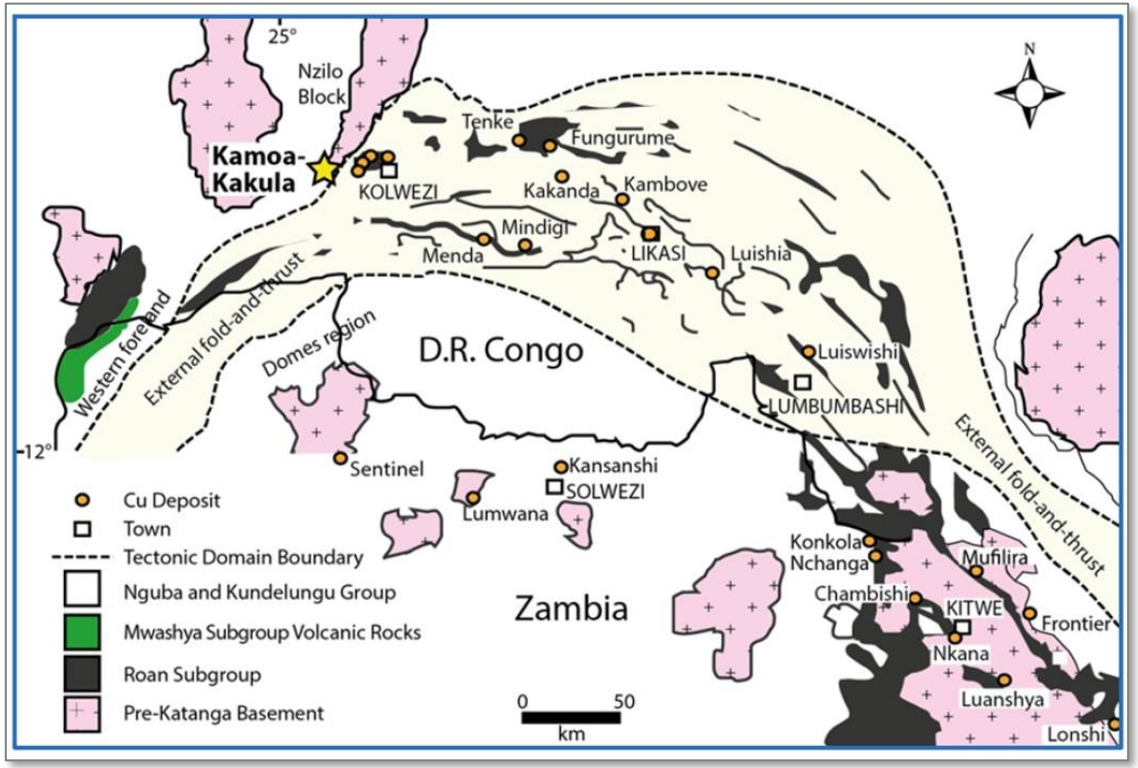




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Central African Copperbelt: Kamoa-Kakula

- World's largest SHC province; over 150 million tonnes Cu.
- Katangan rift basin developed above Meso- to Paleoproterozoic basement.
- Multi-phase deformation: extensional rifting followed by the Lufilian Orogeny.
- Different styles of SHC deposits; autochthonous Zambian-type; Domes Regional; External fold and thrust belt.
- Kamoa-Kakula is an autochthonous reduced-facies-type deposit towards the edge of the basin outside of the fold and thrust belt (Western Foreland).

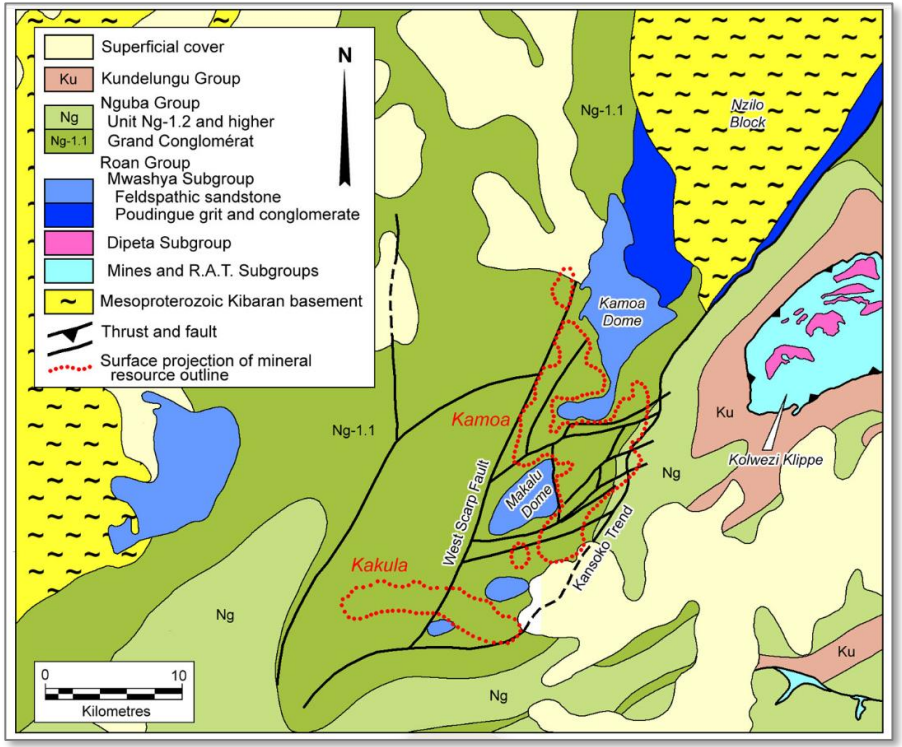


Peters et al. (2023), adapted from Schmandt et al. (2013)

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Central African Copperbelt: Kamoa-Kakula

- Kamoa deposit discovered in 2008 under Kalahari Group cover.
- Kakula discovered in 2015.
- World's largest and highest grade Cu deposit.
- Kamoa-Kakula:
  - 1.39Bt at 2.73% Cu; 37.9Mt contained Cu (2023 Measured and Indicated Resources, 1% Cu cut-off).
- Deposits overlie a NNE trending basement block.
- Mineralization footprint spatially associated with the Kamoa and Makalu domes = structural control by basement topography.

