Charles University
Faculty of Science

Study Programme: Geology
Branch of Study: Geology

Adam Pařízek

Geological pattern and mineral deposits in the Southern Ethiopian Shield

Geologická stavba a ložiska nerostných surovin v oblasti jižního etiopského štítu

Bachelor's thesis

Supervisor: doc. RNDr. Kryštof Verner, Ph.D.
2024

Prohlášení:

Prohlašuji, že jsem závěrečnou práci zpracoval samostatně a že jsem uvedl všechny použité informační zdroje a literaturu. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

V Praze, 30. 7. 2024 ....

Adam Pařízek

Acknowledgments

I would like to express my sincere gratitude to the supervisor of this thesis doc. RNDr. Kryštof Verner, Ph.D. for his patience, willingness to help, and kind attitude, which all created stress-free atmosphere that made working on this thesis remarkably less challenging. The time he dedicated to correction of my mistakes and explanation of various topics is greatly appreciated by me. His commentaries and recommendations regarding both factual as well as formal aspects were of great importance and significantly contributed to the completion of this thesis.

I would also like to thank everyone associated with the Institute of Petrology and Structural Geology at the Faculty of Science, Charles University for valuable information and knowledge I gained when attending multiple courses under the direction of several its members. A lot of what I have learnt there has proven to be of enormous help to me when working on this thesis.

My special thanks are also extended to my classmates, especially to Tereza Křížová and Michal Olta. Their advice and assurances were crucial during the final stages of completing this thesis.

List of Abbreviations

Abbreviation	Meaning
EAO	The East African Orogen
ANS	The Arabian-Nubian Shield
MB	The Mozambique Belt
SES	The Southern Ethiopian Shield
WES	The Western Ethiopian Shield
NES	The Northern Ethiopian Shield
EES	The Eastern Ethiopian Shield
LREE	Light rare earth elements
LILE	Large ion lithophile element
REE	Rare earth elements
Tcf	Trillion cubic feet

Abstract in English

This Bachelor's Thesis serves as an overview compiled from published literature that is supposed to summarize information regarding geological environment and geodynamic evolution of Precambrian rocks in the Southern Ethiopian Shield, including a broad insight into mineral deposits in this important geological unit.

The Southern Ethiopian Shield was formed during East African Orogeny (ca. 750 to 620 Ma) as a prominent orogenic episode within the Pan-African orogenic processes. The Southern Ethiopian Shield consists of complex rock assemblage including low- to medium-grade metamorphic volcano-sedimentary rocks of the Arabian-Nubian Shield and polyphase high-grade metamorphic rocks belonging to the northernmost part of the Mozambique Belt. These sequences are accompanied by frequent granitoid intrusions emplaced during final stages of the East African Orogeny. In addition, two main regional shear zones with occurrences of hydrothermal alteration and secondary mineralization are identified in the Southern Ethiopian Shield

Numerous deposits of mineral and other resources are present all over Ethiopia. Although there is significant potential for mining fossil fuels and non-metallic resources such as salt or limestone, metallic mineralization found in Precambrian rocks remains the most prominent mineral resource of the country. Examples of that can be platinum extracted from mafic sequences of the Western Ethiopian Shield and tantalum deposit found in pegmatites of the Kenticha Belt in the Southern Ethiopian Shield. The most abundant metallic resource, mined in the largest amounts, is however gold. Gold mining in Ethiopia has been for a long time concentrated in Kenticha and Megado metamorphic belts in the Adola area of the Southern Ethiopian Shield. Gold is generally held here in sulfidic minerals associated with quartz veins and other quartz occurrences. The origin of gold mineralization is connected to low-grade hydrothermal alteration related to regional shear (deformation) zones. Both primary and placer gold deposits are present here, as well as Ethiopia's largest active gold mine in Lega Dembi.

Key words: *Southern Ethiopian Shield, Arabian-Nubian Shield, Tectonics, Mineral deposits, Petrology*

Abstrakt v českém jazyce

Tato bakalářská práce poskytuje souhrnný přehled sestavený z doposud publikované literatury, jehož cílem bylo shrnutí informací o geologickém prostředí a geodynamickém vývoji prekambrických hornin v jižním etiopském štítu. Bakalářská práce dále dává čtenáři souborný přehled o indikacích výskytu ložisek nerostných surovin v této významné geologické jednotce.

Jižní etiopský štít byl formován v období východoafrické orogeneze (ca. 750 až 620 Ma) jakožto hlavní orogenní události během panafrických orogenních procesů. Jižní etiopský štít je tvořen souborem nízce až středně metamorfovaných vulkanosedimentárních hornin arabsko-núbijského štítu a polyfázově vysoce metamorfovanými horninami nejsevernější části mozambického pásu. Do prostředí těchto metamorfovaných hornin byly v závěrečné fázi orogenních procesů vmístěny četné granitoidní intruze. Na území jižního etiopského štítu dále vystupují dvě regionální střižné zóny s výraznými projevy hydrotermální alterace a sekundární mineralizace.

Na území Etiopie se vyskytují četná naleziště nerostných surovin. I přes významný potenciál těžby kaustobiolitů a nerudních surovin jako jsou sůl či vápenec, rudní suroviny nalézající se v prostředí prekambrických hornin zůstávají předním nerostným bohatstvím země. Příkladem je platina extrahovaná z mafických hornin západního etiopského štítu a ložisko tantalu v pegmatitech pásu Kenticha v jižním etiopském štítu. Nejrozšířenějším kovem, který je v současnosti těžen v největších množstvích, je zlato. Těžba zlata v Etiopii je soustředěna zejména v oblasti metamorfních pásů Kenticha a Megado spadající do oblasti Adola v jižním etiopském štítu. Zlato je zde součástí sulfidických minerálních asociací vyskytujících se ve vazbě na křemenné žíly či další výskyty křemene. Původ zlatého zrudnění je spojován s výskytem nízkoteplotní hydrotermální alterace s vazbou na regionální střižné (deformační) zóny. V této oblasti se nachází jak primární naleziště zlata, tak rozsypy. Je zde také přítomen největší aktivní důl na zlato v Etiopii – Lega Dembi.

Klíčová slova: *jižní etiopský štít, arabsko-núbijský štít, tektonika, ložiska nerostných surovin, petrologie*

Contents

1. Introduction

The main goal of this bachelor's thesis is to summarize the overall geological pattern and geodynamic evolution of the Southern Ethiopian Shield (Tokar-Barka Unit) with special emphasis on mineral resources and gold deposits. This will be achieved mainly by using already published literature, where currently available knowledge and its compilation are the main object of this study. The thesis is divided into three main chapters that each focuses on one specific part within the overall topic. The first chapter describes the geological settings of the Southern Ethiopian Shield (Tokar-Barka Unit), mainly in the context of the East African Orogeny. The second chapter focusses on detailed description of main structures and lithological assemblage found in the Southern Ethiopian Shield, which includes the medium- to high-grade gneissic terrains, low- to medium-grade metamorphic belts, regional shear-fault zones and numerous granitoid intrusions. The third chapter summarizes the mineral resources and deposits of the Southern Ethiopian Shield including a deeper insight into gold mineralization in the Adola-Moyale Unit.

The Southern Ethiopian Shield (Tokar-Barka Unit) is one of Ethiopia's areas of exposed Precambrian rocks forming the Neoproterozoic basement of the country. This exposed Precambrian basement accounts for about 23 % of the overall Ethiopia's territory (e.g. Assefa, 1985; Stern et al., 2012).

The geological evolution of the Southern Ethiopian Shield was highly influenced by partial orogenic events in frame of the "Pan-African" orogenic cycle (e.g. Kröner and Stern, 2005). As mentioned in Kröner and Stern (2005), the Pan-African orogeny refers to a complex orogenic cycle which occurred approximately between ~870 to ~450 Ma. This orogenic cycle consisted of numerous collisional events between older crustal fragments as the result of the Supercontinent Rodinia break-up and also subsequent closures (subductions) of multiple oceanic basins (Kröner and Stern, 2005). The Pan-African orogenic system is of such extent that it is best described by dividing it into more specific orogenic belts (e.g. East African Orogenic Belt). One of the prominent exposures of Precambrian rocks in the northeastern Africa is the Southern Ethiopian Shield belonging to the southernmost

Arabian-Nubian Shield and neighboring Mozambique Belt where the East African Orogen (EAO) played the principal role (e.g. Meert, 2002).

The Southern Ethiopian Shield in particular is of great interest due to its high economic potential based on numerous mineral deposits identified there (e.g. Assefa, 1985; Tadesse, 1999 and 2003; Ahmed, 2008; Endalew et al., 2024) and also as a way to properly understand the origin of Ethiopia's Precambrian units together with their development throughout time.

2. Geological Setting

2.1 The East African Orogen

The East African Orogen (EAO) refers to complex orogenic structure of enormous size (ca. 8000 km long and ca. 1000 km wide) that appeared during amalgamation of the Gondwana Supercontinent. It is also referred to as the Transgondwanan Supermountain (according to Squire, 2006).

The EAO emerged as a result of complex tectonic events. The first stage in formation of the EAO was described by Stern (1994) as a rifting phase that occurred after the break-up of Rodinia Supercontinent including formation of passive continental margin and oceanic crust of the Mozambique Ocean. Evidence of this rifting episode was found in metasedimentary rocks cropping out the territory from Kenya to Sudan. Their protoliths are interpreted as originating from a sedimentary environment of passive continental margin and were deposited prior to ca. 750 to 720 Ma (e.g. Vearncombe, 1983; Kröner et al., 1987; Key et al., 1989; Mosley, 1993). In addition, the amphibolite-facies mafic and ultramafic rocks found in southern Tanzania that have been dated to ca. 790 Ma are interpreted as the result of early rifting processes (Prochaska and Pohl, 1983). Another indication of rifting activity is the presence of low-grade tholeiitic basalts and rhyodacites in the Arabian-Nubian Shield, which were dated to ca. 870 to 840 Ma (Kröner et al., 1991, 1992). These rocks originated from intra-oceanic arcs and share significant chemical similarities with other rift-associated rocks in the Arabian-Nubian Shield (Reischmann et al., 1984). Furthermore, the presence of quarzitic and pelitic rocks in this area suggests contamination by surrounding crustal rocks during the initial phase of rifting. According to all this evidence the rifting is currently thought to had begun between ca. 900 to 850 Ma with oceanic basin and passive continental margin developed after ~870 Ma (e.g. Stern, 1994).

Following subduction of the Mozambique Ocean (~800 to 700 Ma) caused large volcanic arc construction (dated at ~765 Ma). These processes were continued by Mozambique Ocean closure and led to crustal accretion, including intensive migmatization and MP-HT metamorphic overprint at depths of ~25–35 km (dated at

~720 to 700 Ma). This event was associated with initial collision of East and West Gondwana which also caused a significant thickening of continental crust. The exact timing of this event is indicated by origin of high-grade granulites exposed mainly in the southern part of the EAO (Stern, 1994; Verner et al., 2021 and references therein). Dating of granulites from various locations in Sudan, Tanzania, Kenya and southern Ethiopia suggests that they all underwent granulite-facies metamorphism between ca. 740 to 650 Ma (Coolen et al., 1982; Maboko et al., 1985; Kröner et al., 1987; Stern and Dawoud, 1991; Verner et al., 2021 and references therein). In frame of ongoing compression at ~650 to 620 Ma the key episode of continental collision leading to the Greater Gondwana assembly took place (Fig. 1) (Verner et al., 2021 and references therein). The ~E–W oriented compression resulted in regional ~N–S trending foliation and it is also associated with the syn-tectonic granitoid intrusions yielded at ~650 Ma to ~620 Ma. Following episode (~620 to 450 Ma) was associated with orogenic collapse, crustal extension (transtension) and uplift accompanied by emplacement of numerous post-collisional granitoid plutons, dated in the range ~620 to 530 Ma (e.g. Yibas et al., 2002; Stern et al., 2012 and references therein).

