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Mineralization around J. Addali Area- Sennar State- Sudan

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Abstract

The present study has been carried out on the low-grade rocks of Neoproterozoic age with well developed shear zones and syn-late orogenic granitic, such as scattered exposures of metasediments (chlorite schist, graphite schist, quartzite, marble), metavolcanic (meta-basalt) and associated rocks (iron formation, quartz veins, pigmatite) which distributed in the area around J. Addali in the southwestern part of Sennar State - central Sudan. Tectonically, the study area lies at the junction point between the Arabian-Nubian Shield and Mozambique Belt. The region was studied for mineralogy, textures, alteration assemblages and geochemistry to assess their potential elements mineralization of Au, Ag, Cu, Pb, Co, Mn, Cr, Zn, Ni and Fe. The methodology adopted in this study include geological, geochemical and geostatistical mapping of above elements using grid sampling method supported by digital image processing and interpretation of remotely sensed data. A total of 177 chip samples of rock units were collected from different locations in the study area for petrographical, geochemical and geostatistical studies using polarized microscope, Atomic Absorption Spectrometry (AAS) and Statistical computer program. In addition to 156 samples of quartz veins for gold dissemination. All rock samples have been collectively statistically manipulated due to similar origin, age, and environment, excluding the quartz veins which treated separately. Fifteen metal mineralization zones has been discovered in new mineralize structures as the result of geostatistical interpretation of geochemical dataset of the study area, they are required a sequential exploration programs including detailed mapping, geophysical investigation and drilling. Mineralization of the above elements in the area can be classified as shear zone related, which is formed during the final event accomplished by crustal cooling, and deformation of the low-grade basement rocks.

Keywords: J. Addali area; Mineralization; Geochemical; Sinnar State.

Introduction

The study area is bounded by longitudes 33º 00`- 34º 04` E and latitudes 12º 15`- 13º 00` N. It covers about $^{9500\ Km2}$ (Fig. 1). It characterized by semi-arid to savanna climatic conditions, the vegetation cover consists of grasses and small bushes with scattered Acacia trees such as Acacia *mellifera* with Acacia *senegal*. The hydrographic network represented by wadis and khors which are drained from exposing hills along the center of the area to White and Blue Niles Rivers. The region is generally a flat plain covered by black cotton soil with scattered distinctive morphological features. Due to the scarcity of outcrops, geological interpretation is difficult and therefore, most of geological information obtained were collected from the few basement exposures, drilled ground water wells, pits, quarries and artesian mining wells. An attempt has been made to correlate the interpreted buried surface geology of the area with the nearest basement complex terrains to determine the inferred rocks under black cotton soil. It is difficult to sampling representative rocks and the pattern of distribution of outcrops within an area, so geostatistical approach has been used to helping in solve these problems and to create a good conception about the mineralize zones and elements relations.

Methodology

Digital image processing of satellite image Landsat 8 has been used to helping in geological, geochemical and geostatistical mapping. Three scenes of Landsat 8 OLI data defined by path/; row as 172/51; 172/52 and 173/51, with acquisition date of

September 23rd, 24th and 25th, 2014 have been used in this study. The Atomic Absorption Spectrometry (AAS) is used for analyzing elements. Polarized petrographic and ore microscopic equipment for rocks and ores studies. Computer programs, especially Statistica for geochemical datasets interpretation. The chemical analysis, slides prepared and petrographic and microscopic studies has been done in the Laboratory of Geological Research Authority of Sudan (GRAS). Computer Contour and IDW technique methods have been used to produce single element iso-concentration maps which has been reduced to one anomalous mineralization zones map. Spearman Rank Order Method to determine the interrelationship between the elements. Principal Component Analysis (PCA) method to predicting the underlying geological mineralization direction. Cluster analysis method for more information about the lithology and geological environment.

Regional geology and tectonic setting

Regionally the present of ophiolitic rocks such as the high deformed serpentinized chromitiferous, cumulate mafic-ultramafic, massive gabbros with minor plagiogranites, massive and sheeted dolerite dykes and minor highly altered basaltic pillow lava in Ingessana-Kurmuk area (El Sheikh, 1993), in the south east the study area, indicate the criteria of Arabian-Nubian Shield, while present of the high- grade kyanite and sillimanite bearing supracrustal metasediments at J. Kardos about 35Km east the study area (plate.8: a & b), dioritic, granitic gneisses that located in El Jebelein area in the west side of the study area (Abd elgalil, 2001), in addition to charnockite and enderbite in Jebel Moya area (Bishir, Dawoud, 1993), north the study area indicate the criteria of Mozambique Belt. These are the main criteria of Pan-African region that determined and mapped by Kröner, et.al, 2004 and Fritz, et al 2013 (Fig. 2). Hence, the study area is the junction point between the Arabian-Nubian Shield and Mozambique Belt. it considered as a good example of plate tectonics and associated metallogenesis. It is important link between two terrains of the late Proterozoic Pan African region which characterized by many types of mineralization, so it has been selected for this study.

Geology of the study area

The geology of the area results from poly deformational and metamorphism phases accompanied by magmatic intrusions. Based on previous studies, field observation and petrograhpic studies, the study area consists of a sequence of granulite facies rocks inconformably overlained by low green-schist facies metemorphic rocks all of them are intruded by syn-orogenic intrusive granitoids and unconformably overlain by cretaceous sand stone then covered by black cotton soil.

Granulite facies rocks

Regionally they are the oldest rock units exposed around the study area, they occur either as low lying outcrops, patches or xenoliths within the relatively younger rocks. They are distributed in the north, west and east of the study such as J.Moya, the foot of J.Nafur and J.Kardos respectively, generally their textures are granitic, migmatitic and spillitic.

Metasediments

They are the dominant rock types in the study area, they are strongly folded, faulted, and invaded by quartz veins and iron formation. They are subdivided into schist group, quartzite, brecciaed quartzite and marble.

Schist group

Graphite schist

They exposed at J. Bozi, J. Tozi, J. Algilabe, J. Abulewaita, north east J.Abugorod, appear in artesian mining drilling around J. Aburawag and occurs associated with chlorite schist and ferrougnization of faulting Iron oxides at J. Ahmar Ain area (plate.1 A & B). In hand specimen the rock is black fine grains and weakly hardness, they are stained by iron oxides and green mineral probably phosphate. They cut by numbers of quartz veins ranging from 1cm up to 1m in thickness. Under the microscope graphite schist composed of sutured margin quartz crystals, anheadral grains graphite and foliated iron oxides, these minerals indicate to their sedimentary origin (plate.4 A).