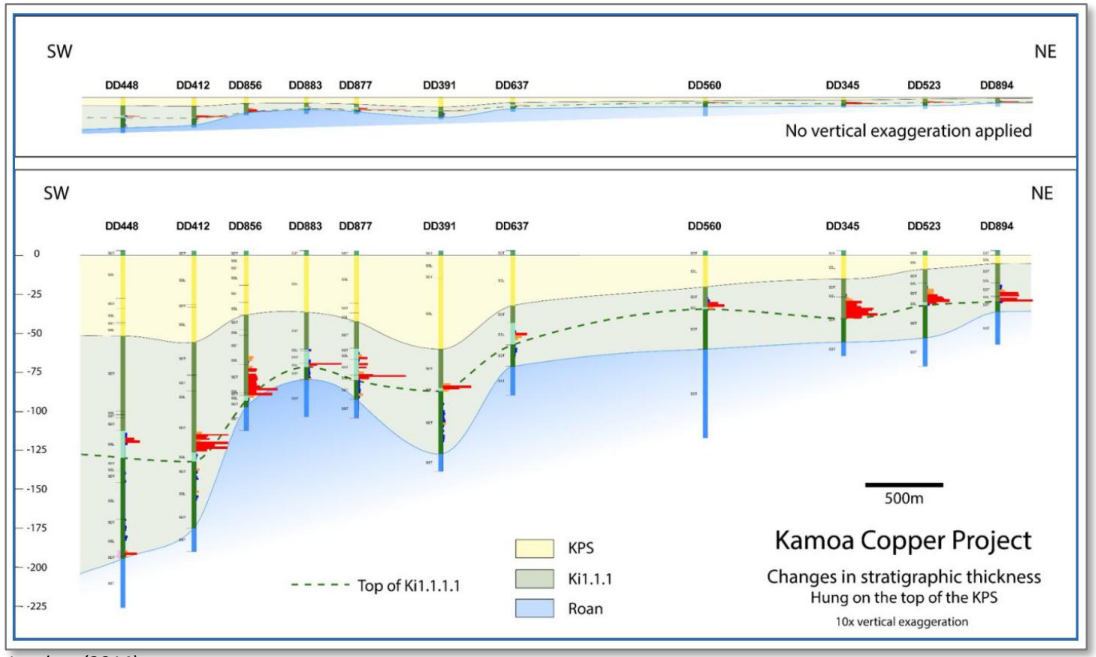


PorterGeo (2019)

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Central African Copperbelt: Kamoa-Kakula

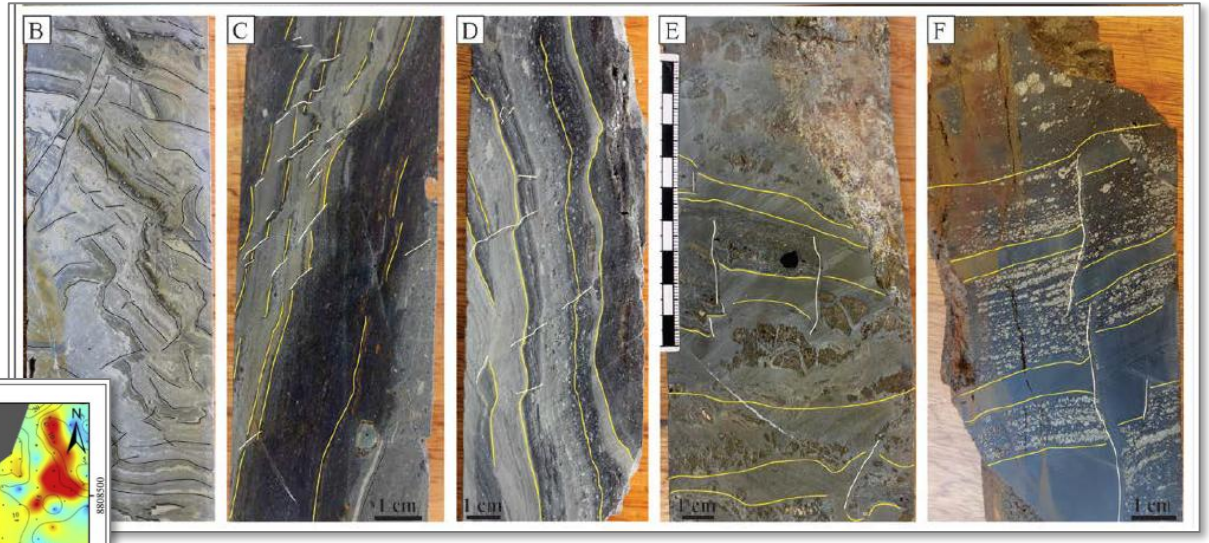
- Long section through Kamoa.
- Mineralization towards the base of the carbonaceous and sulphidic Grand Conglomérat diamictite (redox boundary).
- Mineralization better developed along the edges of structural highs.
- Variations in stratigraphic thickness reflect basin controlling structures active during sedimentation.

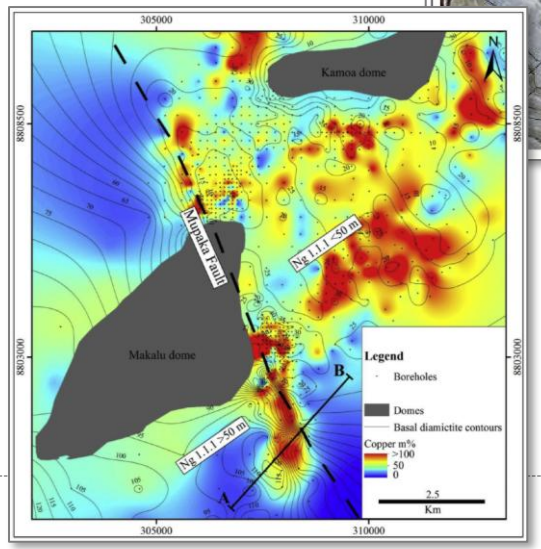


Ivanhoe (2014)

Central African Copperbelt: Kamoa-Kakula

- Frank Twite MSc study.
- Syn-sedimentary growth fault-related structures:
  - Soft sediment deformation, slump folds, steep bedding, mesoscopic faults.

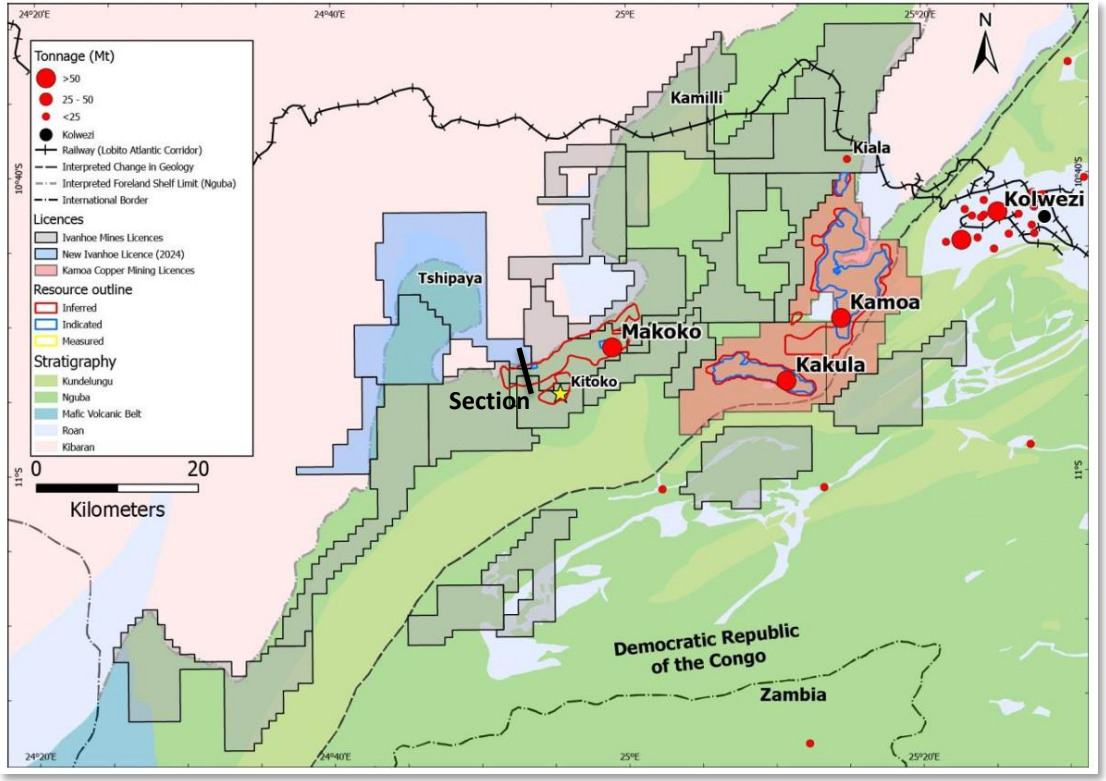




Twite et al (2019)