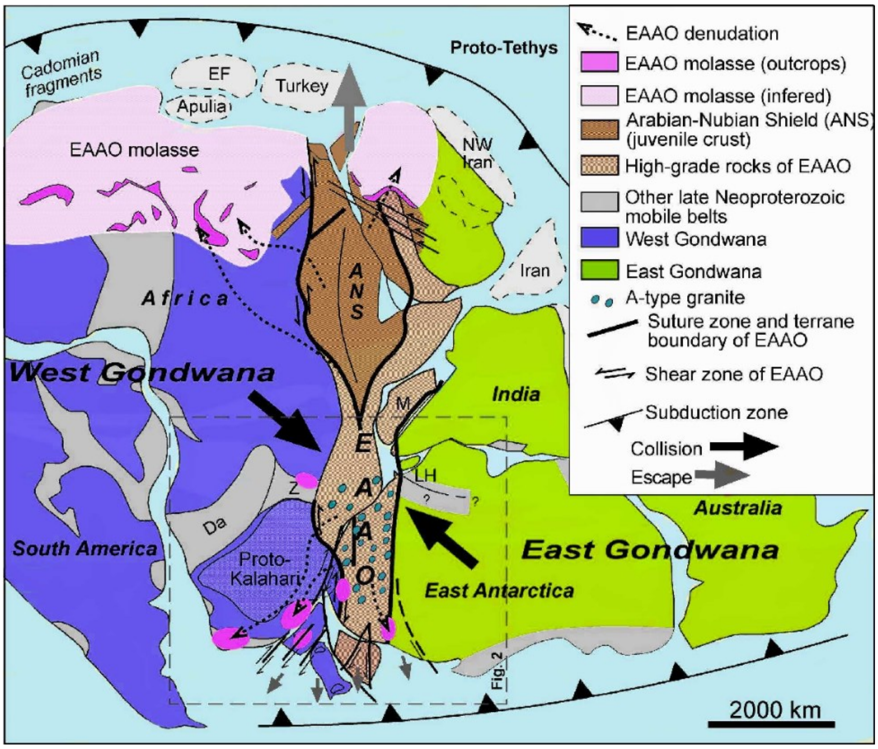

Fig. 1 Pan-African collision of East and West Gondwana forming the East African Orogen (modified after Jacobs and Thomas, 2004)

It is important to mention that even though the east part of the Gondwana Supercontinent was formed by this compression, it was not result of continuous process but more of an effect of two major periods of tectonic activity. Meert (2002) describes the older East African Orogeny (ca. 750 to 620 Ma) which caused the initial joining of crustal blocks as well as arc terranes of the Arabian-Nubian Shield and younger Kuunga Orogeny (ca. 570 to 530 Ma). The Kuunga Orogeny was caused by collision of Australia and eastern Antarctica with the continental block created by the East African Orogeny. This marks the final assemblage of the Gondwana Supercontinent (Meert, 2002).

2.2 The Arabian-Nubian Shield

As mentioned by several studies (e.g. Kröner and Stern, 2005; Fritz et al., 2013), the East African Orogen consists of two main distinct geological units (see Fig. 2). The Arabian-Nubian Shield (ANS) represents the northern part of the East African Orogen, mostly exposed around the Red Sea. The ANS reaches as far as southern Sinai Peninsula in the north and Yemen and Ethiopia in the south, where it connects to the Mozambique Belt as the other of the two geological units within EAO.

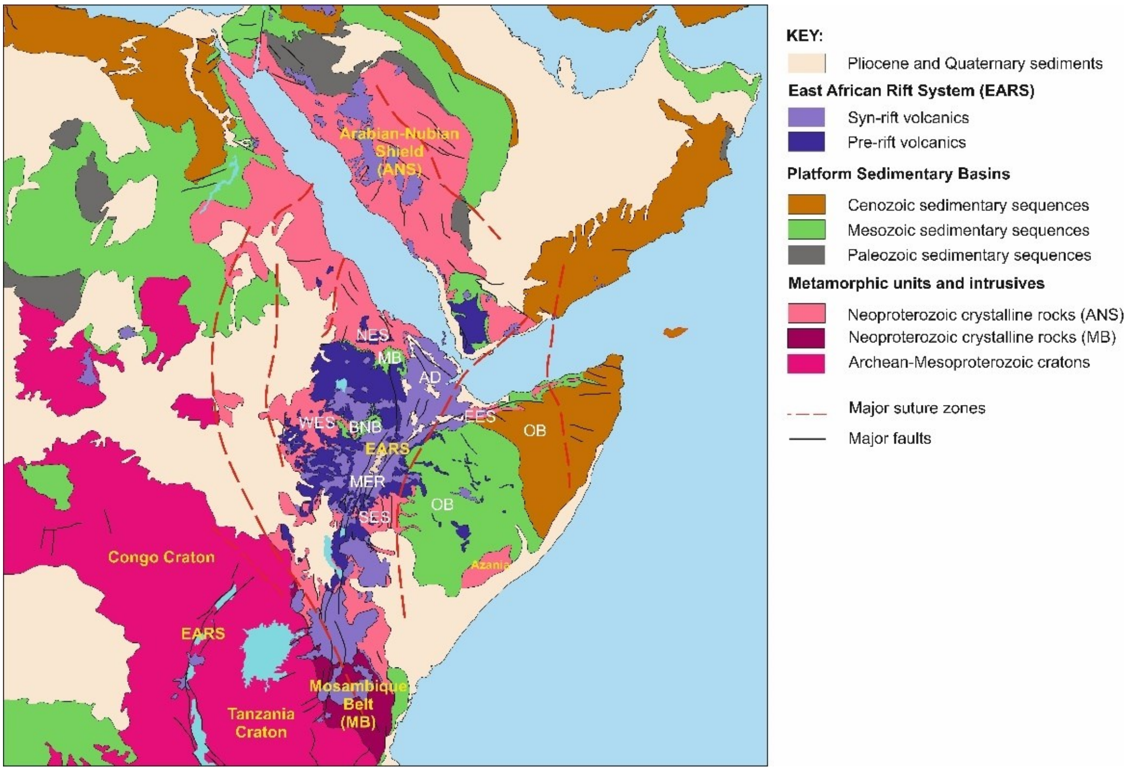

Fig. 2 The Arabian-Nubian Shield and the Mozambique Belt as parts of the East African Orogen (after Fritz et al., 2013 and Verner et al., 2021)

The formation of ANS occurred during the East African Orogeny and was completed when parts of newly formed (juvenile) crust, originating from intra-oceanic plate boundaries or oceanic plateaus, and smaller amounts of older Meso- and Paleoproterozoic continental crust were accreted together with colliding the East and West Gondwana. The lithological composition of the ANS is characterized by mostly low- to medium-grade metamorphic rocks that underwent less intense metamorphic overprint (Kröner and Stern, 2005). The main collisional event in the ANS is supposed to had happened between 650 to 610 Ma (e.g. Kröner and Stern, 2005; Verner et al., 2021 and references therein) and it lasted until early Cambrian in some parts of the EAO. Another important factor which influenced formation of the ANS during final stages of the East African Orogeny was escape tectonics caused by orogenic collapse. According to Stern (1994), the "escape tectonics" began at some point between ca. 660 to 610 Ma and lasted until ca. 530 Ma. It led to development of NW-trending faults that can be found in Egypt and Arabia (Stern, 1994). This event was also accompanied by intrusions of A-type post-kinematic granitoids, bimodal volcanic activity and sedimentation of molasses (Kröner and Stern, 2005).

In the Arabian-Nubian Shield there is also common occurrence of ophiolites which are mostly found by major fault systems indicating sutures dividing specific terranes of the ANS (Stern, 1994; Kröner and Stern, 2005). These ophiolites are of great importance since they reflect the production of oceanic crust and crustal movements of the area. The rocks that these ophiolites contain originate from back-arc or fore-arc basins and were dated to be ca. 880 to 690 Ma old which makes them the oldest significantly abundant ophiolite structures on Earth (Stern, 1994).

2.3 The Mozambique Belt

The Mozambique Belt built by medium- to high-grade rocks and numerous granitoids connects to the ANS in the south (Fig. 2), forming the southern part of the East African Orogen (Kröner and Stern, 2005). It stretches from southernmost Ethiopia and Somalia to eastern parts of Antarctica crossing Kenya, Tanzania, Mozambique, and Madagascar (Kröner and Stern, 2005, Fritz et al., 2013).

MB formed as a result of closure of the Mozambique Ocean during collision of Congo-Tanzania Craton and continental block known as “Azania” consisting of Archean and Paleoproterozoic crust (dated to ca. 2.9 to 2.45 Ga) at around ca. 630 to 600 Ma (Collins and Pisarevsky, 2005, Bingen et al., 2009). In comparison to the Arabian-Nubian Shield the rocks of the Mozambique Belt underwent stronger compression at higher depths during the East African Orogeny resulting in origin of intensely deformed medium- to high-grade metamorphic rocks such as granitoid gneisses and granulite-facies metamorphic rocks. The granitoid gneisses reveal protoliths yielded to ca. 1100 to 1000 Ma that then underwent intense metamorphism and deformation during the Pan-African orogenic cycle.

Based on currently known information it is likely that many sequences of northern MB underwent intense deformation and metamorphic overprint even before the Pan-African orogenic processes during tectonothermal events of the Mozambican Cycle that occurred at ca. 1100 to 850 Ma. This cycle was also accompanied by emplacement of granitic plutons and gabbro-anorthosite massif in Tete, northwestern Mozambique (Kröner and Stern, 2005, Fritz et al., 2013). The Pan-African granulite-facies metamorphism reached its climax in Neoproterozoic era, at around ~640 to ~620 Ma based on dating from granulitic sequences of Tanzania. The exact time however varies in different parts of the Mozambique Belt (Kröner and Stern, 2005, Fritz et al., 2013). Timing of most granulite ages between ca. 655 to 610 Ma indicates that collision of Congo-Tanzania Craton with Microcontinent Azania served as the main cause of metamorphism. Another theory suggests that since both prograde and retrograde P-T paths have been identified in granulites of Tanzania as well as evidence of slow cooling, the metamorphism might have occurred in subduction zone-associated environment related to closure of the Mozambique Ocean (Collins and Pisarevsky, 2005).

Many areas in the MB underwent another wave of granulite-facies metamorphism during later Kuunga Orogeny with peak thickening and metamorphism between ca. 570 to 530 Ma (Fritz et al., 2013). This was especially significant in southern parts of MB where the Kuunga Orogeny is regarded as the main granulite-facies metamorphic event. The compression of Kuunga Orogeny was later followed by abundant post-orogenic magmatism throughout Madagascar, Antarctica and parts of Mozambique (Bingen et al., 2009). Unlike in the ANS there are no ophiolitic structures present here (Stern et al., 2012).

In summary, the main difference between the Arabian-Nubian Shield and the Mozambique Belt is the fact that the Arabian-Nubian Shield consists of newly formed juvenile Neoproterozoic rocks with significant amount of oceanic crust that underwent a lower-grade metamorphism whereas the Mozambique Belt is mostly composed from older (Archean to Paleoproterozoic) crustal rocks that underwent a medium- to high-grade metamorphic overprint (Stern et al., 2012 and references therein).

2.4 Ethiopia’s Precambrian shields

There are in total four main exposures of Precambrian rocks in Ethiopia. They are referred to as the Northern, Western, Eastern and Southern Ethiopian Shields (Fig. 3). These exposures belong to the southernmost exposure of the Arabian-Nubian Shield called the “Tokar-Barka Unit” and northern part of the Mozambique Belt (Miller et al., 2001; Fritz et al., 2013). This sub-chapter includes summarized geological and petrological characteristic of the Northern, Western and Eastern Ethiopian Shields (see chapter 3 for information about the Southern Ethiopian Shield).

The Northern Ethiopian Shield

The Northern Ethiopian Shield accounts for the northernmost exposure of Precambrian rocks in Ethiopia. According to Megerssa et al. (2020) overall geological pattern of the area can be summarized into two main groups. Older Tsaliet Group consisting mostly of low-grade intermediate to felsic lava and welded tuffs accompanied by lapilli tuffs, agglomerates and limestones. The younger sequence overlaying the Tsaliet Group is called the Tambien Group and it contains mainly limestones, quartzitic dolomites and siliciclastic sediments. Both these groups originate from era between ca. 850 and 735 Ma.