Chlorite schist

It is the wide spread rock in the study area, they form low and medium elevation ridge such as J. Abuerafe, J.Allidir and J.

Assalamat, they are invaded by quartz, epidote veins and stained pyrite grains in somewhere (plate.2 A). In hand specimen chlorite schist are green, grey, grey to white, brownish, yellowish color, fine-medium grains with foliated texture. Beside chloritization, the rocks was effected by many alteration processes such as sericitization, biotitization, muscovitization and epidotization, that is the product of sericite schist that exposed on the plain of J. Almigawir and J. Abugurod; Biotite chlorite schist in the north western part of Attaro hills and plain in the boundary of J. Addali; chlorite muscovite schist such as J. Bona and J. Allidir; and epidotized quartzo chlorite schist east Addali. Under the microscope the rocks are foliated deformed, mainly composed of quartz crystals, chlorite, sericite, biotite, muscovite, epidote, iron oxides and opaque minerals (plate.4 B, C &D).

Quartzite and brecciaed quartzite

They are exposed at J. Aburawag, J. Almigawir and occurs as a brecciated bodies injected by iron materials at J. Wagwag, west J. Addali, east Attaro and south J. Bosi. In hand specimen the rock is white brownish-gray color, fine-medium grains, well foliated, they are dominantly cut by quartz veins. The brecciated quartzite bodies are a different size fragments of quartzite and quartz consolidated by iron materials or/and silica in a turbidite texture form. Under the microscope quartzite is deformed rock, mainly composed of elongation and suture margins quartz crystals and small veins of iron oxides (Plate.5 A).

Marble

This type of rocks exposed in the east of J. Addali as scattered boulders appears as discontinuous band (Plate.3 A). They bounded in the west side by lens of meta-basalt. Marble occurs as intercalated with graphite schist buried about 2m at J. Aburawag, also occurs in north east Ahmar Ain area, obscured by superficial deposits appear on the surface as fragments, trending from the north to south. In hand specimen the rocks are grey- white color, fine - medium grains and relatively foliated. Under the microscope the rock are slightly foliated and have rhombic cleavage, they mainly composed of calcite and iron oxide (Plate.5 B).

Meta- Basalt

This type of rocks represents the northern part of J. Addali, they are medium relief, trended from SW to NE. In hand specimen the rocks is black to grey color, fine grains. The schistosity, clearly in the west part of it, they are bounded by altered granite in the north side, chlorite schist in the west and marble in the east. Under the microscope the rock are foliated, they mainly composed of plagioclase, quartz, amphibole, biotite, and iron oxide.

Organic Rocks (Neoproterozoic)

The lithological units described above were intruded by magmatic intrusions, deformed by deformational phases. The magmatic event is syn-kinematic the deformational phase. It is believed to be a product of larger plutons of syn to late-orogenic igneous activities in the late Proterozoic time that have been emplaced in both the high and low-grade sequences as evident from their xenoliths contents. Based on field observation of deformation effect there are two types of syn to late-orogenic rocks in the study area: Shear granite and highly deformed sheared granite. Shear granite occurs as altered and deformed isolated outcrops elongated from north to south cut by pegmatite and quartz veins such as J. Abel and J. Daia in the east part of the study area. They are also exposed in the north sides of the study area such as J. Addali and their patches and J. Muzmum in the south part. The highly deformed sheared one that have affected heavily by the recrystallization process due to shearing such as J. Abugorod in the south west the area. These rocks graduated from foliated to massive types. In hand specimen the rock are medium to coarse-grains, gray to pinkish color, composed mainly of quartz, alkali feldspar and plagioclase. Under the microscope the rocks are composed of quartz, microcline, plagioclase, biotite, sericite, chlorite, epidote, iron oxides, opaque minerals, carbonate, zircon, rutile and apatite. They are aphaneritic altered deformed rocks that indicated by presence of sericite, epidote and iron oxides as well as presence of quartz wavy extinction, ribbons and suture margins structures (Plate.6 A, B, C & D).

Quartz veins, pegmatitic bodies and brecciaed iron formation

Commonly numerous of quartz veins, lesser amounts of pegmatitic bodies, brecciaed iron formation observed invading the country rocks throughout the area. Occurrence of these bodies with the associated alteration features suggests an intense hydrothermal activity. They are strongly deformed, broadly discordant, and irregular or lensoid bodies maintaining a common sinuous feature expressed mainly through swinging along N-S and NE-SW directions with steep dip westwards. In the study area the pegmatites seem to be older than most generations of quartz veins as they found terminating against some quartz veins. The quartz veins represent an important episode in the history of the area since their emplacement was connected with the hydrothermal activities that brought about the gold mineralization. They have variable sizes ranging from stringers, pods and narrow veins up to wide ones, they are present in all unit rocks in the study area, they are varying colors, white, grey, milky, smoky, yellowish, brown, and reddish depending on weathering.

Sedimentary Deposits

Cretaceous Sandstone

Two outcrops of this rock types occurs in the study area, J. Higare Algabia about 20 km north J. Addali and J. Grarisa about 25km north to J. Abel, their rocks are sandstone and conglomerate associated with mudstone and siltstone. These rocks have multicolor, poorly sorted, coarse, medium, and fine grains, composed mainly of quartz pebbles, flake of feldspars and matrixes of silica and iron materials. Additionally, to lateritic soil in the west side of J. Addali and in Assahaba village.

Recent Superficial Deposits

These materials include stabilized black cotton cover and Blue Nile and White Nile deposits, their thickness ranging from few meters up to hundred meters towards the Niles. The field description and characteristics of the various rock units mapped in the study area have been compiled a geological map (Fig. 3).

Structure and Deformations

According to field investigation, petrographic studies, previous investigations and regional correlation between the area and it is adjacent, we can suggest that the area had been affected by four phases of deformation, the earliest one are **D_1** they are manifested by the structural complexities of gneisses in the west side of the study area and supracrustal rocks in the east. These rocks were suffered by a longer deformational history than those tectonically overlying low grade metamorphic facies. The present of folds (**D_2**) and refolds (**D_3**) in the schist group rocks as well as crystallization of quartz, indicate the area had been affected by another deformation associated with the lateral motion deformation (Plate.3 B) so, the study area has been located in the shear zone region. The last deformation phase is **D_4** which related to faults, joints and associated dykes.