Central African Copperbelt: Kamoa-Kakula-Makoko

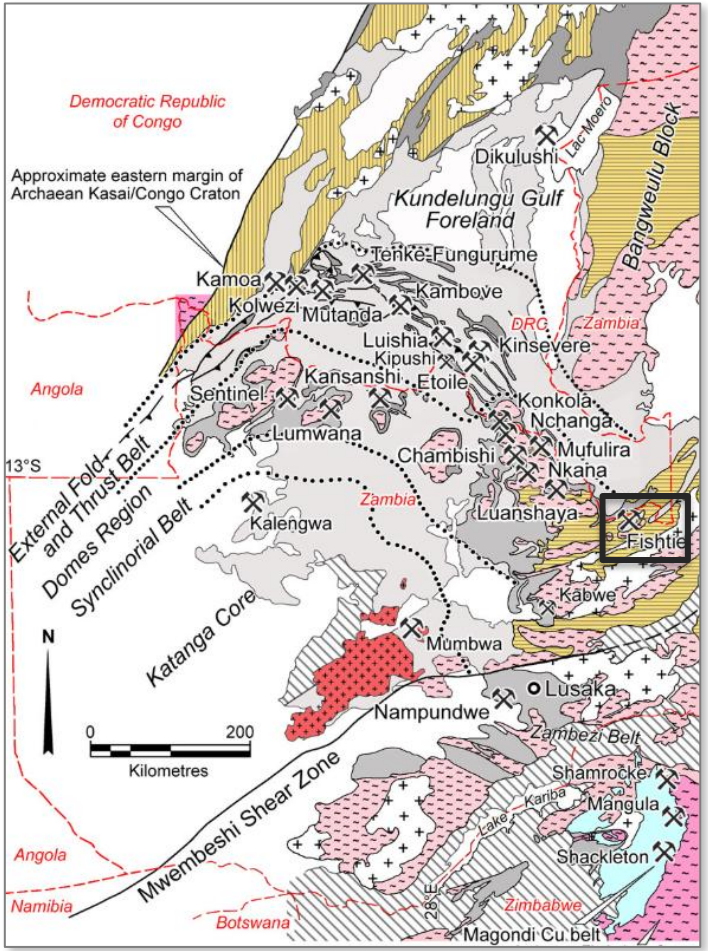
- The Western Forelands is the world's richest copper basin.
- Makoko copper district discovered in 2018 (world's highest-grade and fifth largest copper discovery of the past decade).
- 13km strike length; up to 5km wide (open along strike and downdip).
- Between 200 – 1,250m depth.
- Basement topography (basin architecture) controls copper mineralization.



Ivanhoe Mines (2025)

District to Deposit Scale

- Sediment-hosted copper deposits.
- Basin margin fault control on copper mineralization (first order control).
- Syn-sedimentary growth faults.
- Fault networks and basin-scale fracture systems control the migration of basinal brines and the sites of sulphide accumulation.
- Local structural highs and paleohighs.
- Salt tectonics.

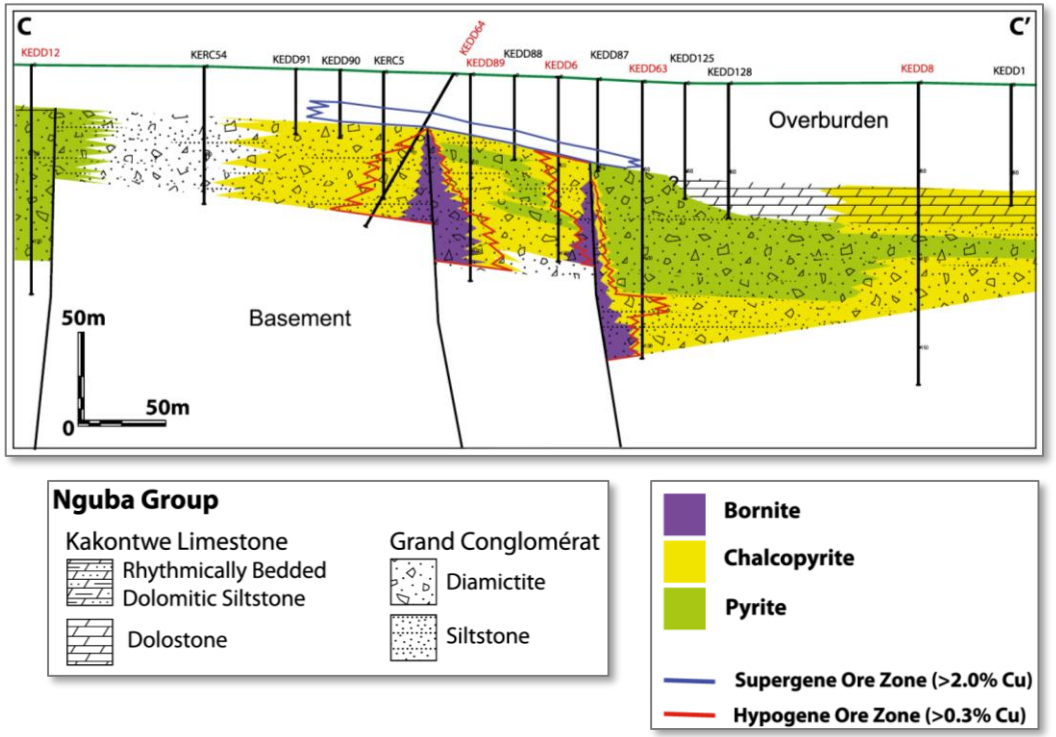


PorterGeo (2015)

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District to Deposit Scale

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- Local structural highs and paleohighs.
- Salt tectonics.
- Fishtie:
  - Fishtie deposit (55Mt at 1.04% Cu).
  - Vertical and lateral sulphide zoning (fault and permeability controlled).



Hendrickson et al (2014)