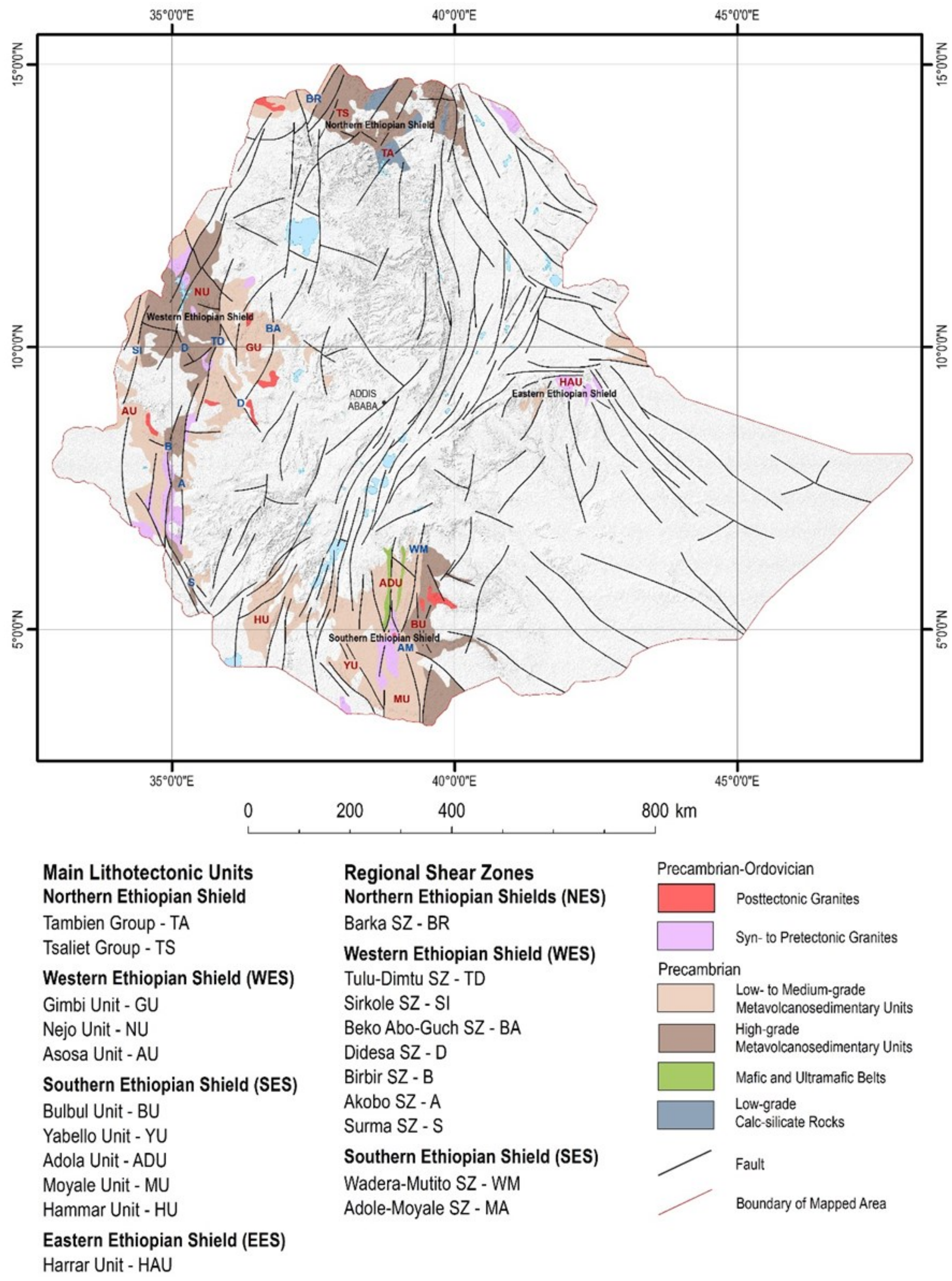

Fig. 3 Simplified map of Precambrian rocks in Ethiopia (after Verner et al., 2024)

The Eastern Ethiopian Shield

The Eastern Ethiopian Shield is the easternmost exposure of Precambrian rocks in Ethiopia, and it is also the smallest Ethiopian Shield by total surface area. It was divided by Berhe (1981) into three main units: lower unit, middle unit (known as the Boye Group) and upper unit (the Soka Group). The lower unit was described by Berhe (1981) as being comprised of biotite, hornblende, biotite-hornblende and garnet-biotite gneisses as well as migmatites with subordinate quartzofeldspathic gneisses, amphibolites and schists. The Boye Group consists of biotite, and quartzo-muscovite schists, meta-arkoses, quartzites, marbles, metapelites, chlorite and andalusite-garnet schist. The Soka Group includes mostly phyllites, chlorite schists, metavolcanic rocks and subordinate ultramafic rocks (Berhe, 1981).

The Western Ethiopian Shield

The Western Ethiopian Shield is the largest exposure of Precambrian rocks in Ethiopia. Based on currently known data from the Western Ethiopian Shield, it can be divided into three N–S trending units separated by shear belts (Alemu, 2021). The three distinct units are Asosa Terrane (includes different types of gneisses and volcano-sedimentary rocks), Nejo Terrane (consisting of metavolcanic and metasedimentary sequences) and Gimbi Terrane (with abundance of gneisses, migmatites and metavolcano-sedimentary rocks). Asosa and Nejo Terranes are divided by Sirkole-Birbir Shear Zone and Tulu Dimtu – Baruda-Akobo Shear Belt separates Gimbi from Nejo Terrane (Alemu, 2021).

3. The Southern Ethiopian Shield

The Southern Ethiopian Shield represents one of southernmost exposures of late-Proterozoic rocks belonging to the Arabian-Nubian Shield. Due to its position on the boundary of two distinct terrains (ANS and MB) within the East African Orogen it accounts for important transition domain between the Arabian-Nubian Shield in the north and the Mozambique Belt in the south (Kröner and Stern, 2005; Stern et al., 2012).

Overall geological evolution of the Southern Ethiopian Shield fits well to geodynamic scenario in the context of the Tokar-Barka Unit forming the southern segment of the Arabian-Nubian Shield (e.g. Fritz et al., 2013; Verner et al., 2021). The regional tectonothermal and metamorphic evolution underwent upper amphibolite-facies overprint in the gneissic terrane and lower amphibolite-facies overprint in the low-grade belts coeval to the folding and thrusting events, greenschist-facies metamorphism during subsequent shear deformations, late hydrothermal alteration, and regional uplift (Yihunie and Hailu, 2007). Based on current knowledge it is possible to distinguish four main stages of geodynamic evolution in the Southern Ethiopian Shield (Fig. 4): (a) Tonian episode (ca. 870 to 800 Ma) including the continental rifting, break-up of the Supercontinent Rodinia, spreading of the Mozambique Ocean and formation of source juvenile crustal rocks; (b) Late Tonian to early Cryogenian episode (ca. 800 to 700 Ma) when oceanic subduction begun with continuation in closing the Mozambique Ocean and formation of large volcanic arc; (c) Late Cryogenian to early Ediacaran episode (ca. 650 to 620 Ma) which represents the main period of E–W oriented continental collision and crustal accretion that resulted in creation of N–W trending metamorphic fabrics and consolidation of Greater Gondwana Continent; (d) Late Ediacaran to Cambrian episode (ca. 630 to 500 Ma) corresponding to orogenic collapse, crustal extension, uplift and emplacement of numerous post-tectonic granitoid intrusions (e.g. Johnson and Woldehaimanot 2003; Stern et al., 2012; Fritz et al., 2013; Bowden et al., 2020; Verner et al., 2021 and references therein).

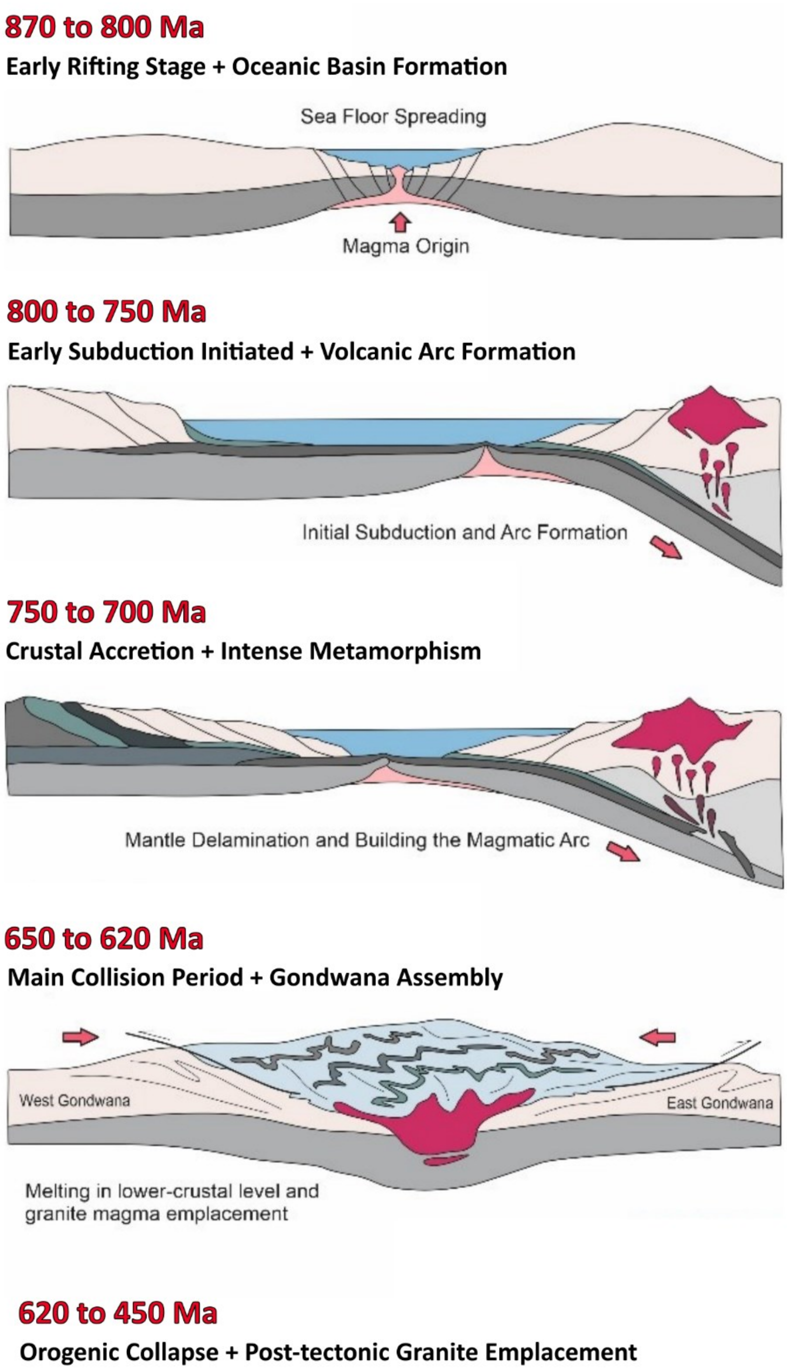

Fig. 4 Visualization of geodynamic evolution in the Southern Ethiopian Shield (modified after Verner et al., 2021)

The principal geological pattern of Southern Ethiopian Shield itself is characterized by presence of two main lithological segments. The first one consists of high- to medium-grade metamorphic rocks and is intercalated by several N–S trending low-grade metamorphic belts. These Neoproterozoic rocks are partially overlayed by Mesozoic sedimentary rocks and Cenozoic volcanic and volcanoclastic sequences of the East African Rift System (e.g. Worku and Schandelmeier, 1996; Yibas et al., 2002; Stern et al., 2012; Verner et al., 2021).

3.1 High- to medium-grade metamorphic terrain

The high- to medium-grade metamorphic basement of the Southern Ethiopian Shield was firstly described by Worku and Schandelmeier (1996) as consisting of several distinct domains and belts defined based on different degree of metamorphism, tectonic pattern and lithology. From west to east these domains are the Sodda Domain, the Shakisso Domain and the Zembaba Domain. Davidson (1983) concluded that the westernmost part of the Southern Ethiopian Shield is called the Hammar Domain and is located west of the Main Ethiopian Rift System. The Sodda Domain is built by various metamorphic rocks such as biotite-hornblende gneiss, amphibolite, quartzofeldspathic gneiss, kyanite schist and ultramafic sequences, intruded by granites and pegmatites (Worku and Schandelmeier, 1996). The Shakisso Domain is mostly consisted by quartzofeldspathic gneiss, amphibolite schist, biotite schist, marble and psammo-pelitic schists with intrusions of syn- and post-tectonic granitoids (Worku and Schandelmeier, 1996). The Zembaba Domain in the east is comprised of migmatized trondhjemitic gneiss, quartzofeldspathic gneiss and mica schist with intercalated greenstone associations (mostly ultramafics and amphibolites) which are all accompanied by syn-tectonic granites and pegmatites (Worku and Schandelmeier, 1996). Lastly, the Hammar Domain separated from rest of the Southern Ethiopian Shield by the Main Ethiopian Rift System is mainly characterized by presence of biotite and amphibole-biotite migmatites, medium-grained two-pyroxene granulites and amphibolites. These rocks are then accompanied by intrusions of ultramafics, diorites, gabbros, and syn- to late-tectonic granites with aplite and pegmatite dikes (Verner et al., 2021).