Geochemical Statistics

Statistically this study takes the mean value of an elements is equal to their background value depending on the nature of distribution of datasets. Following the procedure of Sinclair (1976) the means and standard deviations were used in calculation of thresholds and anomalous values, so the threshold values in this study is equivalent to b+2S, where b is the background, and S the standard deviation of contents, table (1) has been determined the descriptive statistics (statistical and geochemical parameters) of an elements in the rock units of the study area. However, all values above the background were considered as anomalies and all values above the threshold were strong anomalies. Spearman Rank Order with consider the significant correlation value between an elements are greater than 0.5, that have been determined the interrelationship between elements (Table. 2), the results showing a strong positive correlation between Mn, Co, Zn, Ni, Cr and Fe and negative between (Au, Cr and Fe). Following Kelley, K. D. and Kelley, D. L, method the factor analyses of geochemical datasets of the study area with consider the significant factor value greater than (0.40) are obtained two factor loadings (Table. 3); Factor loading 1 is important because Au, Cr, Co, Mn, Zn, Ni and Fe are situated on it. Factor score is the effect of a particular factor on each sample site, it has been calculated in

this study by the mean of concentration of elements of the significant factor in the sample supposing 5 ppm for the highest concentration elements (Table. 4). Factor score (Factor loading 1) has been plotted in the base map, the result is factor anomalous scores map of the study area which determine the NE direction of mineralization process (Fig.5 A). With regards to the cluster analysis dendrograph of the geochemical datasets of the study area, there are three descriptors cluster (Fig. 5 B), the first cluster involved (Mn, Pb, Zn and Ni) and second cluster (Cu and Cr), this metals grouping spatially associated with Archean metavolcanogenic (metavolcanosedimentary), where the third cluster involved (Ag, Co and Au) and these associated elements with metamorphic and igneous as traces.

Results and Discussion

Ore microscopic investigation showing many minerals disseminated in the rock units of the study area such as gold, native cupper, hematite, goethite, azurite, chalcopyrite and malachite (Plate.7), this provided further evidence of mineralization in the study area. The results of chemical analysis of quartz veins samples indicated a highest concentration of gold east Attaro; a highest concentration of Au in the rock unit samples in sheared granite at J. Abel; Ag in basalt at J. Addali; Mn, Zn, Ni and Co in iron graphitic chlorite schist at J. Ahmar Ain ; Cu in chlorite schist at J. Allidir; Cr in lateritic soil at Assahaba; Pb sheared granite at J. Daia and Fe in pyritic chlorite schist south Assalamat village. Geostatistically, the average of coefficient of variation of this elements are high (1.78) that suggests the elements are inhomogeneously (erratically) distributed. Worth mentioning that no all samples showing Ag greater than the detection limit contain anomalous amount of gold, so Ag can be considered as undependable pathfinder element for gold in the area. The interrelationship between metals are strong, therefore they are the same source. Due to multi- generation of quartz veins, Au dissemination in quartz veins have been removed from anomalous mineralization zones map, but in the rock units they have been plotted as other elements, also iron have wide spread and high concentration their zones may covered other elements zones in the map so it has been removed from anomalous mineralization zones map too. The mineralization zones that discovered in new structures in the study area and their "ppm" concentration are: Two zones of **Au** located at Abel, Addali and four zones of it in Attaro areas their grades between 0.67- 2.01; three zones of **Co** one zone located in Ahmar Ain and two in Addali area their grades between 52.95-104.52; Two zones of **Mn** located at Ahmar Ain and Addali areas their grades between 2814.20-6533.26; One zone of **Ag** located at Addali area their grade between 122.66- 367.95; One zone of **Cu** located at J. Allidir their grade between 148.85-444.96; One zone of **Pb** located at J. Daia their grade between 562.99-1238.48; One zone of **Cr** located at Assahaba area their grade between 112.77-253.67; One zones of **Zn** and **Ni** located at Ahmar Ain area their grades between 381.30-1134.85, 291.51-874.55 respectively. These zones have been compiled in anomalous mineralization zones map (Fig. 4).

Conclusions

The study area are mainly underlain by Proterozoic low grade metamorphic rocks relative covered by recent black cotton soil. It is a highly important link lying at the junction between ANS and MB, thus considered as a good example of plate tectonic models and associated metallogeny. It is relatively polymetallic hydrothermal mineralization that revealed by presence of quartz veins and iron brecciaed quartzite rocks in addition to their elements content. Nevertheless, the procedure of factor analysis is a helpful in mineralogy where cluster analysis may still be helpful in geological mapping (lithology). The potential mineralization zones which discovered during this study are Attaro, Addali, Abel, and Ahmar Ain areas they are required a sequential exploration program including detailed mapping, geophysical investigation, and drilling to delineate the potential prospects of this base metals.

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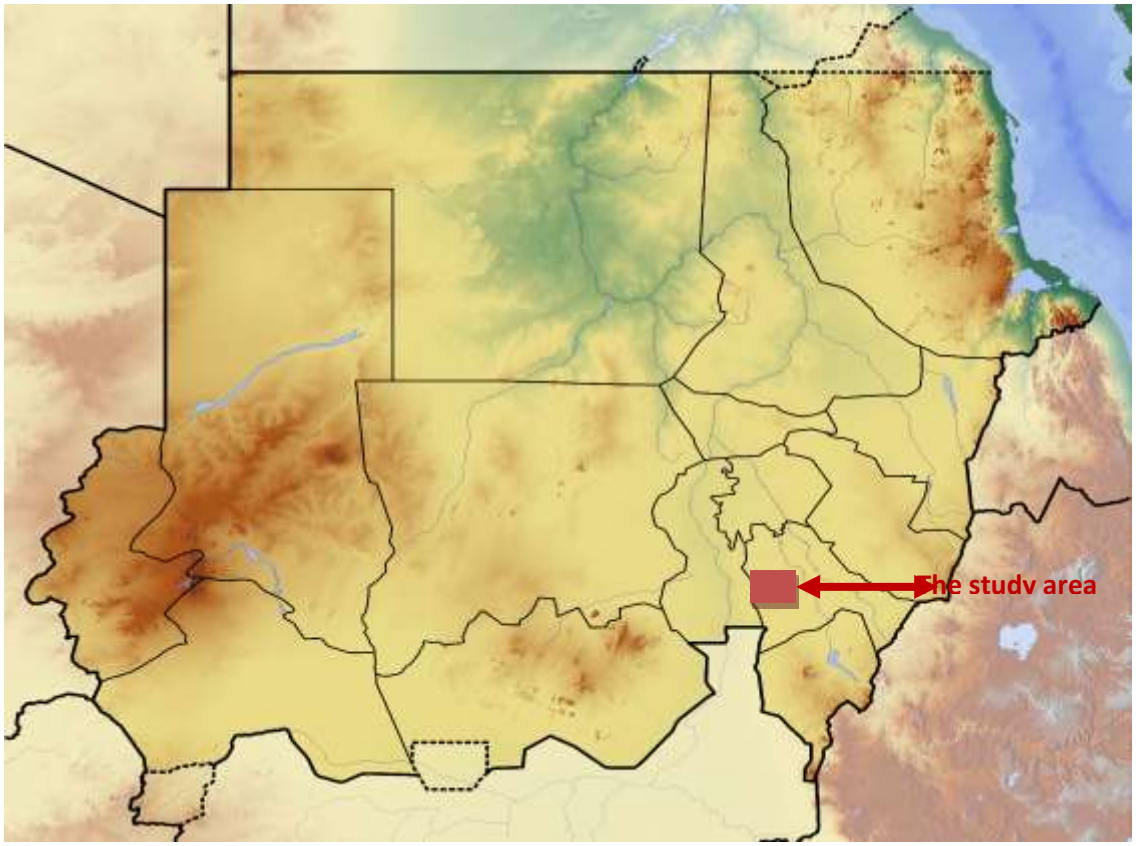