Conclusions

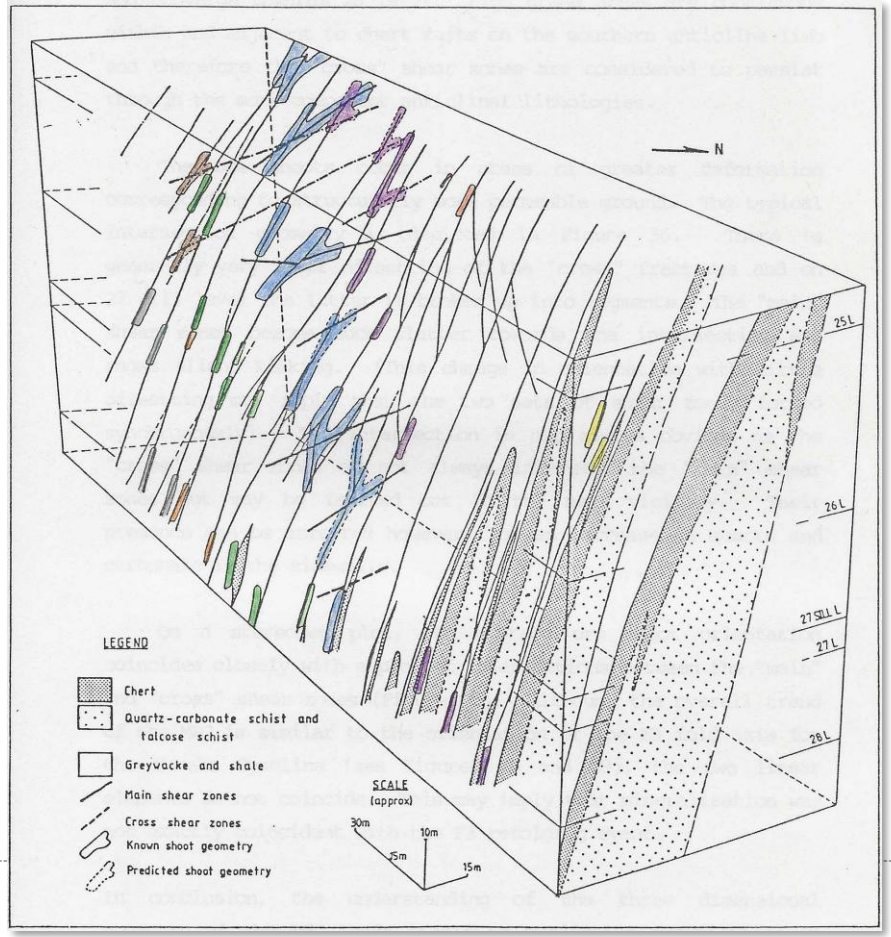
- Mineral systems are inherently dynamic and structurally integrated.
- Structural geology is a primary control on the formation, localization, and preservation of mineral deposits across diverse tectonic environments.
- By considering the entire deformation history—from early regional architecture to late brittle overprinting—geologists can better predict mineralization pathways and targets.
- Integrating structural geology with geochemistry, geophysics, and 3D modelling provides a powerful, holistic approach to both understanding ore systems and improving exploration success across all major deposit types.
- Applied structural geology is a key tool in the discovery of new mineral resources
- Structural analysis is critical for mineral exploration
- Understanding structural frameworks can reduce exploration risk, improve targeting, and enhance resource evaluation.

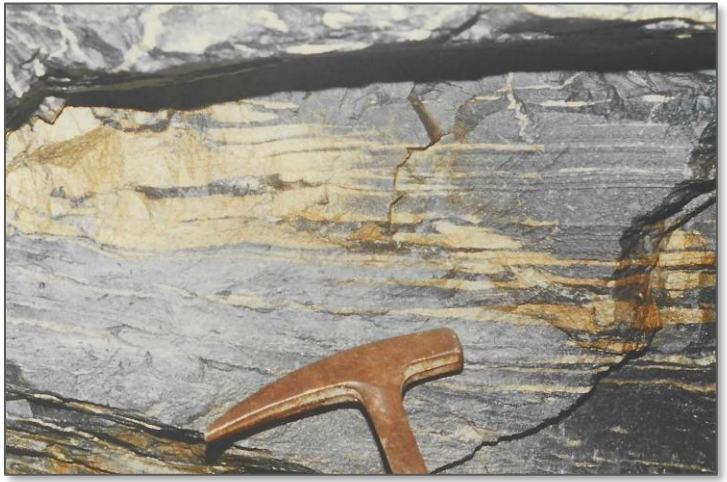
www.msagroupservices.com

Thank you

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Sheba, Barberton Greenstone Belt





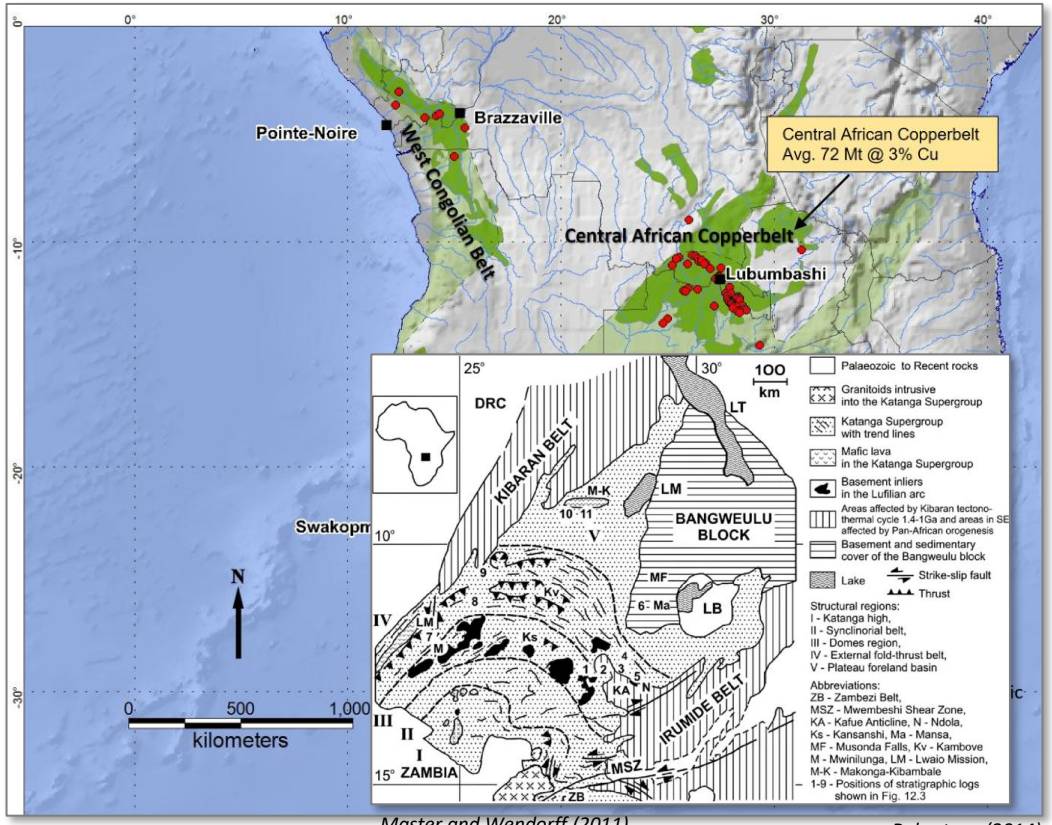


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Regional Scale – SH Copper

- Structure is important **throughout** sedimentary basin history.
- Basin architecture defined by fault-bounded rift basins and sub-basins (half grabens) and local depocenters.
- Faults influence subsidence rates, stratigraphic thickness.
- Faults acts as permeability pathways facilitating basin-wide and local fluid flow.
- Basement topography and folding also influence and control basinal brine fluid movement both as pathways and traps.
- **Example – Central African Copperbelt**