Yibas et al. (2002) classified the high- to medium-grade metamorphic basement as simply “granite-gneiss terrain” based on lithology and divided it into two sub-terrains (Burji–Moyale, Adola–Genale) and four complexes (Burji–Finchaa, Moyale–Sololo, Adola and Genale–Dolo) (Fig. 5). Important structure that separates Burji–Moyale and Adola–Genale sub-terrains is the NW–SE trending Geleba–

Chelanko Shear–Fault Zone which also represents main spot of granitic magmatic activity (Yibas et al., 2002).

3.2 Low-grade metamorphic belts

The four low-grade belts in the Southern Ethiopian Shield built by metavolcano-sedimentary sequences are (from west to east) the Megado Belt, the Kenticha Belt and the Bulbul Domain. Next, southward from the NW–SE trending Geleba–Chelanko Shear Zone is located the Moyale-El Kur Belt (Fig. 5) (Yibas et al., 2002).

The Megado Belt is located between the Sodda and Adola domains. It contains mostly metabasic and metasedimentary rocks like amphibolites, pyroclastic metasediments, metagabbros, graphitic schists, amphibole-chlorite schists, phylites and quartzites (Worku and Schandelmeier, 1996; Yibas et al., 2002). Less common are other meta-ultramafic to mafic rocks like serpentinites and post tectonic granitoids (Worku and Schandelmeier, 1996; Yibas et al., 2002).

The Kenticha Belt located in between Adola and Zembaba domains is mainly characterized by abundance of various ultramafic rocks like talc-tremolite schists, serpentinites, anthophyllite schists that are all dominant over other mostly mafic rocks like biotite schist or gneiss, amphibolite, graphitic schist and late to post tectonic granitic intrusions (Worku and Schandelmeier, 1996; Yibas et al., 2002).

The Bulbul Belt represents the easternmost exposed low-grade area in the Southern Ethiopian Shield. It is described in Yibas et al. (2002) as mostly mafic terrain with minor ultramafic occurrences. Western part of this terrain contains quartzofeldspathic gneisses and dioritic mylonites as tectonically inserted intercalations, whereas the eastern part is overlain by Mesozoic sediments. Dominant lithological types are amphibole-chlorite schists, amphibolites and metagabbros (Yibas et al., 2002).

As for the last one, Yibas et al. (2002) designated the Moyale-El Kur Belt as the southernmost low-grade terrain in the Southern Ethiopian Shield that is split in half by quartzofeldspathic gneisses and schists of N–S trending Roukka Shear Zone and consists therefore of Moyale sub-belt and Jimma-El Kur sub-belt. Both these subbelts contain metasedimentary rocks (like quartz-feldspar schists, conglomeratic gneiss, graphitic schists, amphibolites and quartzites) and abundant metabasic and meta-ultramafic sequences as for example amphibole-chlorite schists, amphibolites, metagabbros, serpentinites, talc-tremolite schists and talc-magnetite-serpentinite rocks (Yibas et al., 2002).

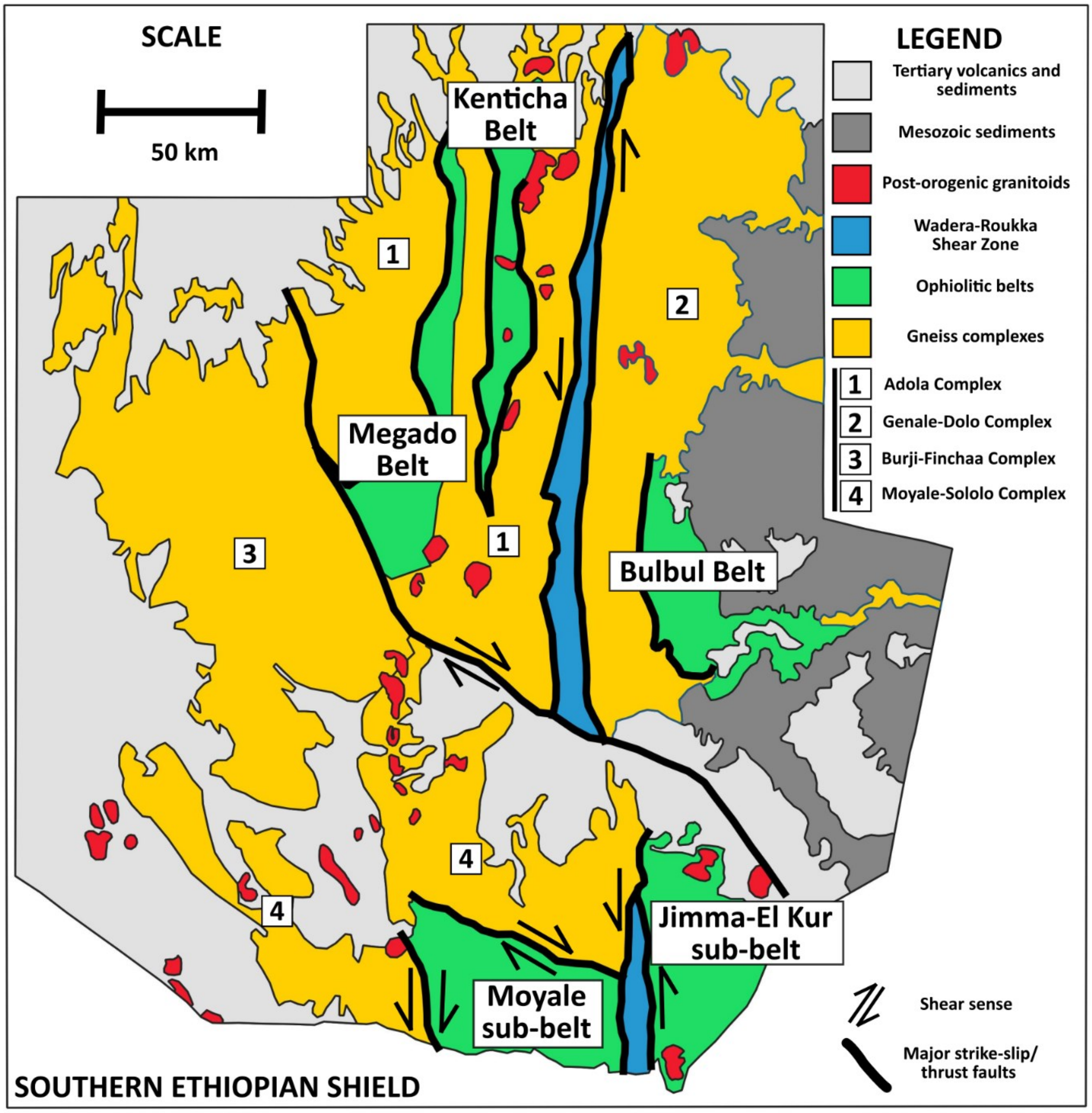

Fig. 5 Simplified geologcial map of the Southern Ethiopian Shield (modified after Yibas et al., 2002)

3.3 Magmatism in the Southern Ethiopian Shield

The zircon evaporation ages were used to determine major periods of magmatic activity within the Southern Ethiopian Shield (e.g. Teklay et al., 1998; Yibas et al., 2002; Stern et al., 2012; Verner et al., 2021). According to Teklay et al. (1998) three major periods of significant magmatic activity occurred in the Southern Ethiopian Shield at ~850, ~750 to 700 and ~650 to 550 Ma. However, Yibas et al. (2002) concluded that there were five distinct tectonothermal events and seven periods of magmatic activity from late Mesoproterozoic (ca. 1160 to 1030 Ma) to late Neoproterozoic (ca. 550 to 500). To take into the account the previous studies, by Stern et al. (2012), using new data to solve the problem with different ages of magmatic activity, four major periods of periods of magmatism were established: (a) Late–Tonian–Early Cryogenian (ca. 890 to 840 Ma), (b) Cryogenian (ca. 790 to 700 Ma), (c) Moyale event (~660 Ma) and (d) Ediacaro–Cambrian (ca 630 to 500 Ma). Prevailing zircon xenocrysts described in this study reveal ages in span ca. 900 to 700 Ma, confirming that the Neoproterozoic rocks are dominant in the Southern Ethiopian Shield. On the contrary, the study by Stern et al. (2012) discovered also granitic rocks which might be relicts of crust as old as 2.5 Ga, consequently making this the first time that presence of Archaean crust is confirmed within the Southern Ethiopian Shield. For visualization of all known magmatic ages from Ethiopia and the Southern Ethiopian Shield, see Fig. 6 and Fig. 7.

Even newer study by Verner et al. (2021) focused on describing the evolution of rocks in the high-grade Hammar Domain in terms of U-Pb zircon dating well corresponds to the information published by Stern et al. (2012). In this context, two main geodynamic / magmatic events within the East African Orogeny were defined (Verner et al., 2021). Firstly, there was the “Late Tonian to Late Cryogenian episode” (ca. 770 to 650 Ma) that included volcanic (magmatic) arc construction followed by crustal accretion accompanied by intense migmatization and HT-MP metamorphism at depths of ~25–35 km. Second “Late Cryogenian to Early Ediacaran” episode (ca. 650 to 620 Ma) represented the main collisional period associated with emplacement of numerous syn-tectonic granitoids. This collisional stage was followed by a period of post-tectonic magmatism, with the youngest manifestations in the Lower Ordovician period (Asrat and Barbey, 2003).

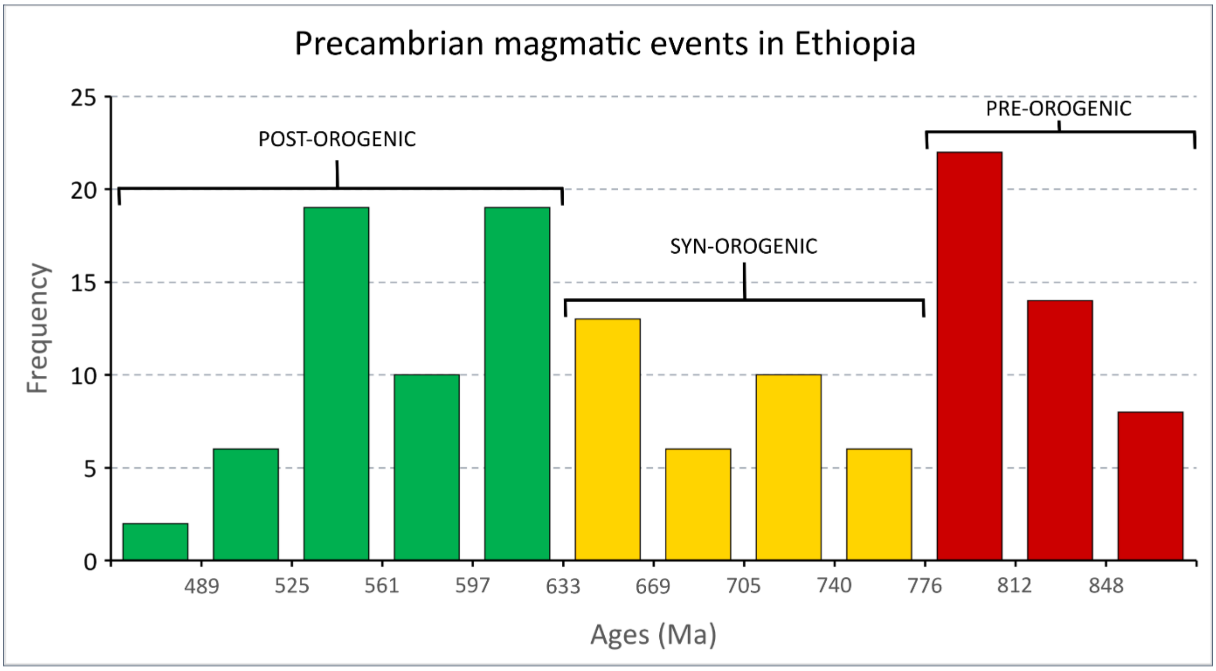

Fig. 6 Neoproterozoic to Early Paleozoic magmatic ages in Ethiopia's Precambrian shields compiled from existing literature (see list of references)