Fig .1 Location of the study area

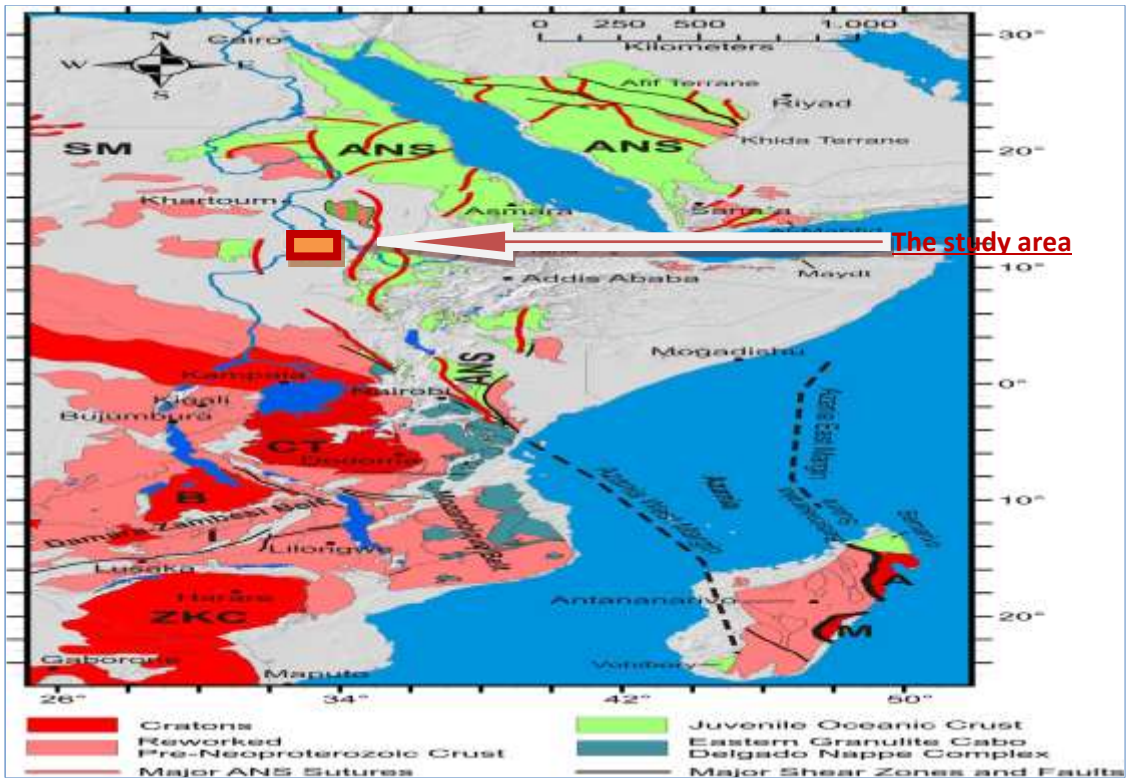

Fig.2 Location map of study area with ANS and MB (after H. Fritz)