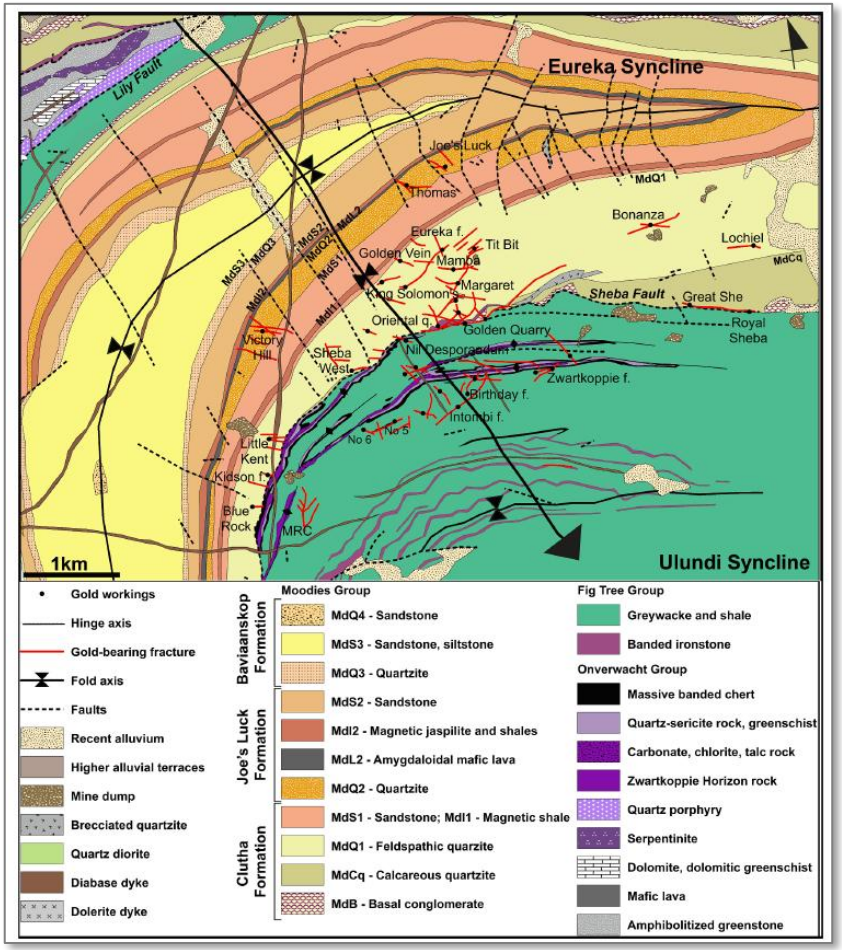


Master and Wendorff (2011)

Robertson (2014)

District to Deposit Scale

- Structural preparation and development of damage zones creates specific physical conditions that enable ore deposition.
- Orogenic gold deposits commonly form in brittle–ductile transition zones where repeated cycles of fault rupture, fluid influx, and sealing generate high-grade ore shoots.
- Individual deposits often associated with 2nd and 3rd order structures related to deep-seated faults.
- Local controls include lithological contacts (rheological boundaries); fold hinges; dilatant zones; jogs; damage zones; late-stage brittle structures; structural intersections (these often control high-grade ore localization).



Jones and Kisters (2022)

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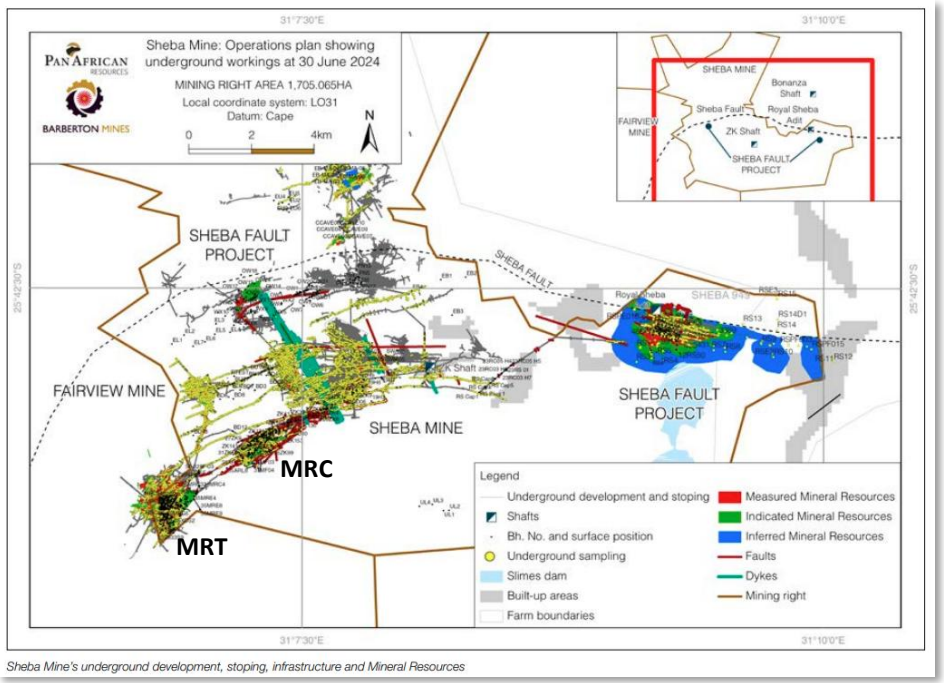
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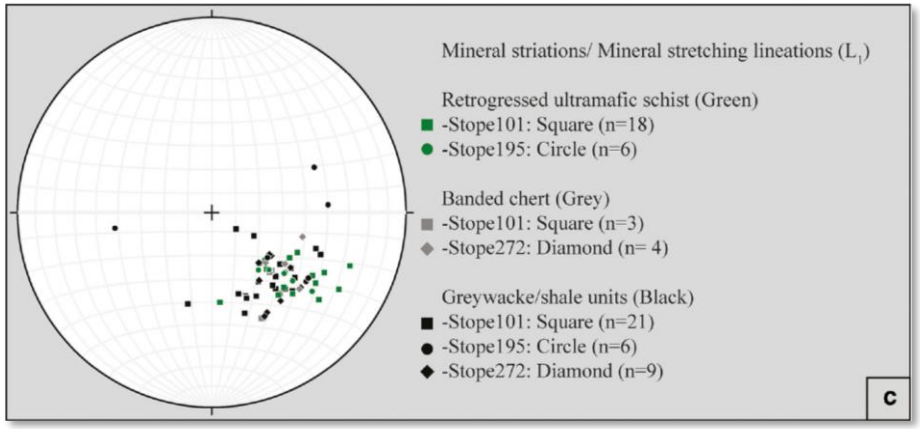
Ore Shoot to Microscale

- Microscale structures within host rocks—microfractures, vein arrays, cleavage-controlled permeability, and dilation zones—govern the efficiency of fluid–rock interaction and the timing of mineral precipitation.
- Features such as jogs, step-overs, fold hinges, and rheological heterogeneities often serve as traps where fluids slow, mix, cool, or react with wall rocks, producing localized zones of high-grade mineralization.
- Microstructural permeability and fluid-rock interaction.