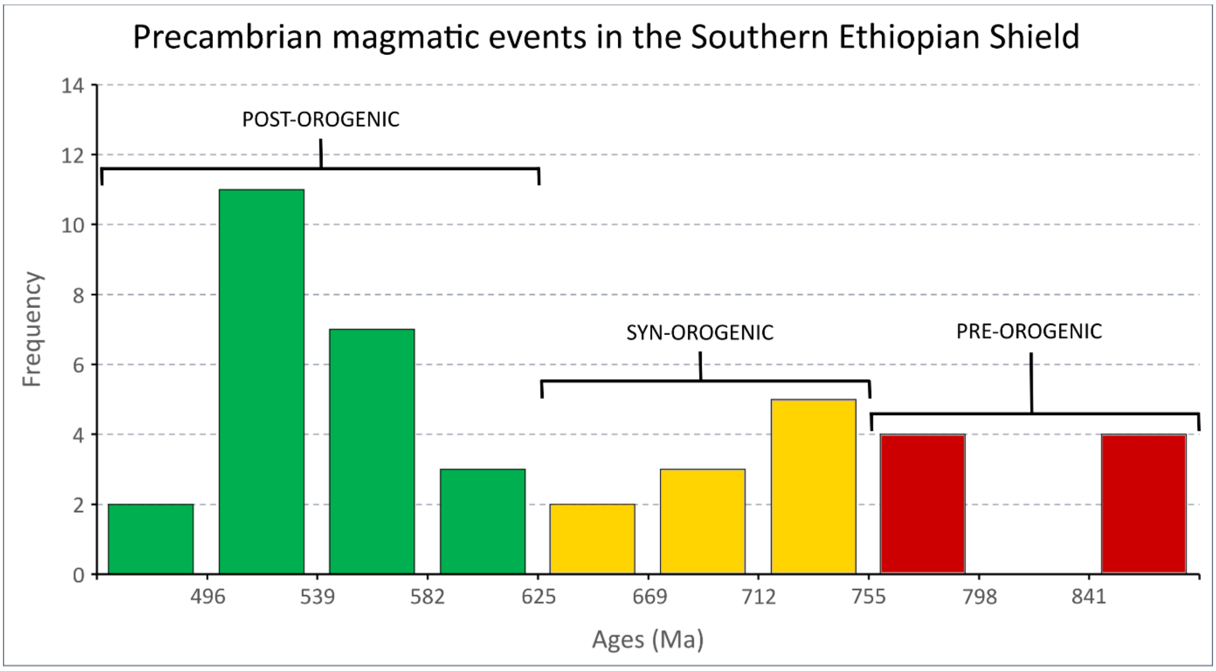

Fig. 7 Neoproterozoic to Early Paleozoic magmatic ages in the Southern Ethiopian Shield compiled from existing literature (see list of references)

3.4 Tectonic pattern and shear zones in Precambrian shields

Based on currently available data, four main deformation phases were identified in the Southern Ethiopian Shield, labelled as D_1 to D_4 (Alene and Barker, 1993; Ayalew and Johnson, 2002; Alemu and Abebe, 2007). The most prominent “folding and thrusting phase” imparted a generally N–S striking regional fabric pattern (phase D_2). Repetitive N–S oriented major antiforms and synforms, thrust and shear zones and related structures were generated as a consequence of the E–W compressional regime during the East African Orogeny (Yihunie and Hailu, 2007). In the southern part of the Southern Ethiopian Shield a gently dipping gneissic fabric of N–S to NE–SW strike (phase D_1) is confined to the high-grade migmatitic gneisses. The migmatitic gneisses were later affected by SE–NW and E–W shortening (phase D_2), which also affected the metavolcano-sedimentary formations and the mafic / ultramafic intrusions (Hussien, 1999). In the western part of the Southern Ethiopian Shield an early gently dipping fabric (phase D_1) was overprinted by multiple folding along N–S trending axes forming the prominent fabric with steeply E or W dipping foliation carrying N–S trending mineral lineations (Genzebu et al., 1994), mostly as the result of deformation phase D_2. These are subsequently overprinted by open, symmetrical, mesoscopic, small amplitude, folding along an E–W trending sub-horizontal axis (phase D_3). The brittle and brittle-ductile deformation affecting all the earlier fabric (phase D_4) have right-lateral kinematics and steep, N–S striking plane such as the Amaro Horst Shear Zone (Genzebu et al., 1994).

Shear zones are abundantly present all across Ethiopia and its Precambrian terrains (Fig. 8). A shear zone is a structure of minimal width that underwent intense brittle to ductile deformation (Ramsay and Huber, 1997). There are several types of shear zones present in Ethiopia where each type corresponds to specific deformation event during geodynamic evolution of the area: (a) “Orogen-parallel” N-trending shear zones mostly associated with phase D_2 representing transcurrent syn-tectonic movement and lateral strike-slip deformation on reactivated shear belts of distinct tectonic units. For example, the Birbir Shear Zone as localized D_2 phase resulted in isotopic resetting initiated by fluid influx (Ayalew and Johnson, 2002). (b) “Oblique” NW–SE or NE–SW trending brittle-ductile strike-slip shear zones associated with D_3

phase reveal a reactivation during D_4. One of the examples is the Adola–Moyale Shear Zone in southern Ethiopia (Worku and Schandelmeier, 1996; Alemu and Abebe, 2007).

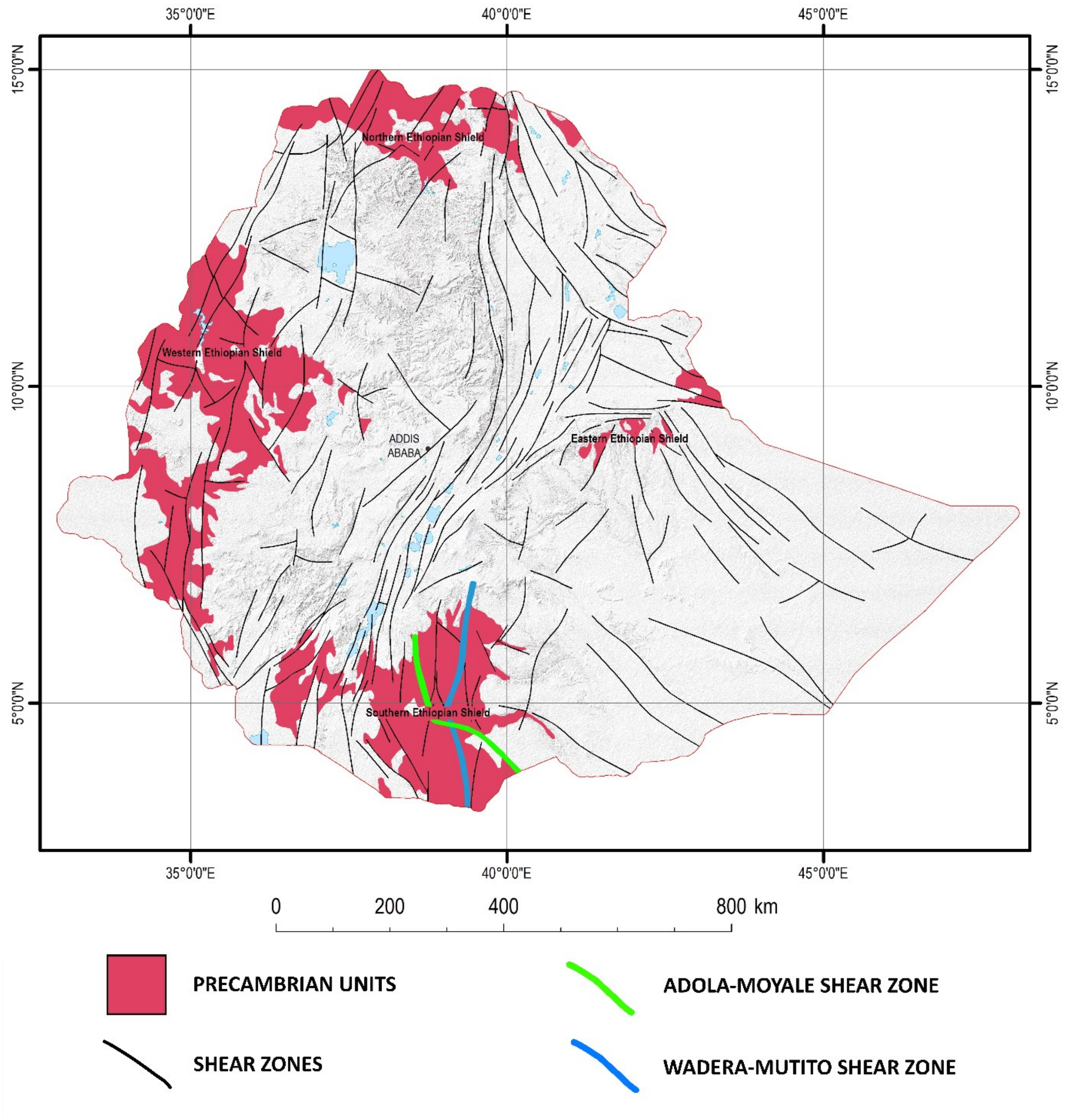

Fig. 8 Regional faults and shear zones in Ethiopia with highlighted significant shear structures in the Southern Ethiopian Shield (modified after Verner et al., 2024)

One of the most significant structures within the Southern Ethiopian Shield is the Wadera–Mutito Shear Zone which is located in the Eastern part of the Adola Belt (Fig. 8) and stretches from south-central Ethiopia southwards into Kenya where it continues into sequences of the Mozambique Belt (Worku and Schandelmeier, 1996).

The formation of the Wadera–Mutito Shear Zone occurred during crucial strike-slip deformation in the era of continental convergence in the East African Orogen alongside lateral escape tectonics. Therefore, the Wadera–Mutito Shear Zone is referred to as the “orogen-parallel” shear zone. It is implied that the Wadera–Mutito Shear Zone was repeatedly reactivated because of presence of two sets of subparallel superimposed stretching lineations. It is also mentioned that unchanging S-C fabric pattern in the mylonitic foliation represents older sinistral shear, whereas outcrop and map-scale asymmetric folds indicate younger dextral shear (Worku and Schandelmeier, 1996).

3.5 Post-collisional intrusions of Ethiopia

Magmatic intrusions of various ages and lithological characteristics are integral part of the Southern Ethiopian Shield and other terrains with exposed Precambrian rocks in Ethiopia (e.g. Tadesse et al., 2000; Yibas et al., 2002). Among these intrusions post-collisional granitoids are of noticeable significance since various mineral and metallic resources are closely associated with these intrusives accompanying the surrounding metamorphic terrain (Tadesse et al., 2003).

3.5.1 Post-collisional intrusions in the Southern Ethiopian Shield

Post-collisional granitoids in the Southern Ethiopian Shield refer mostly to granites and occasionally diorites that were emplaced during era of orogenic collapse and crustal transtension in the East African Orogen typically at about ca. 600 to 500 Ma (e.g. Yibas et al., 2002). Examples of such granites are numerous. The Berguda charnockitic granite and Metoarbasebat granite both located within Burji-Moyale sub-terrane were dated to ca. 540 to 520 Ma. Another example is from Adola-Genale sub-terrane where Robele granite and Lega Dima granite are found, both dated to ca. 550 Ma (Yibas et al., 2002). In the high-grade Hammar Domain, Verner et al. (2021) identified syn- to post-orogenic leucogranite dike swarm dated to ca. 630 Ma. However, the youngest post-tectonic Konso Pluton consisting of leucogranites and biotite to biotite-hornblende granites was dated by Asrat and Barbey (2003) to ca. 449 Ma.

The recent study by Zemene et al. (2023) describes granitoids in Kolme area partly formed by post-tectonic Matera quartz monzonite. This intrusion is predominantly composed of plagioclase, K-feldspar phenocrysts, quartz and biotite. It intruded into unit of quartzofeldspathic gneiss and was produced by alkalic magmatism that reflects beginning of crustal extension caused by orogenic collapse. The occurrence of such alkalic magmatism in contrast to previous syn- to late-tectonic high-K calc-alcaline magmatic intrusions represented by granites of Borkara area symbolizes transition from syn-collisional to post-collisional magmatism (Zemene et al., 2023).

3.5.2 Post-collisional intrusions of other Precambrian exposures (Ethiopia)

The Northern Ethiopian Shield

In addition to main sequences significant number of plutonic intrusions occurs in the area of the Northern Ethiopian Shield. Among them are frequently found calc-alkaline (Neoproterozoic ca. 682 to 545 Ma) to alkaline (Cambro-Ordovician ca. 510 to 449 Ma) post-orogenic granitoids of ages between ca. 640 and 570 Ma (Gebreyohannes, 2014; Megerssa et al., 2020; Johnson et al., 2011). Several post-orogenic granitic plutons are mentioned by Megerssa et al. (2020) for example Hitsas, Sibta, Gurungu and Kisad granites all located within Adi Nebrid metavolcanic block; Shire Granite located on the boundary between Adi Nebrid block and Chila metasedimentary block; Mereb Granite found in the middle of Chila block and granites of Mai'Kenetal block that include Mai Kenetal Granite, Negash Pluton, Hauzien Granite and Chewo Pluton. Megerssa et al. (2020) studied thoroughly the Chewo Pluton and described it as medium- to coarse-grained quartz monzonite and quartz monzodiorite with xenoliths and mafic microgranular enclaves. Most abundant mineral associations are plagioclase, quartz, amphibole and biotite with local occurrences of K-feldspar and clinopyroxene. It was geochemically classified as high-K calc-alkaline and metaluminous unit with enrichment in LREE and LILE and is therefore part of the Neoproterozoic group of post-orogenic granitoids. The Chewo Pluton was emplaced diapirically at around 618 Ma which was also supported by local extension.