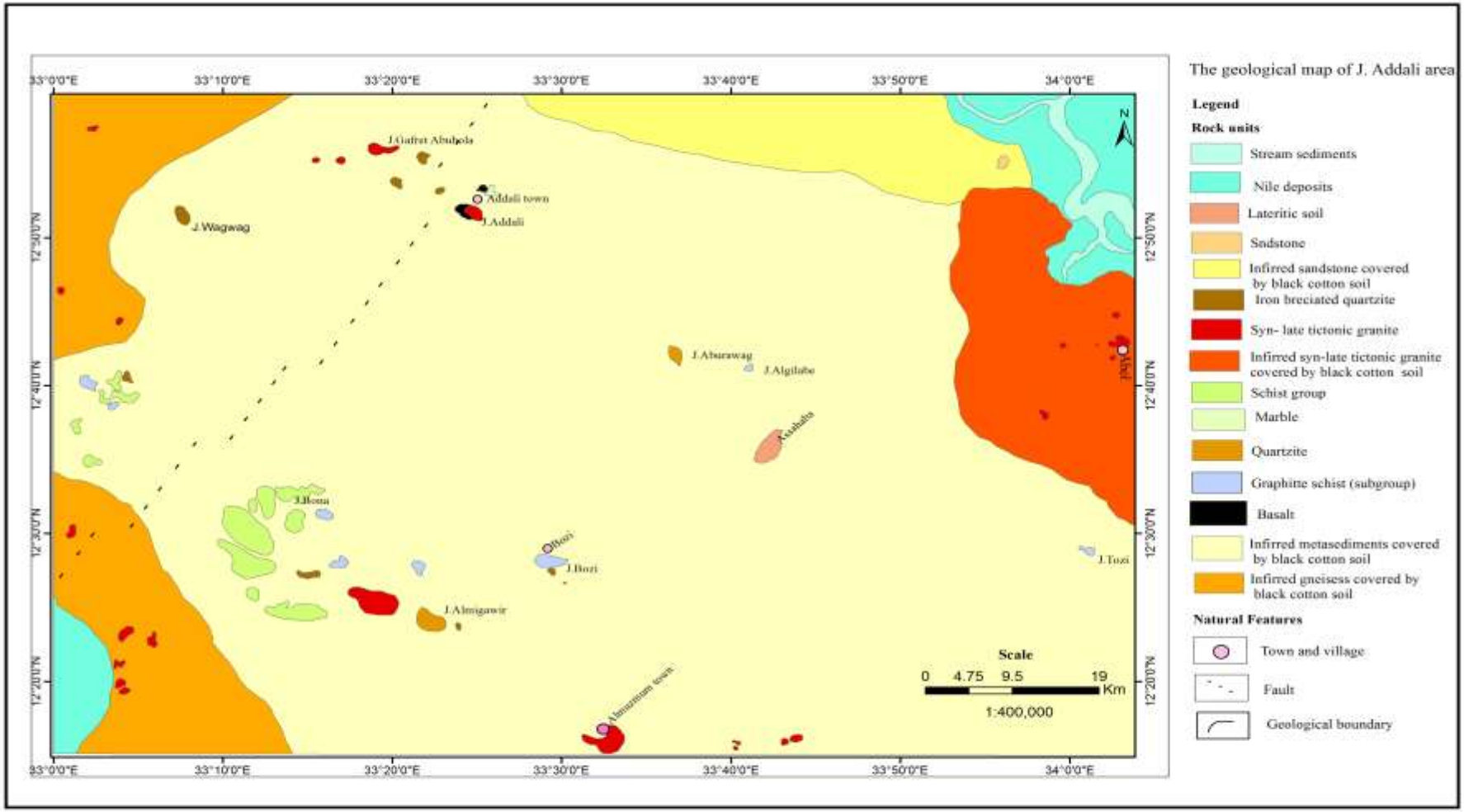

Fig. 3: Goelogical map of the study area

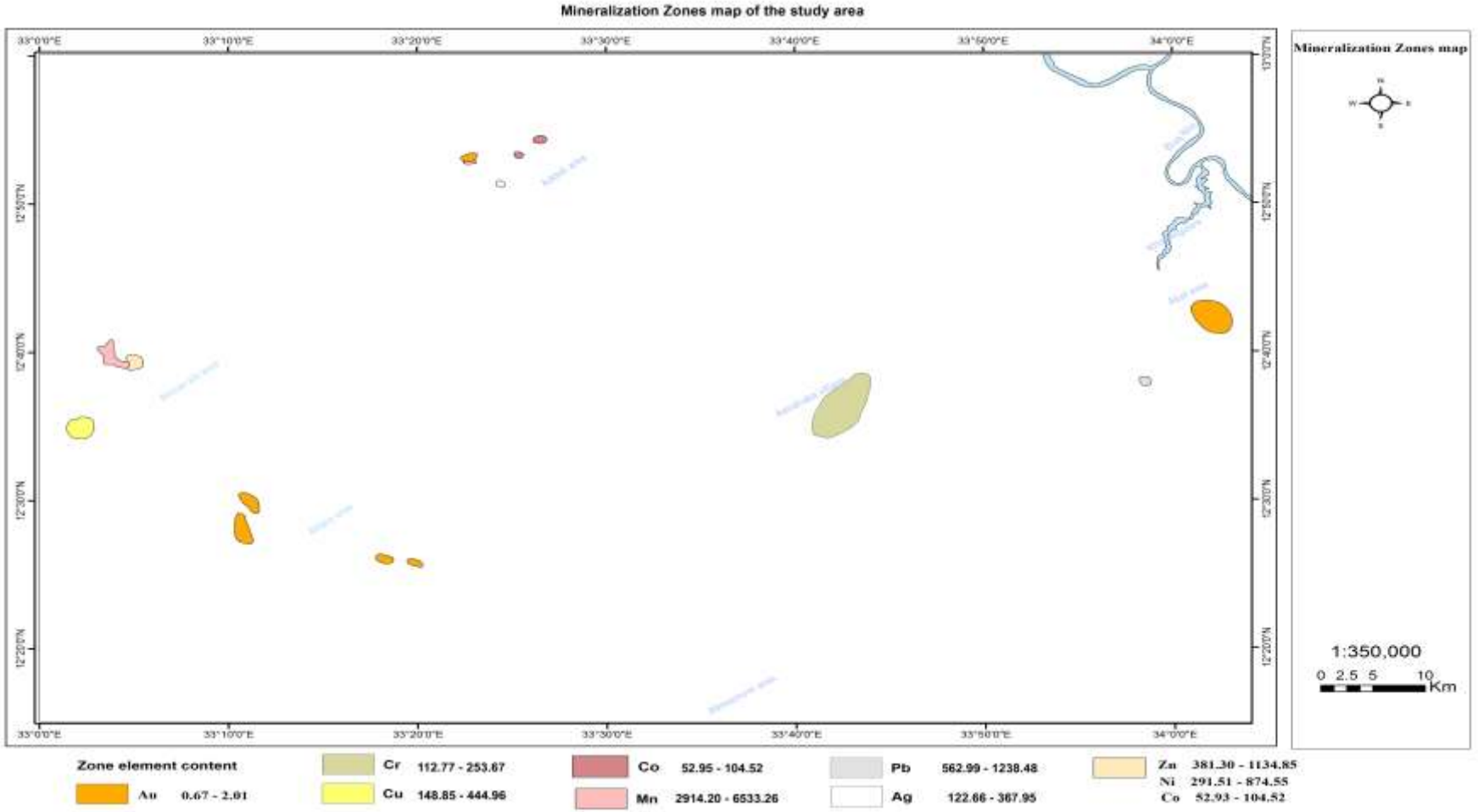

Fig.4: Anomalous mineralization zones of the study area

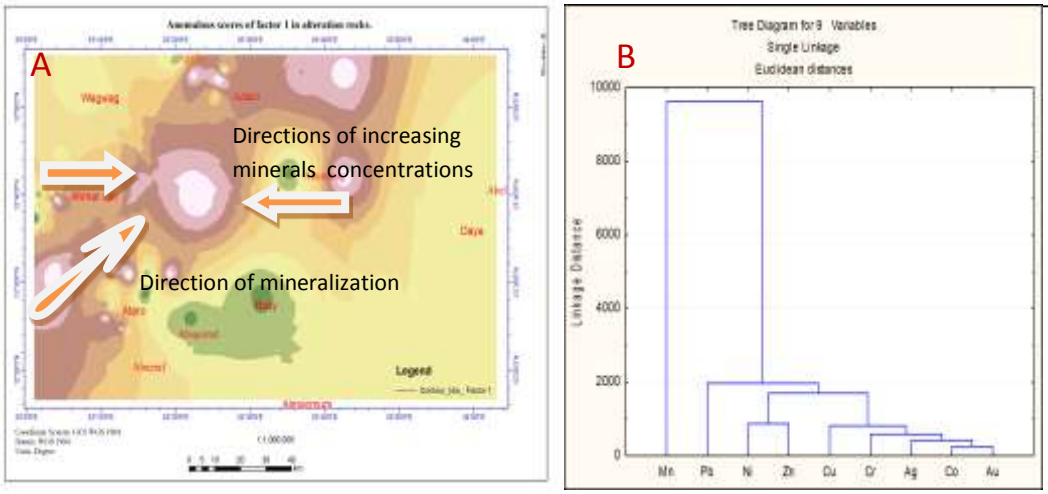

Fig.5. A Photograph showing map of anomalous scores of factor (1), B: Cluster analysis dendrograph of geochemical datasets of the study area.