Sheba Mine - Barberton Greenstone Belt

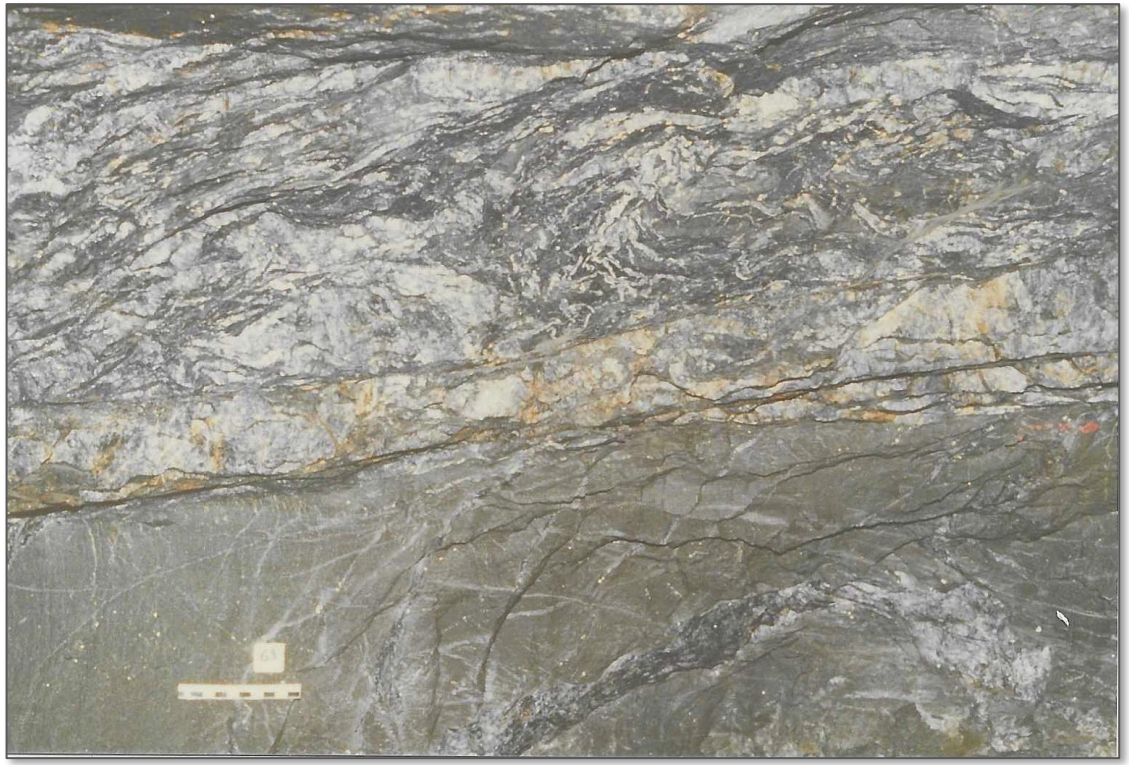


Sheba Mine's underground development, stoping, infrastructure and Mineral Resources



https://www.panafricanresources.com/wp-content/uploads/Pan-African-MR-MR-2024.pdf

Sheba, Barberton Greenstone Belt



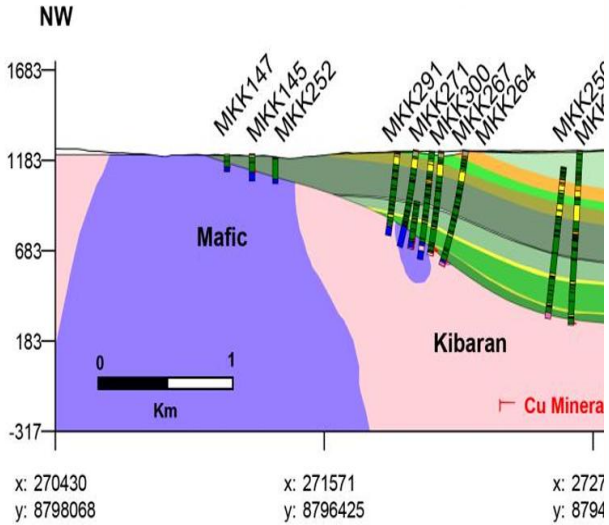


Sheba, Barberton Greenstone Belt

- **Lithological and rheological control**
  - Gold mineralization spatially related to the contact between meta-turbidites (Fig Tree Group) structurally juxtaposed against cherts and ultramafic schists (Onverwacht Group).
  - Interbedded shale-greywacke provided a lithological control (preferential strain partitioning and fluid focussing into shale).
  - Bedding parallel shearing during flexural slip folding resulted in high-grade dismembered graphite- and sulphide-rich shale units.
- **Structural control**
  - Gold mineralization during polyphase progressive deformation.
  - Proximity to regional-scale faults
  - Ore shoot orientations subparallel to fold axis of refolded (F3) Ulundi Syncline (main control at Fairview)
  - At Fairview, ore shoots correspond to deflections that created dilational jogs (SE plunge of the ore shoots can be traced for >2000m down plunge) – related to prominent clockwise rotation of the Ulundi Syncline axis during fold tightening.
  - At Sheba, the intersection between the main steep-dipping shears and crosscutting shallow-dipping shears resulted in northeast-plunging ore shoots.

Central African Copperbelt: Fishtie

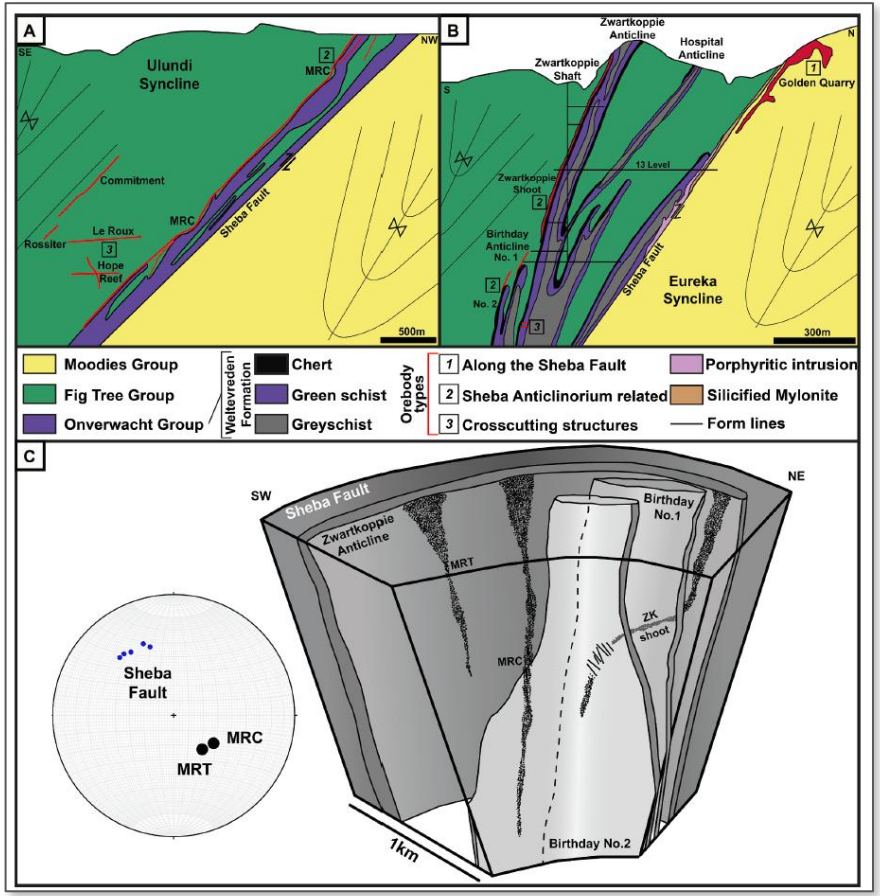
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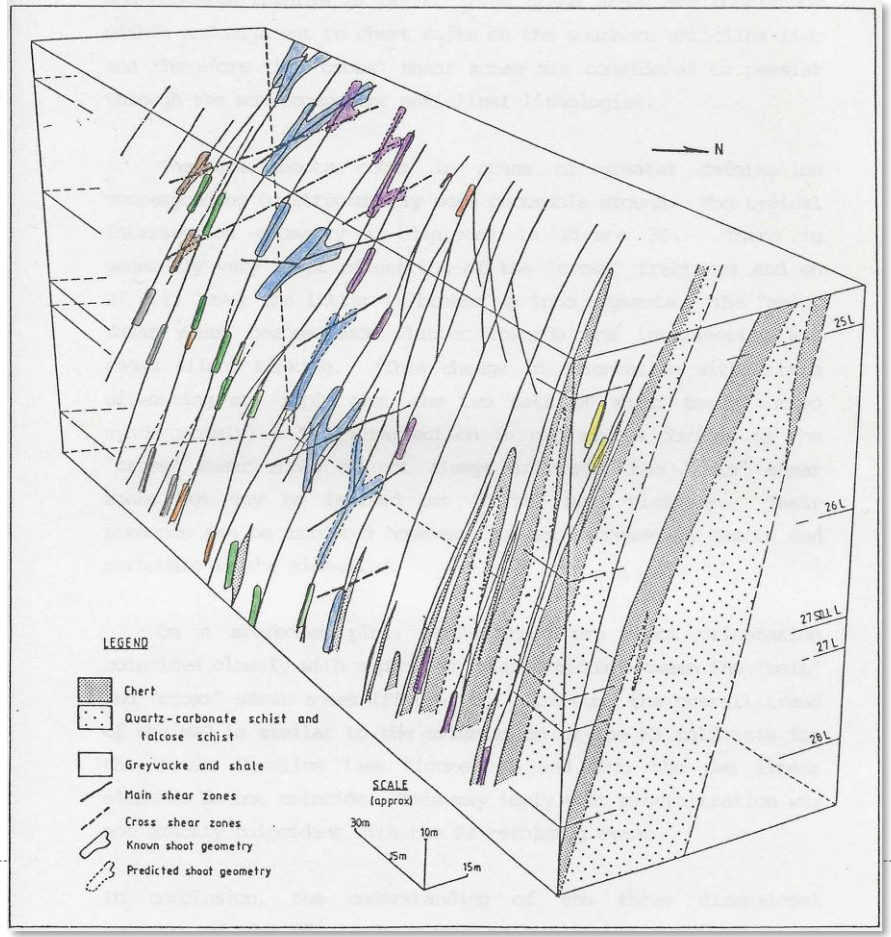
Sheba, Barberton Greenstone Belt