The Eastern Ethiopian Shield

Only a very limited amount of data has been as of now collected in the area of Dire Dawa within the Eastern Ethiopian Shield. The most recent study by Yeshanew et al. (2017) focused on U-Pb dating of zircon ages of rocks in this area. The samples were taken mostly from quartzofeldspathic gneisses and migmatites as well as bodies of unofliated pinkish granites. The study used high spatial resolution secondary ion mass spectrometry (SIMS) to determine crystallization ages of abundant granitic intrusions. The results revealed ages of ca. 790 Ma and ca. 600 to 560 Ma. The study also mentions the fact that some granitoids with crystallization ages around 560 Ma were slightly deformed indicating orogenic activity in the area up until ca. 560 Ma.

The Western Ethiopian Shield

According to Alemu (2021) about 40 % of the Western Ethiopian Shield is accounted for by intrusives. Among these, post-tectonic intrusive rocks are scattered around different parts of the Western Ethiopian Shield and are represented by circular to elliptical bodies. Various lithologies are present as intrusives in the area, according to Alemu (2021) they are mostly granites, syenites, quartz diorite-monzonites and gabbros. Pink to grayish leucocratic granitic intrusions are characterized by homogenous massive structure with most abundant mineral associations being perthitic K-feldspar, quartz, albite and to smaller extent biotite. Intrusive gabbros are concentrated in the central part of the Western Ethiopian Shield and are represented by circular to sub-circular shapes of bodies and consist specifically of olivine gabbronorite, gabbro and olivine diabase. Overall ages of intrusive rocks in the Western Ethiopian Shield range from ca. 580 to 540 Ma (Alemu, 2021).

4. Mineral deposits of Ethiopia

Exploitation of various mineral resources including metallic and industrial minerals in Ethiopia has a long tradition and can be traced back to ancient times (Assefa, 1985; Marcus, 2002). However, in the recent times overall production and export of mineral resources has been rather insignificant both, domestically as well as worldwide. Nevertheless, multiple studies were conducted throughout years (e.g. Assefa, 1985 and 1991; Tadesse, 2003; Binega, 2006; Ahmed, 2008; Balami, 2023; Endalew et al., 2024) indicating a notable potential for both, traditionally extracted resources (i.e. gold or platinum) and newly discovered ones like fossil fuels, building materials or industrial and metallic minerals. There are however no contemporary studies presenting overview of current situation regarding mineral resources of Ethiopia in a similar way like older studies by Jelenc (1966), Assefa (1985) or Tadesse (2003) did. This chapter relies therefore on older studies as a basis and adds newer information if they are available.

The overall surface area of Ethiopia is covered by several types of rocks that differ in lithology, age and origin (Fig. 9) (Yibas et al., 2002, Stern et al., 2012, Verner et al., 2021). At ca. 23 % of surface area is represented by metamorphic and igneous rocks of Proterozoic age bearing significant deposits of metallic resources and other minerals (i. e. gold, platinum, iron, chromite, molybdenite, wolframite, asbestos, talc, nickel, copper, cobalt, manganese, beryl and other less common minerals) (Fig. 10). The rest of Ethiopia’s territory mostly consists of platform Paleozoic to Quaternary sediments and Cenozoic volcanics. Here, mainly industrial minerals and building materials (i.e. limestone, sand, gypsum, sulfur, clay, sandstone and salt) are present (Fig. 11) (e.g. Assefa, 1985; Tadesse, 2003). In addition, there is also notable potential for fossil fuel extraction and mining in platform sedimentary formations in Ethiopia (Fig. 12). Although there is currently no ongoing fossil fuel extraction that would have any significance by world standards, there are noteworthy reserves of coal (up to 297,000,000 tons), oil (ca. 650,000,000 to 1,000,000,000 tons) and about 4 Tcf of gas (for details see Ahmed, 2008).

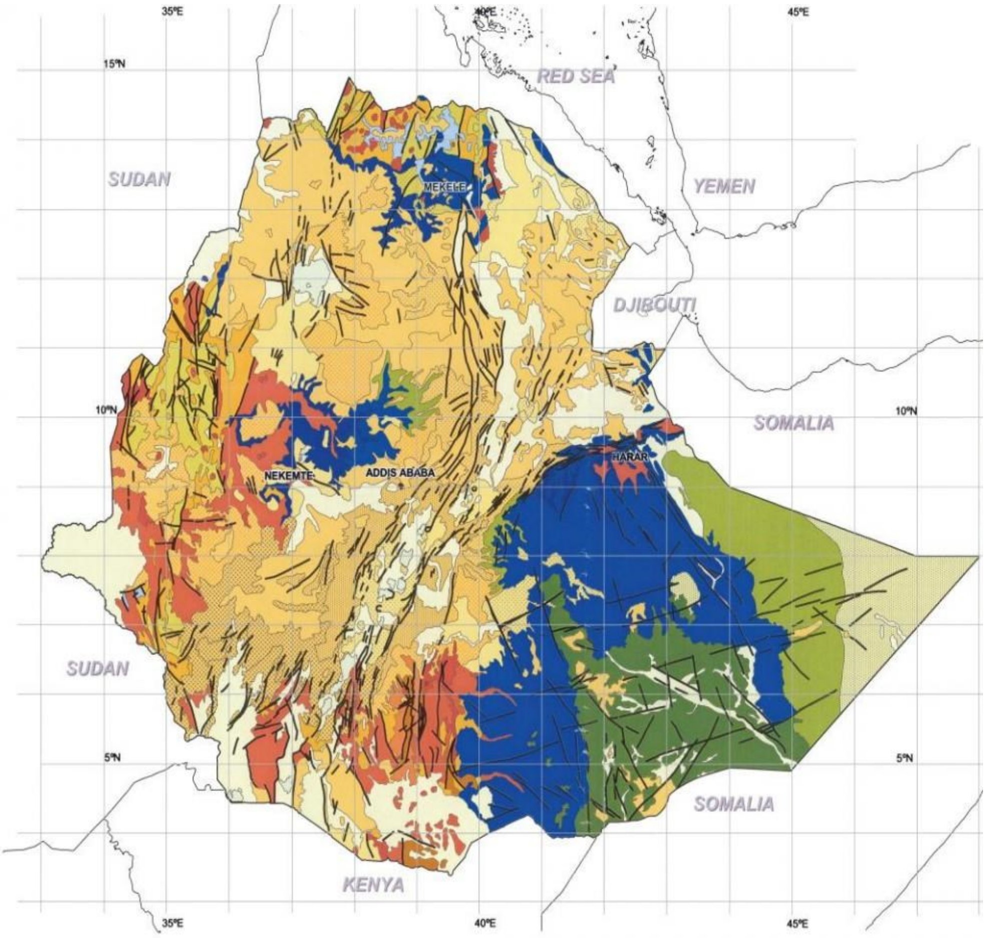

Fig. 9 Main rock types present in Ethiopia (Precambrian sequences are red) (modified after Tefera et al., 1996)

Even though the variety of available mineral resources in Ethiopia seems to be huge, only few commodities account for most of country’s mining production. Among these only gold, platinum and Tantalum are significantly common metallic resources from Precambrian shields, others being mostly rock salt and building materials found in various locations across the country (Assefa, 1985; Balami et al., 2023). According to recent study by Balami et al. (2023) only gold and tantalum have notable economic significance, since they are being extracted in large enough amounts to contribute to exports and trade of the whole country. General overview of Ethiopia’s most important mineral resources based on study by Assefa (1985) with added information from more recent studies (e.g. Tadesse, 2003; Binega, 2006; Endalew et al., 2024) is as follows:

Platinum in Ethiopia

Platinum mineralization in Ethiopia is based on currently available data located and exploited exclusively in mafic rock sequences and products of their hydrothermal alteration in the Western Ethiopian Shield (Assefa, 1985). The most prominent area where platinum is mined today and where the only active platinum mine in Ethiopia exists is Yubdo in Welega Province. The Yubdo platinum deposit consists according to Molly (1959) from pyroxenites and gabbros that surround serpentinized dunitic center of the unit and are covered by layer of so called "birbirites". Birbirites are special type of rocks named after Birbir River that basically account for altered crust of dunititc body. They include mostly quartz and limonite and are result of alteration and concentration. This process is likely shear-related and led also to remobilization and concentration of platinum (Molly, 1959). Concentrates of ore from the Yubdo area are described by Mohr (1962), Jelenc (1966) and Assefa (1985) as being comprised of 79.48 % platinum, 16.58 % iron, 1.41 % osmiridium, 0.8 % iridium, 0.75 % rhodium, 0.49 % palladium and 0.49 % gold with average platinum grade being 0.031 g/m^3. There are no contemporary estimates on the overall platinum reserves in Yubdo. However, several decades old study (Assefa, 1985) supposes that in this region could have been ca. 2000 kg of platinum, although how accurate these estimates might be today is difficult to verify since no new studies have been made on platinum deposits in Ethiopia. Overall, most of the as of yet unexploited platinum exists in a form of clay grain-sized fraction located on older riverbeds of the Birbir River (Molly, 1959; Assefa, 1985; Tadesse, 2003).

Rock salt in Ethiopia

Rock salt is a resource of great value in Ethiopia. Its mining is concentrated in Danakil Depression in the Afar Region. The Danakil Depression is NW–SE oriented graben that formed as a result of rifting in Tertiary era. The surface of this depression is covered by thick crust of rock salt. The most important deposit is located at Assale, and it also accounts for the largest rock salt deposit in the world. More than 35 000 tons of salt are produced here every year, and the total extractable reserves are estimated to be over 1 billion tons (Assefa, 1985; Binega, 2006).

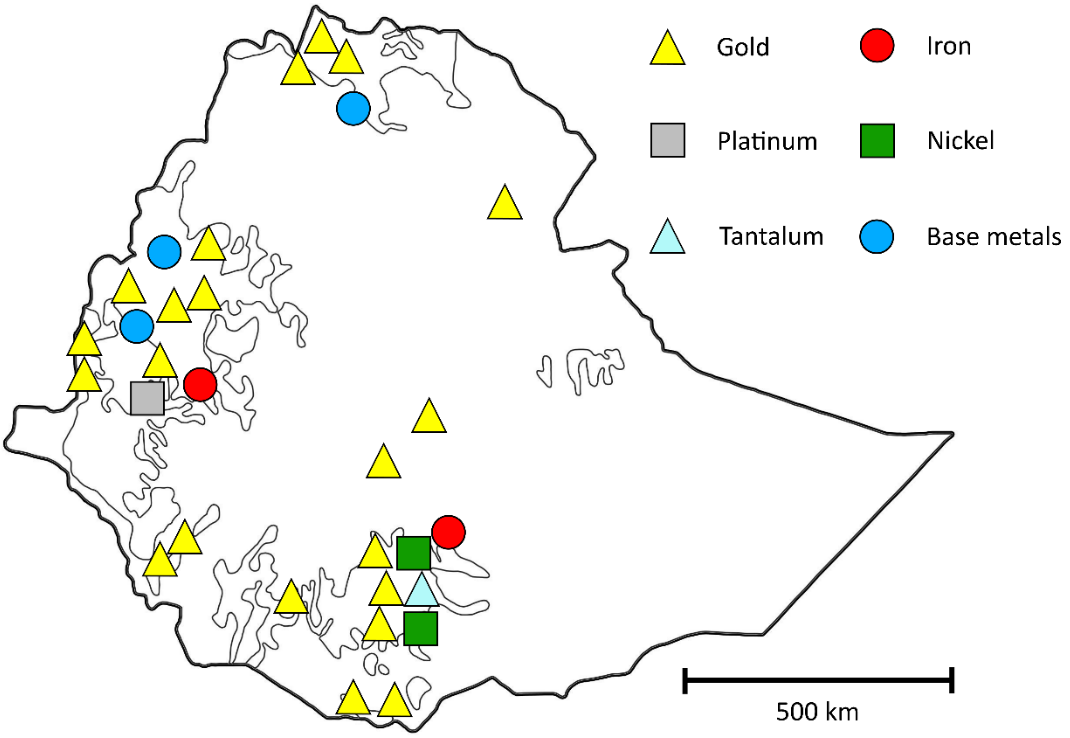

Fig. 10 Significant occurrences of metallic resources in Ethiopia displaying both present and potential deposits, based on information from existing literature (see list of references)

Industrial minerals and building materials

Large variety of minerals and other materials is extensively mined for building and industrial purposes. Among them limestone, gypsum, clay, feldspars, quartz sand, marble, iron and sulfur can be mentioned. Moreover, new deposits that contain some of these and new resources are constantly being discovered, especially deposits of iron and nickel. Limestone is found in enormous quantities all around Ethiopia (for example Welega and Hararghe areas or around Woleqa River) and is mainly associated with Mesozoic to Tertiary calcareous sequences. It is primarily consumed by cement industry. Limestone, gypsum, sandstone, clay and even potential coal deposits are common in Nile River basin where they occur as part of sedimentary sequences. Another abundant resource are feldspars. Feldspars can be found in multiple areas mainly in Negele and Hararghe. Most of the feldspars is accounted for by orthoclase and microcline that are associated with pegmatites and leucogranites. Despite many possible usages of feldspars, its extraction is generally negligible. Some resources are located mostly in Cenozoic or Quaternary terrains that reflect their origin like gypsum which is mostly mined in the Danakil Depression or sulfur which accompanies volcanoes of the Main Ethiopian Rift System. (Assefa, 1985 and 1991; Endalew et al., 2024).