Plate.1. Photographs showing: A. Graphite schist in artesian mining drilled around J. Aburawag. B. Graphite schist associated with chlorite schist and iron materials east side of J. Ahmar Ain.

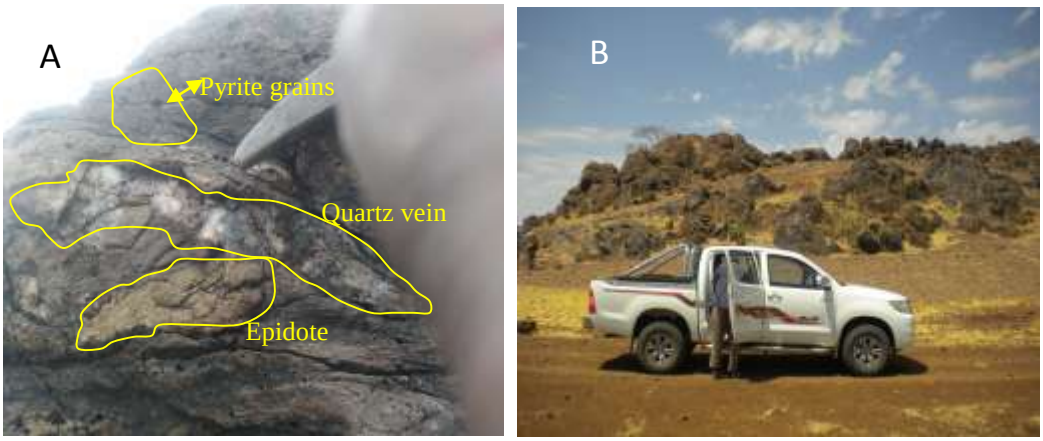

Plate.2. Photographs showing: A. Quartz and epidote veins and distributed pyrite grains in chlorite schist (J. Assalamat). B. Breciated quartzite injected by iron materials west J. Addali.

Plate.3. Photographs showing: A. Boulders of discontinuous marble bands obscured by superficial deposits (east J. Addali). B. Relic of the vertical motion off-set deformation in the east edge of Attaro hills.

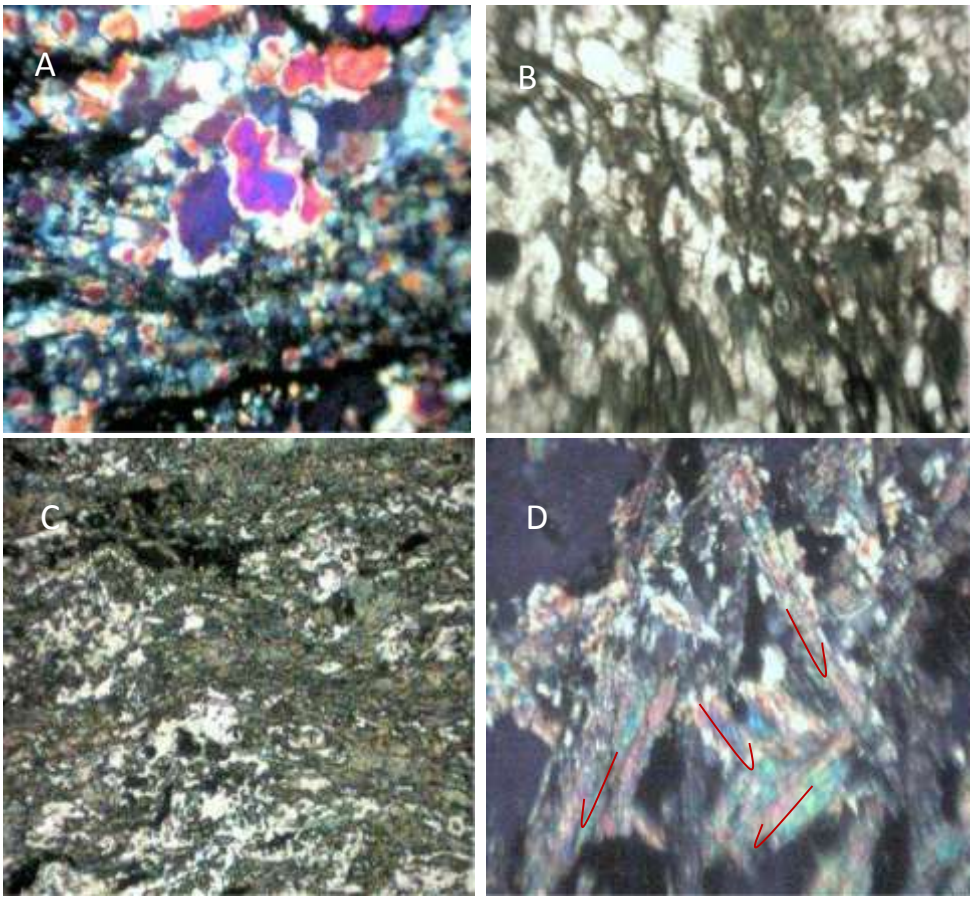

Plate.4: Photomicrographs showing the contents, alteration and deformations occurs in schist group rocks. A: Sutured quartz (white), anheadral grains of graphite (black) and foliated iron oxides (black) - veinlet shape in graphite schist (J. Bozi). B: Foliated chlorite (green), highly deformed quartz crystals (white) and foliated iron oxides (black) in chlorite schist (J. Abuerafe). C: Quartz grains (white) between flakes of chlorite (green), biotite (brown) and opaque minerals (black) in biotite chlorite schist at the foot of J. Addali. D: Different direction of foliated muscovite, sutured margins and triple junction quartz crystals (white) and porous filled hematite (dark) in chlorite muscovite schist (J. Allidir). (All photomicrographs under XPLX4).