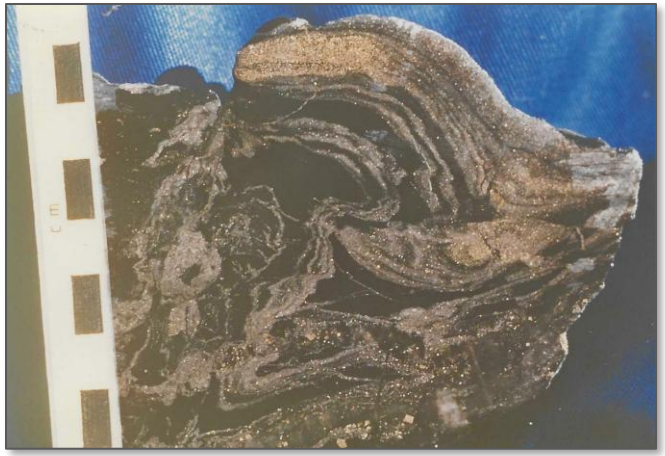
- Current mining is focused on the **MRC** orebody (disseminated sulphides in metagreywacke and. shale)
- At Fairview, SE-plunging ore shoots (~40g/t Au) can be traced for >2000m down plunge.
- Ore shoots correspond to deflections that created dilational jogs – related to prominent clockwise rotation of the Ulundi Syncline axis during fold tightening.



Jones and Kisters (2022)

Sheba, Barberton Greenstone Belt





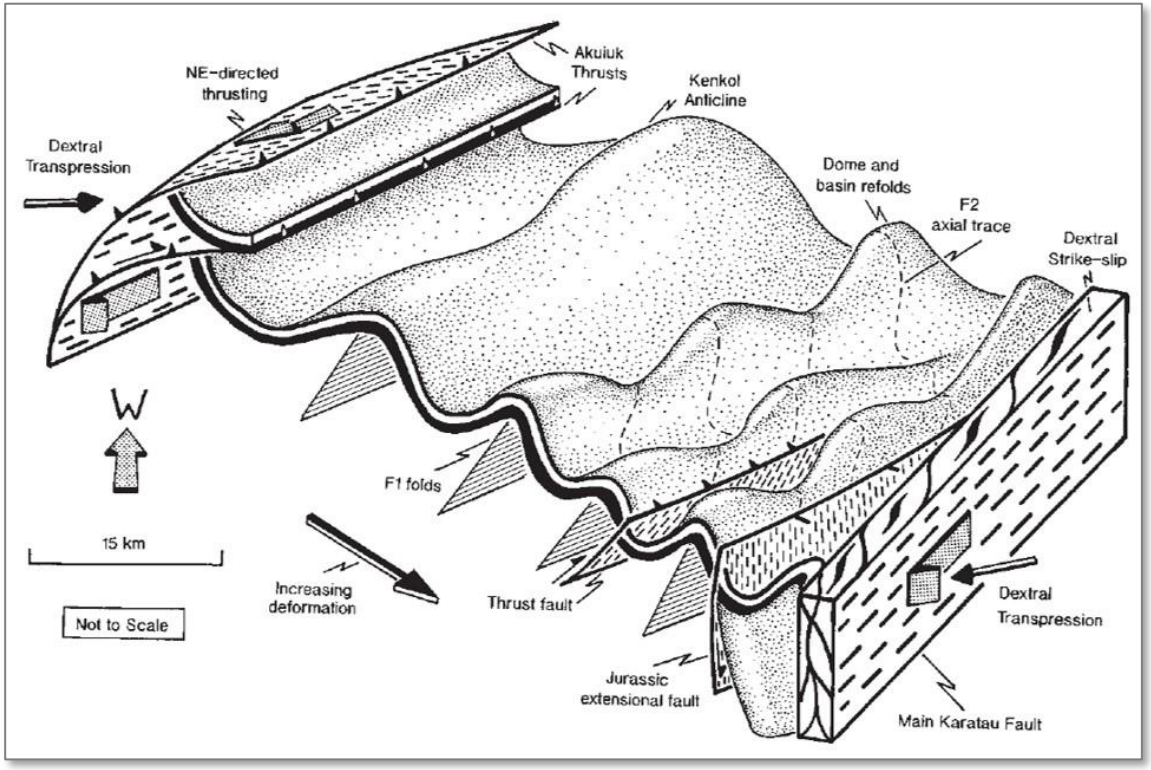


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Chu Sarysu Basin

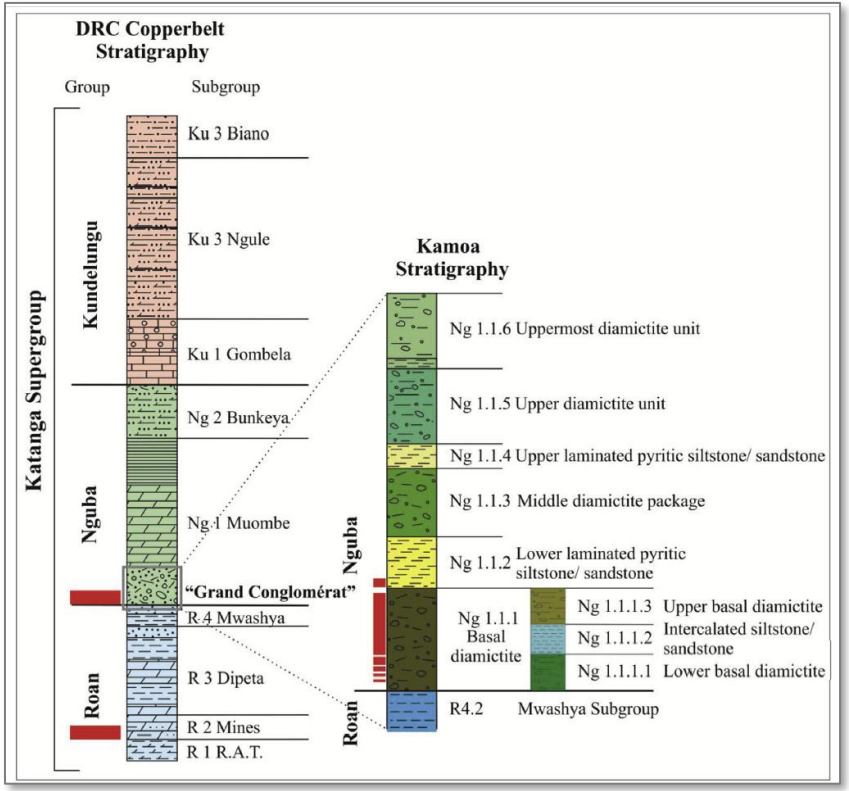
- Dome and basin interference folding.
  - F1: ENE-trending upright folds.
  - F2: Orthogonal NNW-trending upright folds.
- This geometry strongly influenced the migration of hydrocarbons and metalliferous brines.
- The known copper deposits show a spatial association with the interference fold pattern.