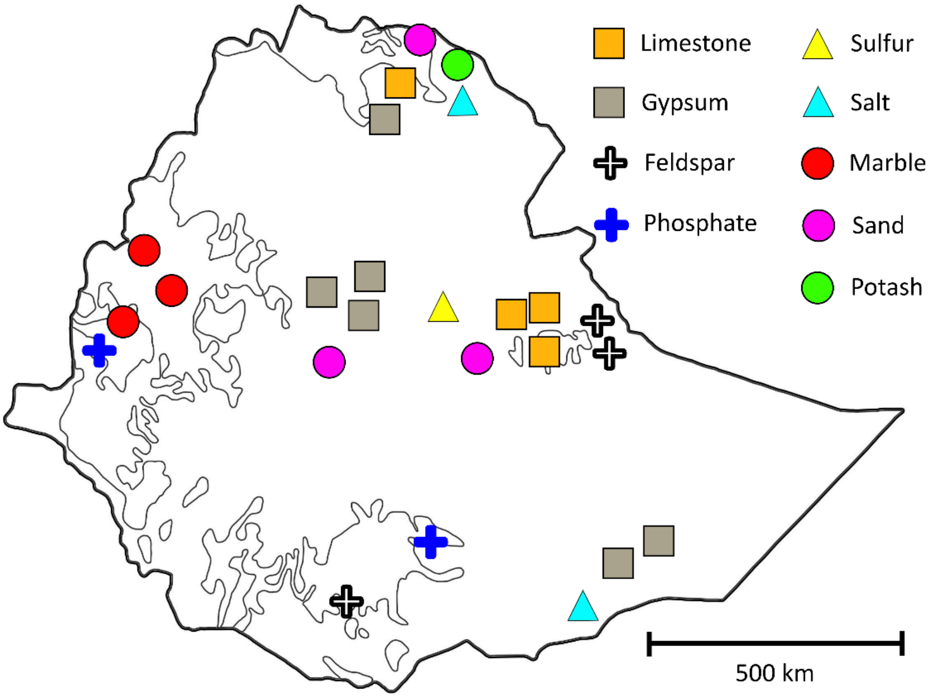

Fig. 11 Significant occurrences of industrial mineral resources in Ethiopia based on information from existing literature (see list of references)

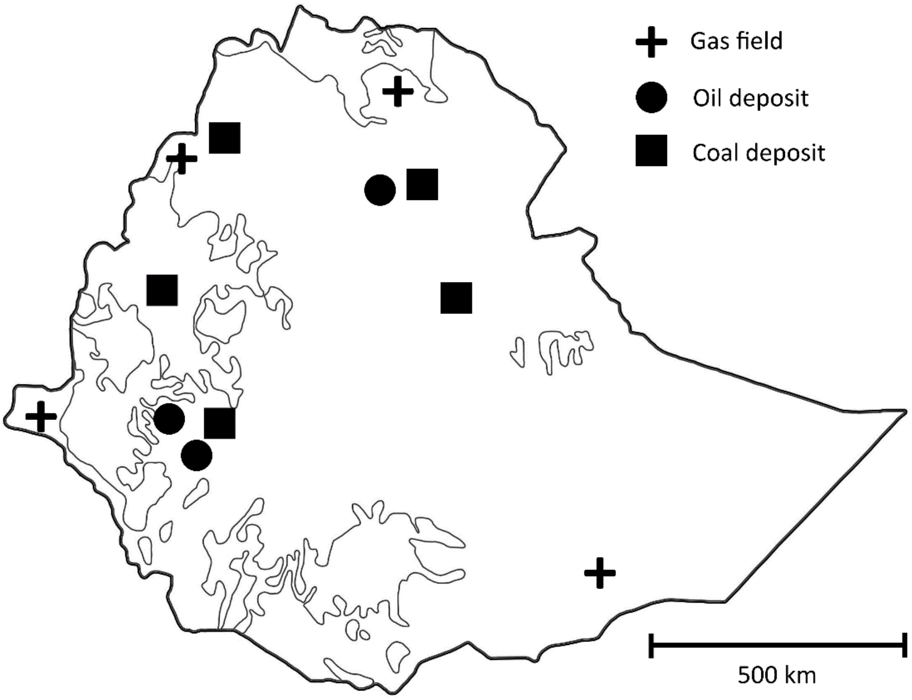

Fig. 12 Potential deposits of fossil fuels in Ethiopia (based on Ahmed, 2008)

Gold in Ethiopia

Gold accounts for Ethiopia's most important metallic resource and one the most abundant and mined resources overall. Gold has been exploited in Ethiopia for more than 2000 years (Marcus, 2002) and remains one of the most prominent mineral resources for future prospection and extraction (Balami et al., 2023). Mining of gold has been conducted by government, private companies and also local population. As mentioned by Zenebe et al. (2024) almost 1.3 % of Ethiopia's population (which is more than 1.2 million people) participates currently on gold extraction from placer deposits. According to recent estimations gold accounts on average for almost 13 % of Ethiopia's exports every year (Balami, 2023). Gold is present in Ethiopia as part of both primary and secondary deposits. Primary deposits are associated with quartz veins within larger bodies, whereas secondary gold deposits are mostly areas with scattered eroded fraction containing quartz, quartzites, amphibolites and granites, oftentimes in form of clay or sand that contains gold or quartz mineralized with gold (Assefa, 1985). Both types of gold deposits are located exclusively within Precambrian terrains and were likely formed by tectonothermal events during geodynamic evolution of the area, specifically the low- to medium-grade metamorphic belts and related intrusives. The areas containing low- to medium-grade metamorphic belts underwent notable deformation that created numerous fractures which later allowed alteration by traversing fluids to happen (Assefa, 1985; Tadesse, 1999).

Primary gold deposits were discovered in most of Ethiopia's Precambrian shields, namely in Adola area (Southern Ethiopian Shield), Tigray Region (Northern Ethiopian Shield), Wollega area (Western Ethiopian Shield) and Akobo area (southernmost tip of the Western Ethiopian Shield). In context of the entire country, three main types of gold deposits were classified (Tadesse, 2003):

a) **Orogenic mesothermal deposits** – The most abundant deposit type that characterizes almost all deposits in the Precambrian shields. Gold is found here in connection to N–S trending shear zones near low- to medium-grade metamorphic belts with mafic to ultramafic sequences (known as greenstone belts) and associated intrusions. It is hosted in sulfides related to quartz veins and other quartz occurrences.

b) **Gold-bearing volcanogenic massive sulphides** – Gold present in VMS-type deposits (also known as volcanogenic massive sulfide ore deposit) has been already discovered in several places in the Arabian-Nubian Shield namely in Sudan and Saudi Arabia. In Ethiopia little to nothing is currently known about these deposits, however gold originating from hydrothermally altered zones connected to submarine volcanism was observed in Kata and Abetselo in the Western Ethiopian Shield.

c) **Epithermal deposits** – This gold mineralization here is associated with calc-alkaline volcanic (and related geothermal) activity of the Main Ethiopian Rift System. Gold that presumably originates from Precambrian sequences was brought to surface by hydrothermal fluids through fractures at various locations for example Gedemsa, Aluto, Corbetti calderas and Tendaho graben. It is hosted here in sulfides like galena, chalcopyrite and pyrite located within quartz veinlets (Tadesse, 2001).

4.1 Mineral Deposits in the Southern Ethiopian Shield

The Southern Ethiopian Shield as one of the exposures of Precambrian rocks in the country is characterized by presence of various mineral resources as well as industrial and building minerals and materials. However most prevalent are metallic minerals. Among them nickel, tantalum and gold deposits can be of note (Tadesse, 2003).

4.1.1 Tantalum deposits in the Southern Ethiopian Shield

Tantalum deposit in pegmatites of the Kenticha Belt was first discovered in 1980 relatively later in comparison to other mineral deposits in the area. Since 1989 there is an active tantalum mine that produces Ta_2O_5 at rate of approximately 1.5 tons annually. Before the mining started preliminary estimations suggested reserves of up to 25,000 tons ore grading 0.02 to 0.03 % Ta_2O_5, however this included only tantalum in weathered pegmatites and alluvial ore. Tantalum mineralization is closely linked to post-orogenic granitic and pegmatitic intrusions emplaced alongside N–S trending shear and fault zones. Abundant mineral associations of these intrusives include Columbo-Tantalite group minerals, tourmaline, beryl, lepidolite and phosphate minerals like apatite. Evidence of magmatic alteration can be recognized in several granitic and pegmatitic intrusions. Noteworthy is for example sericitization, greisenization, albitization or presence of amazonite. Tantalum deposits are also rich in associated elements like niobium, lithium, beryllium and REE, which creates significant potential for future exploitation (Tadesse, 2003).

4.1.2 Nickel deposits in the Southern Ethiopian Shield

According to Tadesse (2003), around 20 nickel deposits are present within the area of the Southern Ethiopian Shield. Nickel is found in deposits associated with the Adola and Kenticha Belts. Notable deposits are for example Ula Ulo, Tulla or Dubicha and Fulanto in Sidamo. Prospects from 1989 reveal overall reserves of as much as 17,000,000 tons of ore grading 1.3 % Ni. Nickel mineralization in the areas of the Southern Ethiopian Shield is held by pimelite which is secondary mineral of garnierite group present here in sequences of laterites. These laterites overlay core consisting of serpentinized ultrabasic rocks that is surrounded by talc and various types of schists. Nickel mineralization is commonly accompanied by chromium and cobalt.

4.1.3 Gold deposits in the Southern Ethiopian Shield

Gold deposits located in the Southern Ethiopian Shield are probably the most prominent gold occurrences in Ethiopia and also the only ones that have been actively producing gold for a long time. Gold mineralization is associated with N–S trending Megado and Kenticha metamorphic belts of the Adola area, where Lega Dembi and Sakaro, which account for the most significant gold deposits, are both located. A large portion of areas with gold mineralization can be found in the low- to medium-grade metamorphic belts or on direct boundary between metamorphic belts and surrounding gneissic terrain. This mineralization is thus associated with N–S oriented shear zones that separates these two terrains. As for the type of gold deposits present here, in area of the Southern Ethiopian Shield primary as well as placer gold deposits were identified (Tadesse, 1999).

Primary gold deposits

Primary gold mineralization is closely related to Megado and Kenticha belts that can also be referred to as greenstone belts because of presence of deformed metamorphosed mafic and ultramafic sequences. Based on current knowledge it is implied that these structures significantly contributed to emplacement of rocks hosting gold mineralization. During brittle deformation, numerous fractures were created in the area that allowed hydrothermal fluids to enter rocks and led to transport and accumulation of gold. It is possible that this gold originates from sources in great depths and was brought to the surface by basic to ultrabasic magmatism. During subsequent deformation and low-grade metamorphism gold was probably remobilized by fluids and concentrated in currently known locations (Tadesse, 1999). Source and characteristics of these fluids were subject of several studies. Whether the fluids were released during regional metamorphic event or during intrusion of granitic bodies is unclear. Study by Tsige (2006) focused on analyzing fluid-originating inclusions in quartz veins of the Kenticha-Katawicha area in the Adola Belt to determine the origin of fluids and gold mineralization. The study mentioned that fluids described to be H_2O- and CO_2-rich with low salinity originated from mafic to ultramafic sequences of greenstone belts and were released during low-grade regional metamorphic event. Results of analysis revealed that gold was most likely deposited during post-peak metamorphism at conditions ca. 350 °C and 2 kbar. P-T conditions and composition of fluids suggests probable origin of fluids to be metamorphism rather than magmatic intrusion. Regarding the gold origin in Lega Dembi, studies by Tadesse (2004) and Tsige (2006) both agree that gold mineralization is associated with retrograde metamorphism possibly related to D_3 shearing event.