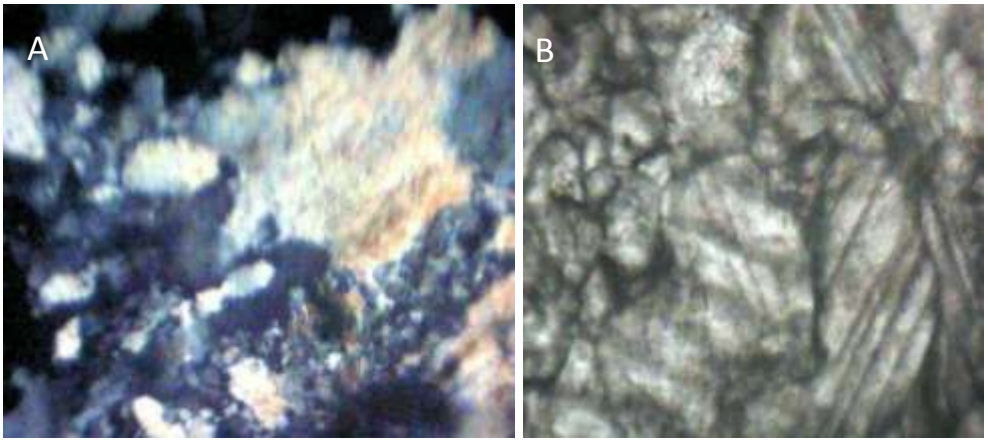

Plate.5: A and B Photomicrographs showing contents, alteration and deformations occurs in quartzite and marble. A: Elongation and suture margins quartz crystals (white) and veins of iron oxides(black) of J. Aburawag quartzite. B: Rhombic cleavage of calcite (hashed white) and slightly foliated iron oxides (black) of Marble east J. Addali. (All photomicrographs under XPLX4).

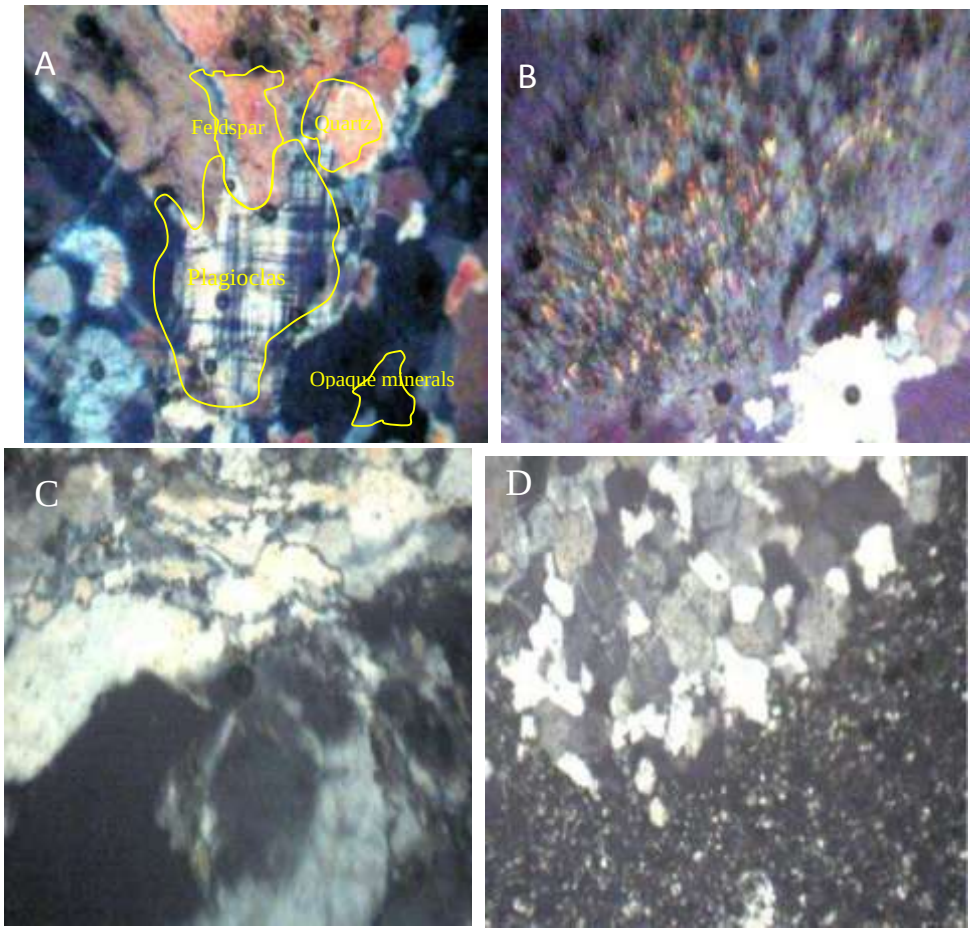

Plate.6: Photomicrographs showing contents, alteration and deformations occurs in syn to late-orogenic grainitiod rocks. A:The general contents of grainitiod rocks (J. Abel). B: presence of serecite (brownish) after feldspars (J. Adaali). C. Wavy extinction, ribbons and suture margins quartz (white) of J. Daia sheare granite. D: Mono crystalline and microcrystalline quartz crystals in highly deformed shear granite (J. Abugurod). (All photomicrographs under XPLX4).