Alan et al (2001)

Central African Copperbelt: Kamoa-Kakula

- Progressive widening of the basin within the Western Foreland region and deposition of the upper stratigraphic units.
- Lower part of the stratigraphy is absent at Kamoa-Kakula.
- Cu mineralization is hosted at the base of the Grand Conglomérat which represents the first reduced horizon above the Mwashya Subgroup red beds.

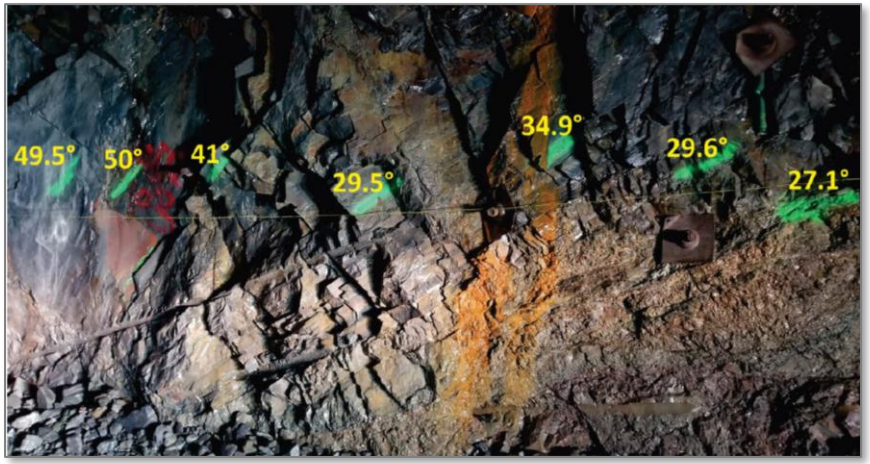


Twite (2019)

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Central African Copperbelt: Kamoa-Kakula

- Steep bedding – characteristic of growth faults.
- Soft sediment deformation (Kakula).



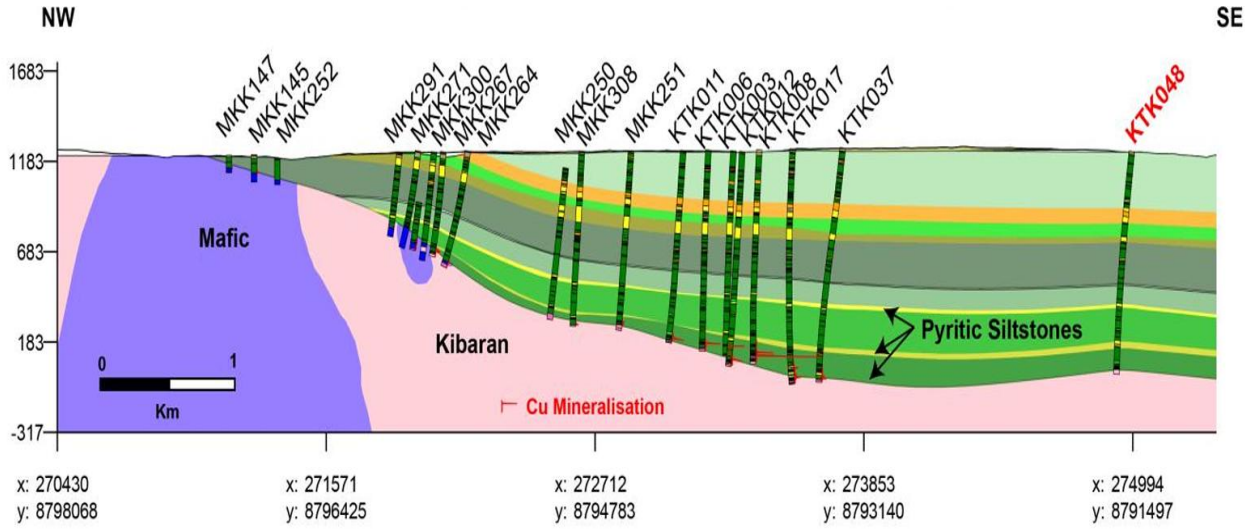
Twite et al (2020)





Central African Copperbelt: Kamoa-Kakula-Makoko

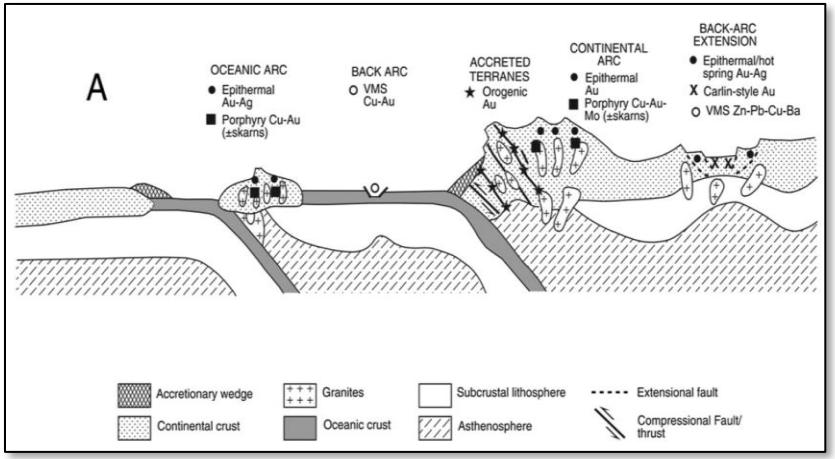
- The Western Forelands is the world's richest copper basin.
- Makoko copper district discovered in 2018 (world's highest-grade and fifth largest copper discovery of the past decade).
- 13km strike length; up to 5km wide (open along strike and downdip).
- Between 200 – 1,250m depth.
- Basement topography (basin architecture) controls copper mineralization.



Ivanhoe Mines (2025)

Structural Control by Deposit Type

- Orogenic gold deposits
  - Almost entirely structurally controlled
  - Associated with major brittle-ductile fault systems and shear zones
- Porphyry copper deposits
  - Often form at the intersections of deep crustal faults and magmatic conduits - locations that focus magmas, heat, and fluids into constrained structural corridors.
- Magmatic deposits
  - Moderately controlled
  - Structures can influence magma emplacement pathways
  - Faults may localize intrusions
- Sedimentary deposits
  - Less directly controlled
  - Structures affect basin formation/architecture and later fluid flow
  - Faults may remobilize and concentrate mineralization



Pirajno (2016)

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