Primary gold mineralization in the Adola area of the Southern Ethiopian Shield occurs in several different types. Tadesse (1999) introduced classification including four main types:

a) **Auriferous quartz veins in schistose rocks of the Chakata Formation** – Lega Dembi, Sakaro, Korkoro and Bedakassa deposits represent this type of mineralization. It is located mainly within volcano-sedimentary sequences of the Chakata Formation (amphibolites, quartz-mica and chlorite-actinolite schists) or its contact with surrounding gneisses and is characterized by presence of several hundred meters long veins (ca. 400 to more than 2000 m). Auriferous veins consist mostly of quartz and carbonates and contain golden grains held in sulfides like galena, chalcopyrite, arsenopyrite, pyrrhotite and pyrite. Sulfides however comprise only about 2 % of the overall composition of the veins. Significant alteration is also present here with types varying greatly, but some examples can be sericitization, chloritization, serpentinization or sulphidization. General gold content of this type of mineralization is around 10 g/t.

b) **Gold mineralization in quartzites of the Chakata Formation** – Quartzitic rock sequences intercalating rock assemblages of the Chakata Formation are found in area of the Megado-Bore ridge and Serdo. These quartzites are comprised of quartz (up to 90 %) and minor occurrences of graphite, biotite and iron oxides or hydroxides. Gold is here mostly dispersed throughout the unit with average content being between 3 to 4 g/t. There are several quartz veins located in this quartzitic body, however they do not contain any gold.

c) **Gold mineralization in conglomerates and arkoses of the Kajimiti Beds** – This type of mineralization was observed at locality in Burikaro in the Kajimiti Beds. Gold is hosted here in several centimeters wide lenticular quartz veinlets found within conglomerates and meta-arkoses. Gold content varies from ca. 1 up to 8 g/t.

d) **Auriferous quartz veins within gneissic terrains** – As of now the only location where this type of mineralization was identified is in Digati. Gold mineralization is associated biotite-hornblend gneiss located on the boundary between low- to medium-grade metamorphic belts and surrounding high-grade gneissic terrain. Gold occurs here as a part of quartz veins and sericite-carbonate alteration zones, mostly hosted within sulfides like pyrite, chalcopyrite and galena. Several estimations on the average gold content have been made, most showing content between 1.5 to 30 g/t. Some studies however suggested content as high as 100 g/t.

Placer gold deposits

Placer gold in the Adola area was the source of most gold production throughout the history. Before modern extraction methods were discovered and utilized in larger scales (like in the Lega Dembi mine) local population produced gold mostly from various elluvial to alluvial placers. Gold placers are located primarily within the Megado Belt. Gold is found mostly in older river terraces or beds, valleys, dried streams and hillsides, where it is incorporated into gravel-sand-silt-clay sedimentary sequences. Placer gold originates from erosion of primary gold deposits and subsequent sedimentation of gold particles. Golden particles have rounded to unrounded shape and reach sizes of several millimeters (ca. 0.5 to 8 mm). Some other minerals accompanying gold in the sediments are titanium rich minerals (ilmenite, rutile or magnetite), pyrite, garnet, tourmaline and apatite. The most important placer gold deposit in the area was identified in in the Bore valley. Average gold content of placer deposits is around 0.1 g/t (Tadesse, 1999).

5. Discussion

Geodynamic evolution of the Southern Ethiopian Shield and associated areas occurred as series of complex events starting with break-up of the Supercontinent Rodinia, followed by assembly of the Arabian-Nubian Shield as well as the Mozambique Belt and ending with post-orogenic processes following formation of the East African Orogen (Kröner and Stern, 2005).

Pre-Pan-African episode

The Supercontinent Rodinia was a large Mesoproterozoic mass of continental crust that was assembled between ca. 1300 to 900 Ma (Cawood, 2005; Li et al., 2008). Shortly after its amalgamation several causes including thermal isolation induced emergence of mantle superplume under continental crust of Rodinia and led to its break-up at ca. 860 to 840 Ma. This resulted in extensive rifting period between ca. 840 to 740 Ma which is characterized by opening of multiple new oceanic basins (Li et al., 2008). Among them, the Mozambique Ocean separated continental assemblages of East and West Gondwana and served as a place of intense juvenile crust formation as well as pelagic sedimentation (Cawood, 2005; Fritz et al., 2013). This rifting period accompanied by calc-alkaline magmatism and formation of back-arc basins is widely accepted (e.g. Kröner and Stern, 2005; Fritz et al., 2013; Johnson, 2021) as initial origin of most sequences within the Arabian-Nubian Shield.

On the other hand, rock assemblages of the Mozambique Belt, their exact origin and relationship to the Arabian-Nubian Shield is still unclear in certain aspects. Samples from various parts of MB reveal protolith ages from Archean to Paleoproterozoic era (ca. 3300 to 2400 Ma) (Fritz et al., 2013). These sequences were then reworked during several amphibolite- to granulite-facies metamorphic events associated with pre-Pan-African orogenic processes (Kröner and Stern, 2005; Fritz et al., 2013).

Pan-African processes

Following the widespread rifting period the tectonic regime changed and extension was instead replaced by convergent processes as part of the Pan-African orogenic events. The term “Pan-African” itself was firstly designated to refer to complex tectonothermal event at ca. 500 Ma, but in contemporary literature its usage incorporates all significant tectonothermal and orogenic events that occurred during Neoproterozoic era (Stern et al., 2012; Fritz et al., 2013). Important events for formation of the Southern Ethiopian Shield (Tokar-Barka Unit) are the pre-orogenic Bulbul-Awata event (ca. 875 Ma) marking the initiation of subduction related processes accompanied by amphibolite- to granulite-facies metamorphism; Megado event (ca. 800 to 750 Ma) associated with obduction of ophiolites, crustal thickening and intense metamorphism; and lastly Moyale event (ca. 700 to 550) related to oceanic basin closure and emplacement of late- to post-tectonic granitoids. (Yibas et al., 2002; Stern et al., 2012; Fritz et al., 2013).

The overall process of convergence led to subsequent closure of the Mozambique Ocean and gradual accretion of juvenile crustal terranes that formed the Arabian-Nubian Shield (Fritz et al., 2013; Johnson, 2021). Based on the latest knowledge the western terranes within ANS are thought to be comprised of exclusively juvenile oceanic crust, whereas the easternmost parts contain both oceanic as well as continental crust (Abd El-Wahed and Attia, 2022). This might be related to contamination by microcontinental crustal rocks from East Gondwana during convergent processes (Kröner and Stern, 2005). The collision of West and East Gondwana during Pan-African era led also to consolidation of the Mozambique Belt mostly from previously reworked rock assemblages. However, the overall assembly of the area was a multistage process that was not fully completed before several other post-Pan-African orogenic events took place (Fritz et al., 2013).

Post-orogenic evolution

Post-orogenic period starts around 620 Ma, when compression loosened and led to orogenic collapse. This caused uplift and exhumation of granulites as well as reactivation of N–S shear zones allowing emplacement of granitoids alongside them (e.g. Johnson et al., 2011; Fritz et al., 2013). It is implied that origin of granitic magmatism in the post-orogenic era is connected to melting of lower crust during crustal thickening (Yibas et al., 2002; Stern et al., 2012 and references therein). This period was also influenced by other tectonothermal events and orogenic processes. The ca. 570 to 530 Ma Kunnga Orogeny led to HP granulite-facies metamorphism followed by exhumation and emplacement of another wave of post-tectonic granitoids (e.g. Kröner and Stern, 2005; Fritz et al., 2013). The Berguda tectonothermal event (ca. 550 to 500 Ma) is accepted as the final stage of the Neoproterozoic orogenic events being marked by late granulite-facies metamorphism (evidence of this was found in the Berguda charnockitic granite) and emplacement of post-tectonic granitoids in southern Ethiopia (Yibas et al., 2002; Stern et al., 2012).

Mineral deposits

It has been known for a long time that Ethiopia is rich in occurrences of mineral resources (Jelenc, 1966; Assefa, 1985; Marcus, 2002; Tadesse, 2003), but as of now most of its mineral wealth remains unexploited (Balami et al., 2023). It is difficult to judge the overall potential of Ethiopia's mineral resources since contemporary estimates and accurate studies are scarce. The only mineral resource with economic significance as of now is gold, since its exports accounted for around 12 % of Ethiopia's GDP in the recent years (Balami et al., 2023). Noteworthy gold occurrences were found in several Precambrian sequences (Johnson et al., 2017) and some of them are even being exploited by local population (Zenebe et al., 2024), but the only active primary gold mines are Sakaro and Lega Dembi in Megado Belt, Southern Ethiopian Shield (Johnson et al., 2017; Balami et al., 2023). Primary gold mineralization in this area is held in sulfidic mineral associations within quartz veins (Tadesse, 1999 and 2003). Gold was likely brought there during processes of remobilization and concentration by H_2O- and CO_2-rich low saline fluids (Tsige, 2006). The exact event(s) corresponding to release of these fluids remains unclear. Whether it was one or multiple regional metamorphic events or direct influence of granitoid magmatism is uncertain. Nevertheless, it is implied in Tadesse (2004) and Tsige (2006) that due to chemism and P-T conditions the origin of fluids was more likely associated with regional metamorphic event (possibly related to D_3 deformation period) rather than directly with granitoid magmatism itself.

6. Conclusion

The aim of this bachelor’s thesis was to describe the currently known geological structure of the Southern Ethiopian Shield in the context of the origin and geodynamic development of East African Precambrian terrains belonging to the Arabian-Nubian Shield and the Mozambique Belt. An integral part of the work was also to create a consistent overview regarding the occurrence of mineral resources in this area. This bachelor’s thesis will be thematically followed by a diploma thesis on the topic of evaluating hydrothermal mineralization along regional shear zones in the area of the Southern Ethiopian Shield and the potential for occurrence of critical mineral resources.

The Southern Ethiopian Shield represents the southernmost exposure of Precambrian rocks in Ethiopia. It is located in the southern part of the Tokar-Barka regional unit, which itself represents the southernmost terrane within the Arabian-Nubian Shield. The southwestern edge of the Southern Ethiopian shield probably belongs to the highly metamorphosed rocks of the Mozambique belt. The overall geodynamic evolution of the Southern Ethiopian Shield Unit includes several sub-stages that resulted in the consolidation of the Gondwana Continent at ca. 620 to 550 Ma. Overall consolidation of the Gondwana Continent began ca. 900 Ma ago. The main orogenic event that significantly influenced the assembly of the Gondwana Continent in NE Africa was the "East African Orogeny (EAO)" at ca. 890 to 550 Ma (e.g. Abdelsalam and Stern, 1996; Fritz et al., 2013; Verner et al., 2021 and references therein).

In the polar regions of the southern hemisphere a successive collision (accretion) occurred involving a partial segments of juvenile volcano-sedimentary protolith of the Arabian-Nubian Shield (ANS) and extensively remobilized older crust of the Mozambique Belt (MB) with the Sahara and Congo-Tanzania Cratons, Azania and Afif terranes giving rise to an extensive orogenic belt called the East African Orogen (e.g. Abdelsalam and Stern, 1996; Fritz et al., 2013 and references therein). These processes were followed by post-orogenic magmatic activity and overall extension which took place in individual episodes from ca. 620 Ma until the Cambrian era.

The surface of Ethiopia includes many different lithological environments, which also provide the opportunity for extraction of a large number of mineral resources. Common resources such as salt, feldspar or limestone are currently mined in mainly Mesozoic to Tertiary areas, but although there is considerable economic potential, their production remains rather low. However, the metallic resources found in the Ethiopian Precambrian shields have not only been mined for some time, but also in remarkable quantities. For example, gold mining has traditionally been prevalent for many centuries. Tantalum, nickel and gold are particularly important in the Southern Ethiopian shield. The Adola Region, with the associated Kenticha and Megado metamorphic belts, is the center of Ethiopia's gold production, as well as the location of Ethiopia's largest active gold mines in Sakaro and Lega Dembi.

Gold is found here both in placers and in primary deposits. The origin of gold mineralization can be traced to low-grade hydrothermal fluids that were released into the faults and fractures after previous deformation events and caused remobilization and alteration, producing gold-bearing sulfidic minerals associated with quartz veins.

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