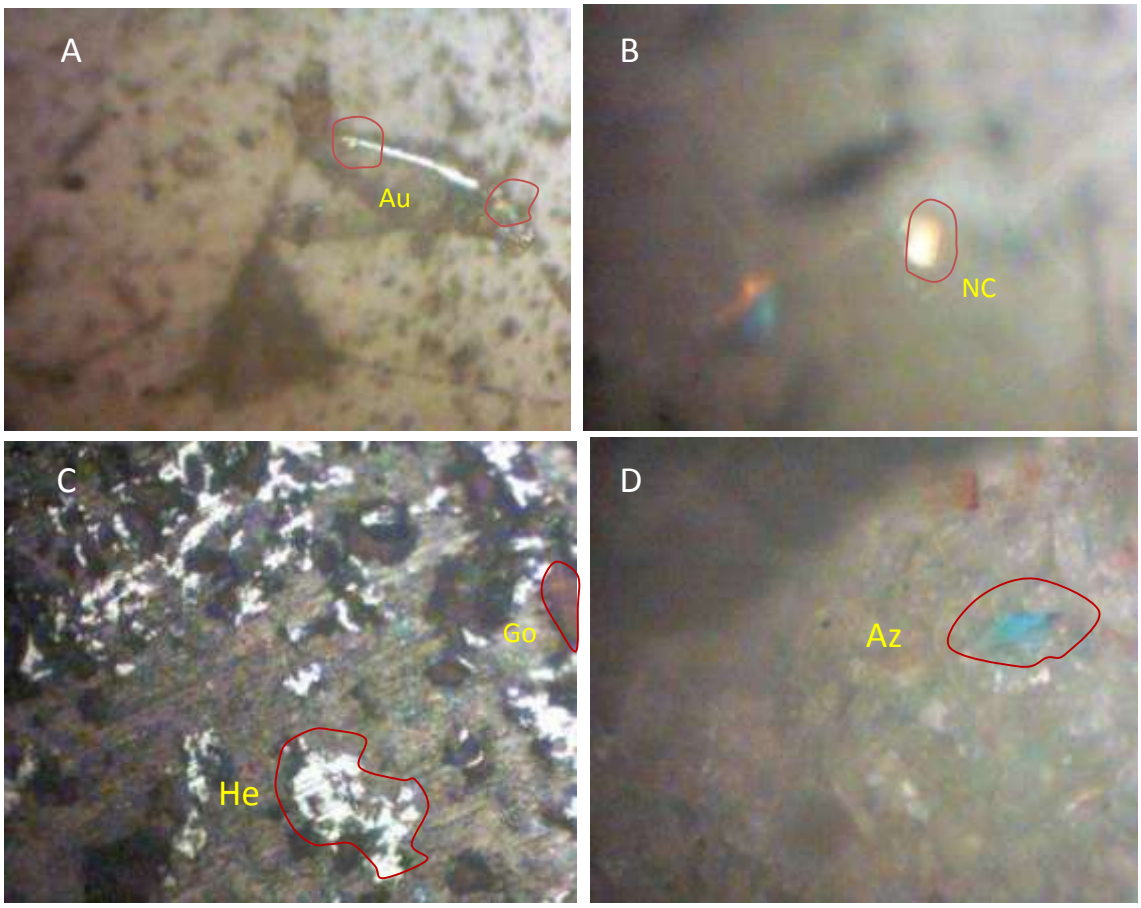

Plate.7 Photomicrographs showing ore minerals dissemination. A: Gold (Au) in sheared granite (J. Abel). B: Native copper (NC) in highly deformed shear granite (J. Abugorud). C: Hematite and goethite (He, Go) in quartzite (J. Amigawir) D: Azurite (Az) in chlorite schist (Attaro south Asalamat village).) (A,B and C under X10. D under X20).

Plate.8: Photomicrographs showing the high grade metamorphic minerals (kyanite and sillimanite) of supracrustal formation of J. Kardos. a: under PPL, b: under XPL.

Au ppm: Concentration of gold in quartz veins; Min : minimum; Max : maximum; S : standard deviation; b : background; X : mean; Th : Threshold; C.V : coefficient of variation; A.V : anomaly coefficient.*

Table.1: Descriptive Statistics (statistical parameters and geochemical parameters per ppm) of an elements in the rocks units.

Element	Valid	Min	Max	S	b = X	Th= b+2S	C.V= S/X	A.C
Au*	156	0.00	6.15	0.84	0.41	2.1	2.05	0.69
Au	71	0.00	2.04	0.63	0.59	1.85	1.06	0.63
Ag	71	0.00	402.00	47.88	13.95	109.71	3.43	0.85
Mn	71	17.00	7164.00	1175.71	661.82	3013.24	1.78	1
Co	71	0.50	114.90	25.31	17.40	68.02	1.45	1
Cr	71	0.03	261.80	67.05	45.55	169.65	1.47	1
Cu	71	0.00	446.20	88.62	60.14	237.38	1.47	0.97
Pb	71	0.00	1239.00	184.68	172.40	541.74	1.07	0.99
Zn	71	1.80	1305.60	271.18	121.33	663.69	2.24	1
Ni	71	0.00	1228.70	218.03	66.94	503.00	3.26	0.44
Fe	71	16756	87240	15762	62853	94379	0.25	1

Table .2: Spearman Rank Order (Marked loadings > 0.5 are significant correlation between an elements).

Variable	Au	Ag	Mn	Co	Cr	Cu	Pb	Zn	Ni	Fe
Au	1.00									
Ag	-0.02	1.00								
Mn	-0.09	0.06	1.00							
Co	-0.21	0.06	**0.72**	1.00						
Cr	**-0.50**	-0.10	0.13	0.32	1.00					
Cu	0.17	0.02	0.11	0.20	-0.20	1.00				
Pb	-0.17	0.07	-0.04	-0.04	-0.02	-0.04	1.00			
Zn	-0.11	-0.05	**0.67**	**0.88**	0.13	0.09	-0.01	1.00		
Ni	-0.19	-0.04	**0.54**	**0.85**	0.22	0.03	0.00	**40.96**	1.00	
Fe	**-0.63**	0.08	0.20	0.29	**0.56**	-0.13	0.01	0.23	0.27	1.00

Table .3: Factor analyses result, Marked loadings is the significant factor (Kelley, K. D./ Kelley, D. L).

Variable	Au	Ag	Mn	Co	Cr	Cu	Pb	Zn	Ni	Fe
Factor 1	**0.40**	0.02	**0.74-**	**0.93-**	**0.45-**	0.06-	0.01	**0.90-**	**0.89-**	**0.52-**
Factor 2	**0.73-**	0.12-	0.29-	0.23-	**0.66**	**0.48-**	0.16	0.33-	0.21-	**0.67**

Table .4: Factor (1) scores of an elements in the rock unit samples

S. No	Factor 1	S. No	Factor 1	S. No	Factor 1	S. No	Factor 1
1	3.32	19	2.88	37	2.73	55	5.00
2	3.23	20	3.35	38	3.34	56	5.00
3	3.35	21	3.01	39	2.78	57	5.00
4	3.34	22	2.74	40	3.36	58	5.00
5	3.35	23	3.36	41	3.35	59	5.00
6	3.34	24	3.36	42	3.35	60	5.00
7	3.36	25	3.28	43	5.00	61	5.00
8	3.11	26	3.35	44	5.00	62	5.00
9	3.35	27	4.18	45	5.00	63	5.00
10	2.98	28	3.35	46	5.00	64	5.00
11	3.35	29	2.97	47	5.00	65	5.00
12	3.09	30	2.60	48	4.33	66	4.53
13	2.96	31	3.35	49	5.00	67	5.00
14	2.94	32	2.70	50	5.00	68	4.47
15	2.62	33	4.20	51	5.00	69	5.00
16	3.35	34	3.35	52	5.00	70	5.00
17	3.36	35	3.35	53	5.00	71	5.17
18	3.30	36	3.24	54	5.00		